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Preparatory study for solar photovoltaic modules, inverters and systems

Final report

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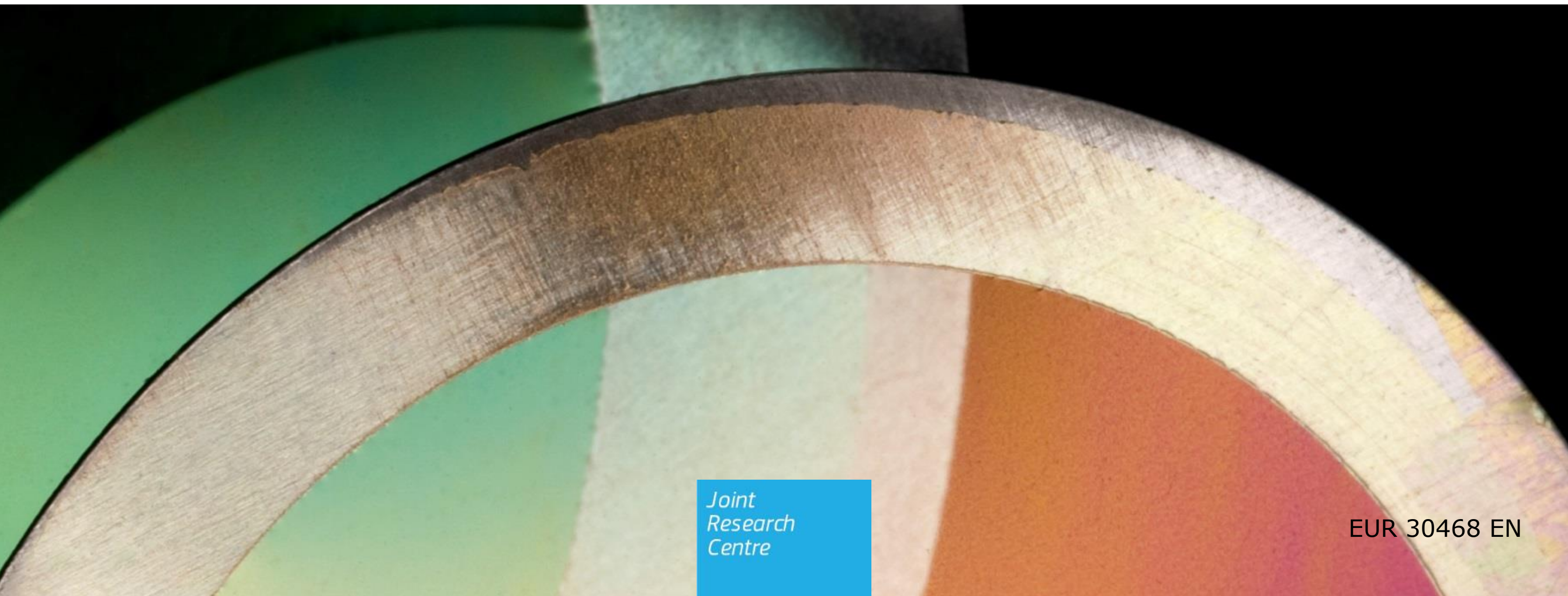

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Contents

Foreword

This document contains the preparatory work for the assessment of EU product policies for photovoltaic products, including Ecodesign,Energy Labelling, Ecolabel, and Green Public Procurement.

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Executive summary

Policy context

As announced in the 'European Green Deal', decarbonisation of the EU energy system is crucial to reach Europe's climate objectives. To this extent, a power sector largely based on renewable sources must be developed, complemented by a rapid phasing out of coal and by decarbonising gas. In particular, the Renewable Energy Directive 2018/2001/EU establishes a binding renewable energy target for the EU for 2030 of at least 32% of the Union's gross final consumption in 2030, with an upwards revision clause by 2023. To reach that goal of 32%, the cumulative solar photovoltaic capacity in the EU and the UK would need to increase to 455–605 GW, corresponding to an increase of four times the current capacity in the EU.

It is therefore imperative that newly installed photovoltaic products in the European Union do not create new future burdens on the environment. In this context, regulatory measures in the field of sustainable product policy will play an instrumental role ensuring the environmental sustainability of photovoltaics by improving their environmental performance as well as their energy yield, while reducing the overall life cycle environmental footprint.

What does this report address?

This preparatory study offers a comprehensive techno-economic and environmental assessment for photovoltaic products in order to provide policy makers with the evidence basis for assessing whether to implement four policy instruments: Ecodesign, Energy Label, Ecolabel and Green Public Procurement (GPP). It evaluates the feasibility of the application to solar photovoltaic modules, inverters and systems and their significance for the EU sustainable policy. The study comprises a comprehensive analysis of these three photovoltaic products using the Methodology for Ecodesign of Energy related Products, with the aim to develop a research evidence base to feed into decision making on the aforementioned policy instruments.

This evidence base contains information on:

- environmental,
- user-related,
- technical and
- economic

characteristics of the solar photovoltaic modules, inverters and systems.

The study makes an analysis of the Best Available Technology (BAT) and Best Not yet Available Technology (BNAT) options for each photovoltaic product. It subsequently tests a series of future potential policy scenarios, and concludes with policy recommendations in terms of the feasibility of packages of Ecodesign, Energy labelling, EU Ecolabel and GPP requirements, bearing in mind the specificities of the different policy processes.

The work was carried out by the JRC 'Industrial leadership and circular economy' Unit for the Directorate General Internal Market, Industry, Entrepreneurship and SMEs (DG GROW).

Key conclusions and main findings

The environmental performance of several 'design options' was analysed using primary energy (Gross Energy Requirement in MJ) as the lead indicator. In addition, secondary environmental indicators were also identified based on their relevance to the life cycle of the products, e.g. global warming potential (GWP). The gross energy requirement (GER) was deemed to be in line with the objectives of Ecodesign, which is to identify improvement options associated with the energy use of the product and its associated manufacturing processes (as opposed to emissions from associated grid infrastructure).

Upon analysing the results obtained for the lead indicator of primary energy (GER), the following was observed when benchmarking design options with a base case for each product:

- Solar photovoltaic modules:
    - ✓ In the residential market segment, the BAT is the Cadmium Indium Gallium Sulphide thin film design
    - ✓ For the commercial and utility segments, the Cadmium Telluride thin film design was the BAT, although composite design improvements based on the family of Passivated Emitter Rear cell (PERC) architectures have the potential to deliver a comparable performance to the CIGS design for the GER results. This is particularly the case if BNAT options such as kerfless wafers and design for recycling were to be implemented.
- Inverters:
    - ✓ In the residential market segment, the option that considered longer life and the repairability potential option were the two BATs, with both achieving a significant margin of 54-61% improvement upon the base case

- ✓ In the commercial segment, the repairability option comes out as the BAT, showing a 52% improvement.
- ✓ In the utility segment there appears to be very limited margin to identify a BAT based on the design options modelled.

- PV systems:
  - ✓ In the residential market segment, options which include a long life inverter or an inverter designed for repair, as well as options that have had the system performance ratio (PR) optimised – either from a design or an operation & maintenance perspective - were identified as BAT.

A sensitivity analysis of the influence of the electricity grid mix in difference global regions was also made, showing that a variance of up to 38% can be seen in the results when using life cycle GWP, suggesting that GWP could also be used to screen for the geographical influence of electricity and fuel infrastructure.

The greatest improvement in yield until 2050 is estimated to be achieved by the combination of the mandatory instruments (i.e. Ecodesign and Energy Label) and the voluntary Green Public procurement (named COM 6.1), according to the results of modelling policy scenarios.

However, in terms of the annual GER, the scenario with the combined mandatory instruments and the EU Ecolabel (named COM 6.2) appear most beneficial according to the results of the scenario modelling. This scenario is modelled as providing a benefit of up to 21% on the business as usual (BAU) for the period 2025 – 2035, with the improvement largely driven by the mandatory Ecodesign instrument, supported by the EU Ecolabel.

Given the policy significance of renewable energy deployment and consequently renewable energy yield to the EU's climate change mitigation objectives, it is considered that COM 6.1 (consisting of mandatory instruments plus Green Public Procurement) is the preferred option. This option is driven by mandatory instruments that can strongly influence the life cycle energy yield, and in the case of Ecodesign this can be used to lay down market entry requirements that can influence the stock life cycle GER. The GPP voluntary instrument could, moreover, be used to exert a range of broader market influences via local and regional government, with a particular focus on increasing residential solar PV system deployment. In the case of the EU Ecolabel, the potential influence on the residential market segment is considered to have a higher level of uncertainty compared to GPP.

This study has also identified that solar PV technology achieves a relatively high Energy Return on Investment across all the policy options. This is because the energy invested in the production stage to extract raw materials and manufacture modules and inverters is, even in the worst case scenarios modelled, a factor of approximately 4-7 times less than the use stage benefit from energy generation.

There is momentum to implement Ecodesign and Energy Label regulations for photovoltaic products, as there is a need to foster photovoltaic products in the EU markets with higher efficiency (understood as in terms of the conversion of energy but also material efficiency including durability). The expected and substantial growing that the photovoltaic market will experience (10 TW for 2030) and especially in the residential sector, makes the regulation opportune.

Related and future JRC work

The JRC has produced several related works to support this study. A technical report studying separately the feasibility of the voluntary policy tools was produced, which is listed here:

- Dodd N., Espinosa N., Solar photovoltaic modules, inverters and systems: options and feasibility of EU Ecolabel and Green Public Procurement criteria, Preliminary report, Publications Office of the European Union, Luxembourg, 2020, JRC122430

To further support this preparatory study, there have been produced two standards JRC technical reports listed below:

- Dunlop E.D., Gracia Amillo A., Salis E., Sample T., Taylor N., Standards for the assessment of the environmental performance of photovoltaic modules, power conversion equipment and photovoltaic systems, EUR 29247 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-86608-1, doi:10.2760/89830, JRC111455
- Dunlop E.D., Gracia Amillo A., Salis E., Sample T., Taylor N., Transitional method for PV modules, inverters, components and systems, EUR 29513 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-98284-2, doi:10.2760/496002, JRC114099.

The JRC will continue the support on the potential impacts that this legislation may have in the EU.

Introduction

The European Commission launched in 2017 the Preparatory study on sustainable product policy instruments to assess the feasibility of applying Ecodesign, Energy Label, Ecolabel and Green Public Procurement instruments to solar photovoltaic modules, inverters and systems. The preparatory study has been coordinated by the European Commission's DG Internal Market, Industry, Entrepreneurship and SMEs, in colaboration with the DG of the Environment and DG Energy. It has been undertaken by the Commission´s Joint Research Centre (JRC) with support from VITO.

The four policy instruments assessed by the study are either mandatory - in the case of Ecodesign and the Energy label – or voluntary in nature - in the case of the EU Ecolabel and Green Public Procurement criteria. Each of the four policy instruments has been assessed in accordance with the relevant framework legislation that governs how each of them shall be implemented:

- The Ecodesign The Directive 2009/125/EC on Ecodesign [4] establishes a framework for EU Ecodesign requirements for energy-related products with a significant potential for reduction of energy consumption. The Directive requires manufacturers placing products on the EU market to improve their environmental performance by meeting mandatory minimum energy efficiency requirements, as well as other obligatory environmental requirements such as water consumption, emission levels or material efficiency aspects.
- The Energy Labelling Regulation [5] provides consumers with a straightforward informative and visual tool to make a better purchase choice, by grading products according to a well-known A-G/green-to-red seven class label. It is to be supported in the future by the establishment of a product database on energy efficiency and by the introduction of a safeguard procedure to improve national market surveillance.
- The EU Ecolabel Regulation [7] establishes the label as a tool to encourage businesses to develop products with a reduced environmental impact throughout their whole life cycle, and to help consumers find the best environmentally performing products in their category.
- The Communication on Green Public Procurement (GPP) promotes the development of criteria [6] that can be used to identify environmentally friendly goods, services and works; their voluntary use by EU public authorities is intended to stimulate demand for more sustainable goods and services which otherwise would be difficult to bring onto the market.

The main objective of the study is to provide technical support for the development of a preparatory study to assess the feasibility of Ecodesign and/or Energy labelling requirements, as well as the potential for Ecolabel and Green Public Procurement criteria, for the PV panels, inverters and systems product group. The methodology of the study follows the Commission's Methodology for the Evaluation of Energy related Products (MEErP) (COWI and VHK 2011b), consisting of the following steps:

- Task 1 – Scope definition, standard methods and legislation
- Task 2 – Market analysis
- Task 3 – Analysis of user behaviour and system aspects
- Task 4 – Analysis of technologies
- Task 5 – Environmental and economics
- Task 6 – Design options
- Task 7 – Policy analysis and scenarios
- Task 8 – Policy recommendations

Given that for solar photovoltaic panels, inverters and systems, the preparatory work on the assessment of Ecodesign/Energy Labelling was intended to occur at the same time as the preparatory work on the assessment of EU Ecolabel product criteria for the same products, it was the intention of the European Commission to develop the evidence base in one single research process, simultaneously providing supporting information to Ecodesign/Energy Labelling, GPP and EU Ecolabel decision making processes. To that end special subtasks have been incorporated into the MEErP methodology that are designed to systematically assess the environmental impacts that are associated with the different products in a standardised manner that provides the technical evidence also required for the voluntary instruments. In this way, the study identifies the hot-spots across different life cycle stages and at the level of specific material flows/inputs and emissions in order to facilitate the identification of potential criteria areas for EU Ecolabel and GPP.

The research is based on available scientific information and data, uses a life-cycle thinking approach, and is grounded in a three stage stakeholder engagement process, which sought expert input in order to discuss key issues, gather data and information and, to the extent possible, reach consensus on the proposals. A set of information of interest has been collected, revised, updated and integrated to reflect the current state of play, following the MEErP methodology.

A Technical Working Group (TWG) of stakeholders has been created in order to support the JRC along the study. This Technical Working Group is composed of experts from Member States, industry, NGOs and academia who have voluntarily requested to be registered as stakeholders of the study through the project website (https://susproc.jrc.ec.europa.eu/solar_photovoltaics/).

The TWG has contributed to the study with data, information and written feedback to questionnaires and working documents. Interaction with stakeholders has also taken place in the form of three meetings organised by the JRC during 2018 and 2019:

- 1st Technical Working Group (TWG): 29th of June 2018, in Brussels.
- 2nd Technical Working Group (TWG): 19th of December 2018, in Brussels.
- 3rd Technical Working Group (TWG); 10th and 11th of July 2019, in Brussels.

Structure of this report

This document is structured in the following chapters, following Tasks 1 to 7 of MEErP puls Task 8 Policy recommendations:

- Chapter 1 – Task 1. Scope and definitions, defining the products and presenting relevant standards and legislation;
- Chapter 2 – Task 2 Markets, presenting economic and market data of PV products and systems at the EU28 level;
- Chapter 3 – Task 3 Users and system aspects, describing user behaviour, key aspects influencing such practices and system aspects related to PV products and systems;
- Chapter 4 – Task 4. Technical analysis including end of life, analysing products from a technical point of view with a special focus on design, technology and innovation.
- Chapter 5 – Task 5. Environment and economics: an environmental and economic assessment of base-cases
- Chapter 6 – Task 6. Design options: an analysis of the improvement potential achievable for this product group through the implementation of best available technologies and best not available technologies
- Chapter 7 – Task 7. Policy scenarios assessment: a streamlined impact assessment of different policy options
- Chapter 8 – Task 8. Policy recommendations

1 Task 1: Product Scope

The aim of Task 1 is to analyse the scope, definitions, standards and assessment methods and other legislation of relevance to the product group and to assess their suitability for classifying and defining products for the purposes of analysing Ecodesign and Energy Label requirements, and in turn to analyse the suitability of using this product scope for the EU Ecolabel and Green Public Procurement.

1.1 Product Scope and Definition

The following sections first provide a brief introduction to photovoltaics, and then an analysis of existing definitions of photovoltaic modules, inverters and systems, as used for example in European statistics, EU legislation, standards and other voluntary initiatives such as ecolabels; together with stakeholder feedback on the suitability of existing scope and definitions for each of the policy instruments in question.

1.1.1 Basic introduction to photovoltaic technology

The solar photovoltaic effect was discovered in 1839 as an off shoot from photochemical experiments. The first silicon photovoltaic cell was created in the 1950's and this technology has been constantly refined since then. At a fundamental level the process is founded on the ability of a semiconductor to convert light into electrical energy.

The photovoltaic effect when a semiconductor material absorbs light and positive and negative electrons are released. These are then extracted from the semiconductor as electric current. The effect takes place in a solar cell which is usually very small and fragile. The electricity generated by a single cell is very small, but when connected together in the form of a solar panel, this output is greatly increased. The cells are also protected by being sealed in a weather proof module consisting of a glass and polymer encapsulation.

The first uses of the more familiar PV module form factor were in the US space program, which required a lightweight and compact energy source for its satellites. This ensured that further research took place on the photovoltaic effect and how to produce more efficient solar panels.

There are different types of solar cells and these are formed into different types of solar panels. Several different generations of solar cells have been developed. The first generation corresponds to *crystalline* silicon solar cell; the second generation comprises solar cells in thin films that includes *amorphous* and *micro crystalline* structures. *Crystalline* cells are cut from a solid ingot of silicon whereas *thin film*s are made by depositing a semiconductor compound on to a substrate. Crystalline PV cells are in general more efficient in their conversion of light to electricity because of their contiguous crystalline structure but usually this comes at a higher manufacturing cost. One of the main activities in the PV industry is to increase the level of efficiency of cells, in relation to their cost. Later generations of cell structures under research and development include organic, dye sensitized or perovskite solar cells. Hybrid or tandem have been developed which combine several generations of cell structures.

Into the first generation, there are two types of crystalline silicon cell: the monocrystalline and the polycrystalline. Monocrystalline is the more efficient of the two, but has been traditionally more expensive because it requires ingots that are grown using special processes and that are made of silicon with a higher purity. The first modules manufactured relied on the use of cells made from reject monocrystalline wafers from the semi-conductor industry (see Figure 1).

Figure 1. Early example of monocrystalline cells in a module

Source: Green Building Advisor (2018).

While the performance of thin films has steadily improved, they did not until recently achieve the same level of performance as the best wafer-based crystalline PV cells. Despite being less expensive, have not had the same market penetration either. The success of thin film has been detrimentally affected by the constant reduction in the cost of crystalline panels.

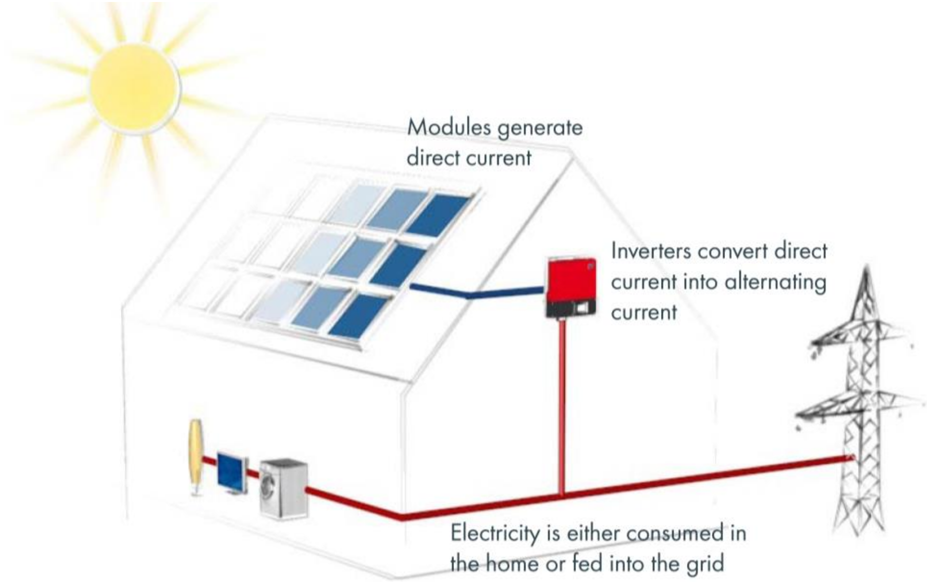
Whatever the technology, the electrical current that is created in the PV cell and subsequently extracted as a current, is direct current (DC) not the alternating current (AC) of the type produced by the alternating magnetic generators in power stations or wind turbines on which the normal mains supply in the EU operates.

Solar power systems

Solar cells made into modules to optimise the electricity generated, normally form part of a system. There are two types of systems: those connected to the grid and stand-alone systems or off grid. The latter use the power created on site, and normally include an electricity storage arrangement. In many EU countries however almost all systems are connected to the grid. They can be mounted on a building or they can be free standing When in a building, the following components are usually present (see Figure 2):

- The solar panels or module array: the combination of solar cells in a weatherproof package
- The racking: this is the equipment that attaches the solar panels onto the roof of the building.
- Cabling: to transport the current generated from the module array to the inverter
- The inverter: this unit(s) converts the DC current from the modules to AC current that can be used in the building or transferred to the grid
- Combiner box(es): this is the terminus of the DC wiring from each module
- The meters: in order to measure the amount of electricity generated. It is usually a legal requirement to claim subsidies such a feed in tariff.

Figure 2. Basic installation of a domestic solar photovoltaic system.

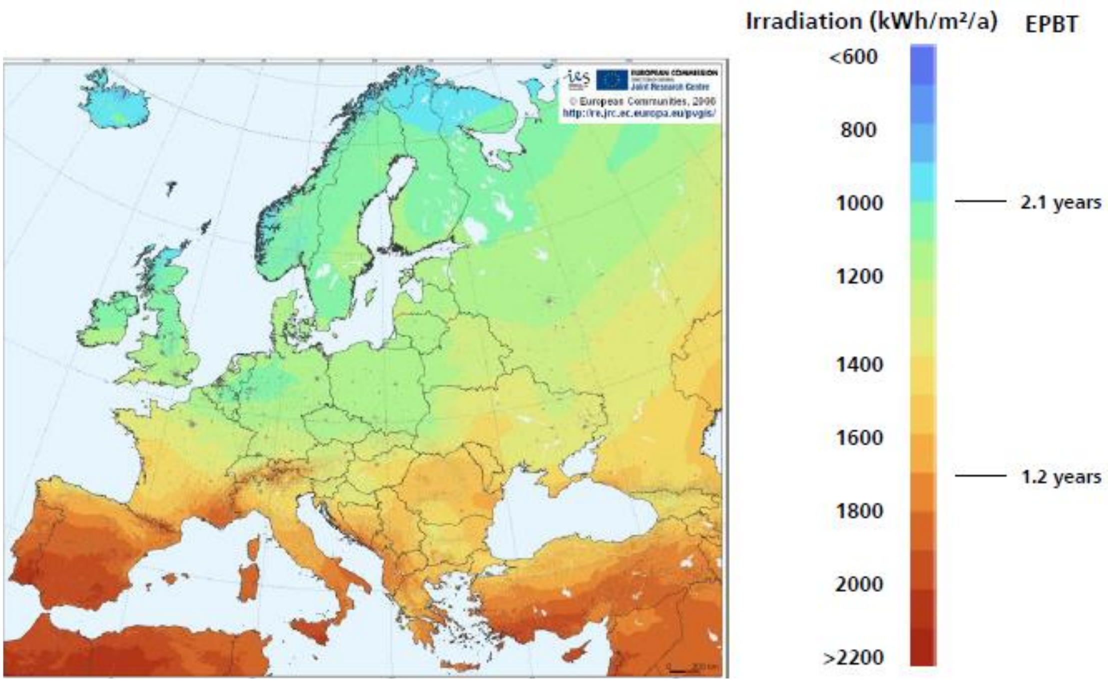


Source: SMA (2018)

The sun's energy

The impact of the suns rays on earth is called irradiance. Levels of irradiance differ depending on the location. Attention therefore has to be paid to the level of irradiance available for a solar project as this will influence the electricity yield. Figure 3 reproduces the map of the EU levels of irradiance. This shows that the Southern latitude (e.g. Spain and Italy) are the best places for solar power, where the average irradiance is 2000-2200 kWh/m2yr. This level makes the energy payback times (EPBT) – the amount of time it takes to generate more energy than it took to make the system - are shorter. However, the greatest interest in installing solar PV has, to date, been in central EU. Germany, France and Italy have been the pioneers in the deployment of solar energy.

Figure 3. EU irradiation and solar electricity potential



1.1.2 Product scope and definition for Ecodesign and Energy labelling

The following section provides an overview of existing definitions of photovoltaics modules, inverters and systems, using as its starting point the following categorisations:

- PRODCOM codes and activities;
- Definitions and categorisations for the purpose of CE marking requirements;
- Definitions and categorisations according to EN, IEC and ISO standards;
- Other product specific definitions and categories e.g. labels, Product Category Rules;

The product scope and definition is analysed within the frame of the Ecodesign and Energy label Directives, in turn for each of the three sub-products that are a focus for the Preparatory Study. A proposal of scope, definition and functional unit for modules, inverters and systems is shown in section 2.4. Conclusions and recommendations.

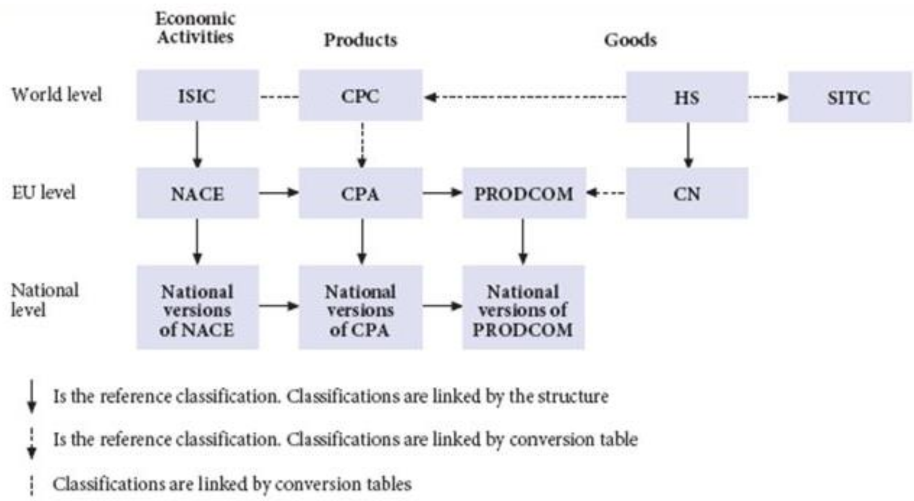
1.1.2.1 Definitions found in Eurostat PRODCOM codes

The EU's industrial production statistics are compiled in the PRODCOM (PRODuction COMmunautaire) survey and also in the EUROPROM database, which includes external trade statistics. The economic activities surveyed by PRODCOM are classified according to the Statistical Classification of Economic Activity (NACE). The statistics for production under each economic activity are in turn reported by each Member State according to Statistical Classification of Products by Activity (CPA) codes. The link between the NACE and CPA codes is illustrated in Figure 4.

The main indicators of the production sold during the calendar year are collected and published both in monetary units (EUR) and physical units of production (kg, m^2, number of items, etc.). Data is provided, where available at Member State level, for:

- the physical volume of production sold during the survey period,
- the value of production sold during the survey period,
- the physical volume of actual production during the survey period, including any production which is incorporated into the manufacture of other products from the same undertaking.

Figure 4. Overview of the revised EU system of integrated statistical classifications. Source: Eurostat (2017)



These statistics provide an outlook on the volume of imports, as well as enabling the actual and apparent production to be estimated based on the balance of EU sales and trade.

Table 1 presents the divisions and classes of potential relevance to the product group, identified using the NACE and CPA Revision 2 classifications[1]. Potentially relevant CPA activities span four broad types:

[1] Obtained from the Eurostat RAMON (Reference and Management of Nomenclatures) metadata, accessed in November 2017, http://ec.europa.eu/eurostat/ramon/nomenclatures

- Module and system sub-components e.g. wafers, junction boxes, transformers.
- Solar photovoltaic modules, which could be reported as 'other' electrical equipment.
- Renewable electricity generation, of which solar photovoltaic is a reported component.
- Electrical solar energy installations.

It can be seen that the only specific references to solar photovoltaics are made under Section C ('photovoltaic cells'), which refers to the cell component of a module, and Section F ('electric solar energy collectors'), which relates to electrical installations. CPA code 26.11.40 aggregates a range of semiconductor devices, including Light Emitting Diodes (LEDs). The supply and consumption of solar photovoltaic electricity is reported in terajoules for each Member State as a component of Eurostat's energy database[2].

With the exception of solar photovoltaic electricity generation, it is not possible to identify specific disaggregated production or trade data related to solar photovoltaic modules or system components produced for solar photovoltaic end-use applications. This lack of specific photovoltaic manufacturing and installation codes appears to have been reflected in the Product Environmental Footprint Category Rules (PEFCR) pilot on solar photovoltaic electricity generation's choice of reference CPA code 35.11.10 Production of electricity (photovoltaic).

[2] *Eurostat, Energy from renewable sources, http://ec.europa.eu/eurostat/web/energy/data/shares*

Table 1. NACE economic activities and Classifications of Products by Activity (CPA) codes of potential relevance to the product group

Section	Division	Class	Sub-class	Activities (CPA code)
C Manufacturing	26. Manufacture of computer, electronic and optical products	26.1 Manufacture of electronic components and boards	26.11 Manufacture of electronic components	26.11.10 – Manufacture of dice or wafers, semi-conductor, finished or semi-finished
				26.11.22 – Photosensitive semiconductor devices; solar cells, photo-diodes, photo-transistors, etc.
				26.11.40 – Parts of diodes, transistors and similar semiconductor devices, photosensitive semiconductor devices and photovoltaic cells, light-emitting diodes and mounted piezo-electric crystals
	27. Manufacture of electrical equipment	27.1 Manufacture of electric motors, generators, transformers and electricity distribution and control apparatus	27.11 Manufacture of electric motors, generators and transformers	27.11.01/02 – Electrical apparatus for switching or protecting electrical circuits 27.11.04 – Electrical transformers
			27.12 Manufacture of electricity distribution and control apparatus	27.12.04 – Parts of electricity distribution and control apparatus
		27.2 Manufacture of batteries and accumulators	27.20 Manufacture of batteries and accumulators	27.20.10 – the manufacture of non-rechargeable and rechargeable batteries
		27.3 Manufacture of wiring and wiring devices	27.33 Wiring devices	27.33.10 – manufacture of boxes for electrical wiring (e.g. junction, outlet, switch boxes) – manufacture of bus bars, electrical conductors (except switchgear-type)
		27.9 Manufacture of other electrical equipment	27.90 Manufacture of other electrical equipment	27.90.10 – miscellaneous electrical equipment other than motors, generators and transformers, batteries and accumulators, wires and wiring devices, lighting equipment or domestic appliances.
D Electricity, gas, steam and air conditioning	35. Electricity, gas, steam and air conditioning supply	35.1 Electric power generation, transmission and distribution	35.11 Production of electricity	35.11.10 – Electricity (solar photovoltaic)
			35.14 Trade of electricity	35.14.10 – Sale of electricity to the user – Activities of electric power brokers that arrange the sale of electricity via power distribution systems operated by others – Operation of electricity and transmission capacity exchanges for electric power
F Construction	43. Specialist construction activities	43.2 Electrical, plumbing and other construction installation works	43.21 Electrical installation	43.21.10 – Electrical installation works of other electrical equipment, including electric solar energy collectors and baseboard heaters of buildings

1.1.2.2 Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS)

Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011[3] on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast), referred to as the RoHS Directive, lays down rules on the restriction of the use of hazardous substances in electrical and electronic equipment (EEE). These restrictions apply to the following substances, to which maximum concentration values in products apply:

- Lead (0,1 %)
- Mercury (0,1 %)
- Cadmium (0,01 %)
- Hexavalent chromium (0,1 %)
- Polybrominated biphenyls (PBB) (0,1 %)
- Polybrominated diphenyl ethers (PBDE) (0,1 %)
- Bis(2-ethylhexyl) phthalate (DEHP) (0,1 %)
- Butyl benzyl phthalate (BBP) (0,1 %)
- Dibutyl phthalate (DBP) (0,1 %)
- Diisobutyl phthalate (DIBP) (0,1 %)

In terms of the product scope considered by this study, it is important to note that photovoltaic modules (referred to in the Directive as panels) are specifically excluded according to the following definition:

'*photovoltaic panels intended to be used in a system that is designed, assembled and installed by professionals for permanent use at a defined location to produce energy from solar light for public, commercial, industrial and residential applications;*'

Despite this exclusion it can be observed that manufacturers in the sector seek to differentiate themselves by claiming the absence of substances restricted under RoHS - such as lead, cadmium and phthalates. In later tasks the potential to minimise the use of lead and cadmium is therefore briefly reviewed against the background of current usage.

1.1.2.3 CE marking conformity requirements

There are currently no CE marking conformity requirements nor related European harmonised testing standards established at EU level that relate specifically to solar photovoltaic modules or inverters[4]. There are, however, relevant generic CE marking requirements that establish market entry requirements for:

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[3] *Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast): "photovoltaic panels intended to be used in a system that is designed, assembled and installed by professionals for permanent use at a defined location to produce energy from solar light for public, commercial, industrial and residential applications"*

[4] *DG GROWTH, Manufacturers and product groups, https://ec.europa.eu/growth/single-market/ce-marking/manufacturers_en*

- Construction products in accordance with Regulation (EU) No 305/2011 [5],
- Electromagnetic compatibility in accordance Directive 2014/30/EU [6],
- Low voltage electrical equipment in accordance with Directive 2014/35/EU [7], and
- Restriction of Hazardous Substances in Electrical and Electronic Equipment (RoHS) in accordance with the recast Directive 2011/65/EU [8].

These set requirements that solar photovoltaic modules, inverters and other components of photovoltaic systems must be in conformity with in order to be placed on the EU market. They also set requirements that AC and DC power supply systems must be in conformity with.

The certification of conformity CE requires modules and inverters to pass several electrical and mechanical tests in line with CE quality and safety rules, including co-operability/ compatibility tests involving the assessment of the electromagnetic interference of the solar products which may not exceed certain levels as this could otherwise lead to operation and performance impacts on other nearby electronics.

The Construction Products Regulation requires all products that are covered by a harmonised standard to provide a Declaration of Performance (DoP) in support of CE marking. Products therefore need to pass equivalent tests for building materials that they may substitute e.g. roof tiles. These Declarations are intended to relate to what are referred to in the Construction Products Regulation (EU) No 305/2011 as the 'Basic requirements for construction works'. These requirements are explained further in section 2.3.1.4.1.

As can be seen, these CE marking requirements provide only generic categories or classes related to, for example, types of construction product or electrical equipment voltages. These may, however, be useful in setting cut-off thresholds for the purpose of the types of product to be analysed and their related market segments.

Even though the self-certification for the CE Mark greatly facilities solar product production, export to and consumption in the EEA, manufacturers however are bound to the conformity self-assessments. Therefore, identified non-compliant manufacturers knowingly producing non-conforming solar products and self-issuing the CE mark face severe penalties and sanctions.

1.1.2.4 Photovoltaic module definitions

A photovoltaic module forms a fundamental part of a solar photovoltaic system, being the primary component that converts solar irradiation into DC electricity. The modules installed as part of a system must be interconnected in order to form an array, the DC electrical output from which is then supplied to the Balance of System components of a system for conversion into AC current.

1.1.2.4.1 Standardised product category definitions for photovoltaic modules

The International Electrotechnical Commission (IEC) defines photovoltaic panels or modules as a complete and environmentally protected assembly of interconnected PV cells. (IEC 61836:2016, 3.1.48.7)

> *"Photovoltaic modules constitute the photovoltaic array of a photovoltaic system that generates and supplies solar electricity in commercial and residential applications. Each module is rated by its DC output power under standard test conditions (STC), and typically ranges from 100 to 365 Watts (W). The efficiency of a module determines the area of a module given the same rated output – an 8% efficient 230 W module will have twice the area of a 16% efficient 230 W module".*

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[5] DG GROWTH, Construction, https://ec.europa.eu/growth/sectors/construction_en

[6] DG GROWTH, Electromagnetic compatibility (EMC) standards, https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards/electromagnetic-compatibility_en

[7] DG GROWTH, The Low Voltage Directive, http://ec.europa.eu/growth/sectors/electrical-engineering/lvd-directive_en

[8] DG Environment, Restriction of Hazardous Substances in Electrical and Electronic Equipment http://ec.europa.eu/environment/waste/rohs_eee/legis_en.htm

Photovoltaic module is frequently used as general term to refer to for both panels (framed modules) and laminates (unframed module).

1.1.2.4.2 Other non-standardised product category definitions

The Underwriters Laboratories' 1703 Standard for Flat-Plate Photovoltaic Modules and Panels is the industry standard for baseline safety and performance and the gateway to the marketplace. It is the basis for the IEC 61730 document, which is the international safety standard, and defines PV modules as:

"...the smallest environmentally protected, essentially planar assembly of solar cells and ancillary parts, such as interconnects and terminals, intended to generate DC power under unconcentrated sunlight. The structural (load-carrying) member of a module can either be the top layer (superstrate), or the back layer (substrate), in which:
a) The superstrate is the transparent material forming the top (light-facing) outer surface of the module. If load-carrying, this constitutes a structural superstrate.
b) The substrate is the material forming the back outer surface of a module. If load-carrying, this constitutes a structural substrate "

The latter definition for PV modules covers:

- flat-plate photovoltaic modules intended for installation on or integral with buildings, or to be freestanding (that is, not attached to buildings), in accordance with the National Electrical Code, NFPA 70, and Model Building Codes.
- These requirements cover modules intended for use in systems with a maximum system voltage of 1000 V or less.
- These requirements also cover components intended to provide electrical connection to and mounting facilities for flat-plate photovoltaic modules.

UL 1703 does not cover however the following elements in the definition of PV module:

a. Equipment intended to accept the electrical output from the array, such as power conditioning units (inverters) and batteries;
b. Any tracking mechanism;
c. Cell assemblies intended to operate under concentrated sunlight;
d. Optical concentrators; or
e. Combination photovoltaic-thermal modules or panels.

Another definition is provided by the Product Environmental Footprint Category Rule (PEFCR) for a PV module:

"...of 48, 60 or 72 photovoltaic cells (156 x 156 mm crystalline technology), or a semiconductor layer (thin film technology), a substrate and a cover material (glass, plastic films), the connections (used for the interconnection of the cells), the cabling (used for the interconnection of the modules) and the frame (in case of panels)."

The product scope definition in the context of the PEF Initiative for, the term "photovoltaic module" is used as general term for panels (framed modules) and laminates (unframed module). The scope of the PEFCR is the production of DC electricity with photovoltaic modules. Mounting is considered as part of the product. Not considered in the product scope are balance of system components such as inverter and AC cabling (connection to the grid).

According to IEA technology roadmap, the basic building block of a PV system is the PV cell, which is a semiconductor device that converts solar energy into direct-current (DC) electricity. PV cells are interconnected to form a PV module, typically up to 50-200 W.

Table 2. Categorisation of solar photovoltaic module definitions according to IEA, IEC, UL and PEF

Categorisation	**IEA**	**IEC**	**UL**	**PEF**
Size (m^2)				✓
Power output (kWp)	✓	✓		
Number of cells (e.g. 48, 60, 72)				✓
Structure load bearing form (substrate or superstrate)			✓	✓
Framed or unframed	✓			✓
Building integration products (e.g. façade panels, sloped and flat roofs, brise soleil, louvres, glass-glass laminates and roof tiles)				
Environmental protection features (e.g. isolation from weathering)			✓	✓
Components of a module (e.g. encapsulants, interconnections, junction box)			✓	✓

Table 2 gathers the main features or concepts used in the definitions of photovoltaic modules that have been analysed. The most complete definition is the one provided by PEF, followed by the Underwriters Laboratories. None of the definitions mention explicitly building integration products, which are reviewed separately in the next section.

1.1.2.4.3 Building integration of photovoltaic cells or modules

A high level of solar photovoltaic deployment will suppose a greater level of integration of photovoltaic technology into buildings and their fabric. The CENELEC makes a distinction in EN 50583-1:2016 between Building Attached PV (BAPV) modules and Building Integrated PV (BIPV) modules. It defines BAPV as:

> *'photovoltaic modules [that] are considered to be building-attached, if the PV modules are mounted on a building envelope and do not fulfil the* [BIPV] criteria for building integration'

Moreover it defines BIPV modules as:

> *'photovoltaic modules [that] are considered to be building-integrated, if the PV modules form a construction product providing a function as defined in the European Construction Product Regulation CPR 305/2011. Thus the BIPV module is a prerequisite for the integrity of the building's functionality'*

Further clarification is then provided on the functional overlap between a BIPV module and a construction product:

> *'If the integrated PV module is dismounted (in the case of structurally bonded modules, dismounting includes the adjacent construction product), the PV module would have to be replaced by an appropriate construction product. The building's functions in the context of BIPV are one or more of the following:*
>
> - *mechanical rigidity or structural integrity*
> - *primary weather impact protection: rain, snow, wind, hail*
> - *energy economy, such as shading, daylighting, thermal insulation*
> - *fire protection*
> - *noise protection*
> - *separation between indoor and outdoor environments*
> - *security, shelter or safety*
>
> *Inherent electro-technical properties of PV such as antenna function, power generation and electromagnetic shielding etc. alone do not qualify PV modules as to be building-integrated.'*

In the case of BIPV, photovoltaic cells are required to be integrated into form factors that are equivalent to the construction products they will replace. The IEA PVPS makes reference to modules that are *'specialised products for building integrated PV systems'* and states that these may be at larger sizes than their reference rating range of 50 W to 350 W. They also make reference to the different mounting structures that may be used for BIPV, including facades, sloped and flat roofs, glass-glass laminates and roof tiles.

The potential for a range of different form factors suggests that a broader and more flexible definition of 'module' may be required if Building Integrated PV (BIPV) products are to be considered within the scope. This is also because cells, rather than modules, are commonly the starting point for the design of a building integration PV product.

1.1.2.4.4 Summary of the results from the first stakeholder questionnaire

In this section the scope related questions asked in the first stakeholder questionnaire of December 2018 are reprised and the responses briefly summarised in order to identify the main findings.

<u>Q1.1 Could the photovoltaic module scope and definition provided below be appropriate for use in this study?</u>

The product category scope corresponds to the production of photovoltaic modules used in photovoltaic power systems for electricity generation.

A photovoltaic module is defined as being a panel (framed module) or a laminate (unframed module). A photovoltaic module basically consists of 48, 60 or 72 photovoltaic cells (crystalline technology), or a semiconductor layer (thin film technology), a substrate and a cover material (glass, plastic films), the connections (used for the interconnection of the cells), the cabling (used for the interconnection of the modules) and the frame (in case of panels).

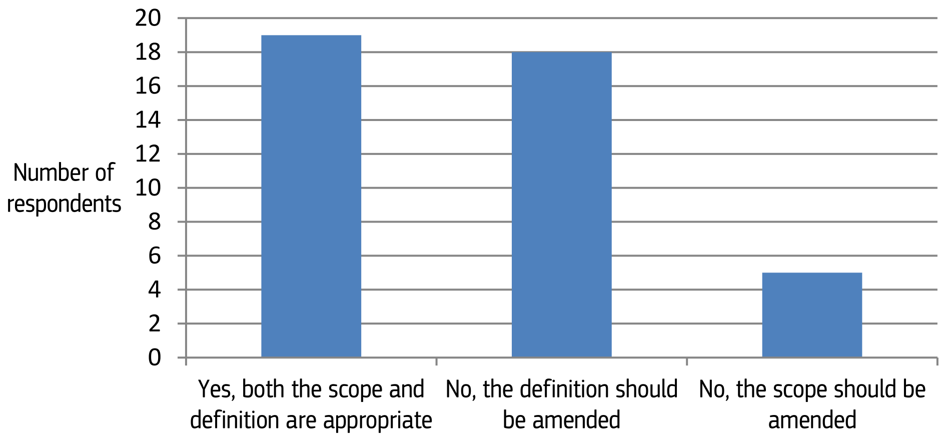
Adapted from: Product Environmental Footprint Category Rules definition of scope, 2014

The stakeholders were asked to react to a proposed definition and scope for the modules. Three options were given as seen in Figure 5. Of the 39 respondents a slim majority (51%) considered the scope and definition to need amending.

In terms of the product definition, of the respondents that were in favour to amend it, 78% recommended to leave out the number of cells. Encapsulants and junction boxes were mentioned as needing be explicitly included in the definition by 2 respondents. A complete definition was proposed as follows by 6 of the respondents:

A photovoltaic module is defined as being a panel (framed module) or a laminate (unframed module). A photovoltaic module basically consists of photovoltaic cells (crystalline technology), or a semiconductor layer (thin film technology), a substrate and a cover material (glass, plastic films), the connections (used for the interconnection of the cells), the cabling (used for the interconnection of the modules) and the frame (in case of panels).

Figure 5. Agreement on the proposed scope and definition



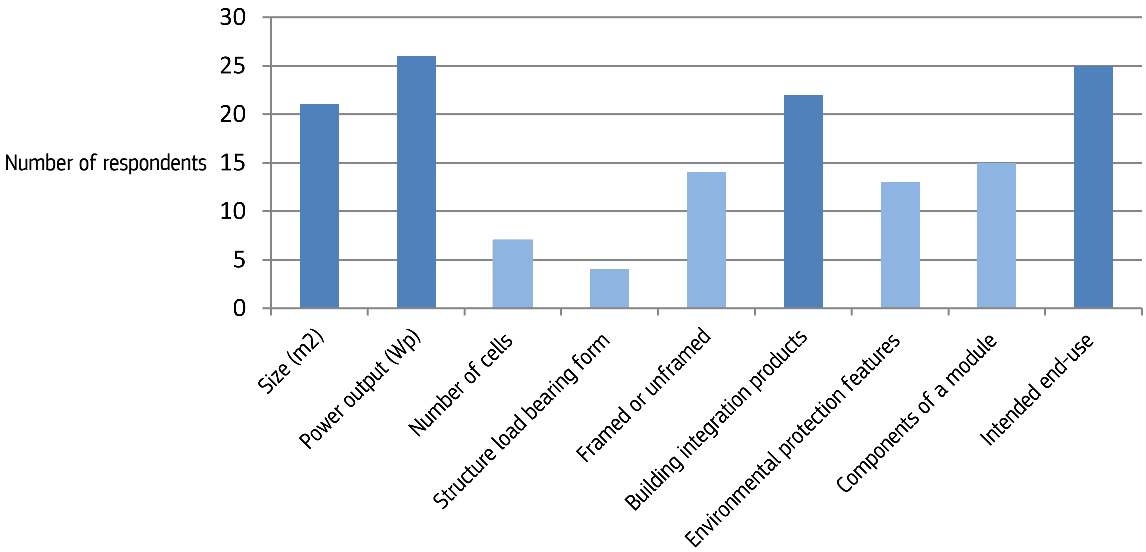
Specific reference was also made by 8 respondents to the IEC 61836 standard.

<u>*Q1.2. Of the aspects listed below, which should be taken into account in determining the scope and definition of modules to be analysed?*</u>

The majority (64%) of respondents chose *'as many as required'* as their preference. Of these respondents, 47% were from 'contractors and supply chain' and 23% from 'performance and standards'.

It can be seen in Figure 6 that the aspects selected by 50% or more of the respondents were: *size (m^2), power output (kWp), building integration products and intended end-use*. *Number of cells* and *structural load bearing form* were considered the least relevant.

Figure 6. Aspects selected by respondents that should be taken into account in determining the scope and definition of modules



In terms of comments on the listed aspects, many related to the *intended end use* and *framed or unframed* aspects:

- Intended end use: seven stakeholders consider that only the "intended end-use" is an aspect relevant in determining the scope and definition of modules to be analysed. They believe the scope should be limited to the production of terrestrial photovoltaic modules used in photovoltaic power systems with the sole purpose to generate electricity for public, commercial, industrial, rural and residential applications. PV modules in mobile applications, such as electric vehicles, watches, calculators, power banks and other gadgets should be excluded from the scope. Hence, the integration into a consumer product should not be included. (Remark: tracker applications should be included on these grounds)
- Framed or unframed: one respondent stated that as long as only the PV modules and not the whole PV systems are regulated via Ecodesign, the module frames should be excluded from the Regulation/Evaluation, as otherwise the market could be distorted towards unframed PV modules without an overall positive effect as the material would be put into more rigid mounting structures.

Respondents also mentioned other aspects that were not listed but that could be taken into consideration, such as:

- Active area of modules, weight or semiconductor materials, photovoltaic cell nature/type/ technology
- Energy yield (kWh/kWp): one respondent considered it important to have a broad scope and definition which should not be limited through a priori lock-in / lock-out decisions. Since the most important factor (in terms of environmental and socio-economic performance) is the life-time energy production of a PV module. It was suggested to consider the aspect of energy yield (for a given number of standardised installations and insulation conditions) measured as kWh/kWp.

Q1.3 Should any form of threshold for the inclusion/exclusion of products in the scope be used? If so, based on which of the following aspects?

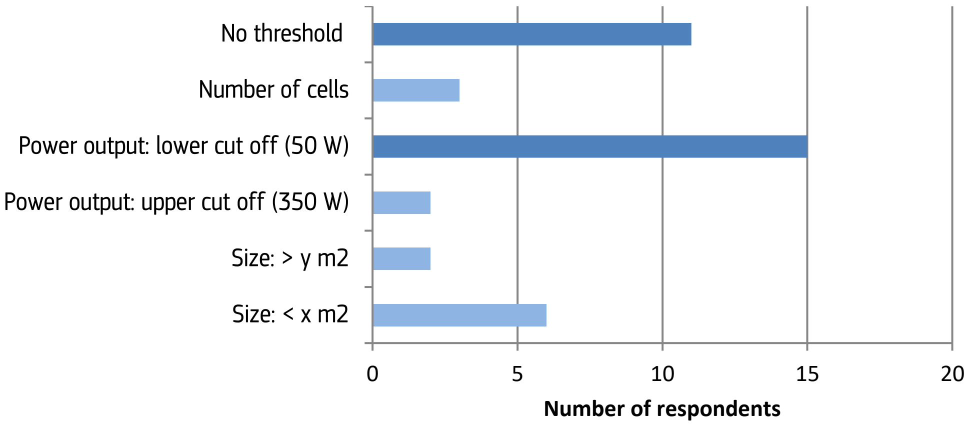
Among the respondents to this question the majority (15 out of 20) were in favour of considering a power output cut off for modules below 50W , so that they are not in the scope of the preparatory study. This is in line with the replies for the previous question where respondents recommended leaving out of the scope the applications of modules intended for mobile use or gadgets as watches and calculators. However 5 respondents noted that the cut off should be perhaps lower than 50W proposed.

There were however 11 stakeholders that argued that thresholds for inclusion/exclusion of products in the scope was not in line with a technology-neutral, innovation-friendly approach of a preparatory study, since the innovation cycles in the industry are very short and new technology concepts can emerge within 3 to 5 years. Some of the reasons given were that:

- since there is no standard *form factor* in the industry, a restriction by size is not viable.
- considering the potential broad range of *power outputs* between small form factor solar tiles (10 – 30 W) and large form factor utility scale PV modules (> 400W).
- there are fundamental technological differences in device architectures which could lead to a wide variety of *cell numbers* (i.e. solar tiles with 1 to 2 cells vs. utility scale thin film modules with more than 300 cells).

The overall results are presented in Figure 7.

Figure 7. Options selected by respondents for inclusion or exclusion from the scope of photovoltaic modules



Q1.4. Should Building Integrated Photovoltaic (BIPV) products, as defined below, be included within the module scope?

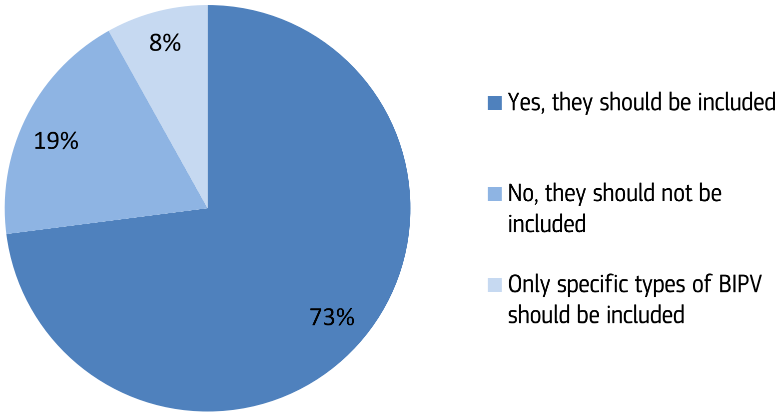
> *'Photovoltaic modules are considered to be building-integrated, if the PV modules form a construction product providing a function as defined in the European Construction Product Regulation CPR 305/2011. Thus the BIPV module is a prerequisite for the integrity of the building's functionality. If the integrated PV module is dismounted (in the case of structurally bonded modules, dismounting includes the adjacent construction product), the PV module would have to be replaced by an appropriate construction product.'*
>
> Definition taken from EN 50583-1:2016

The majority of respondents supported the inclusion of BIPV products in the scope (73%). One respondent answered it would probably be better to consider BIPV products as part of a 'system', since it is a multifunctional element, not only producing electricity (Figure 8).

There were however also a significant share of respondents (19%) that considered that BIPV products should not be included within the module scope. The reasons given were that BIPV products represent a very specific category of products, notably in terms of:

- Market size: BIPV products approximately account for only 5 GW of installed capacity worldwide.
- Type of market: BIPV products correspond to a construction product. This market is therefore very distinct from PV modules markets which correspond exclusively to electricity generation function.
- Functionality: Adding PV functionality to a construction product improves the LCA of the corresponding construction product.
- Product characteristics: BIPV products combine electricity generation in addition to functions related to any traditional building envelope: weather impact protection, energy economy, fire and noise protection, and architectural and aesthetics considerations.
- Technologies involved: Several different technologies have various levels of development and correspond to different levels of efficiency usually linked to their level of ability to be easily integrated in buildings.

Figure 8. Should Building Integrated Photovoltaic (BIPV) products, as defined, be included within the module scope?



Overall BIPV were to be considered a distinct product group besides PV. A combined trade association response highlighted the following issues to take into account:

- Setting up minimum performance requirements for products that still correspond to a niche market would risk impeding the development of innovative products and technologies that could have reached higher efficiency in the future.
- Energy labelling measures showcasing the benefits that such products have in comparison with traditional construction products / building envelopes, may be a driver for market uptake of the products.

1.1.2.5 Inverters for photovoltaic applications definitions

An inverter is a power conditioning device used in electrical systems to convert DC voltage and DC current into AC voltage and AC current. They are directly connected to the photovoltaic (PV) array (on the DC side) and, where grid-connected, to the electrical grid (on the AC side), and convert the DC energy produced by the array into the AC energy required by the grid or end-user.

1.1.2.5.1 Standardised product category definitions

There are many interrelated definitions of inverters provided within IEC standards series that are of relevance to solar photovoltaics. The simplest definition is:

> *'[an] electric energy converter that changes direct electric current to single-phase or* polyphase alternating currents' (IEC 61836:2016)

The IEC also note in relation to the above provided definition that an inverter is:

> *'...one of a number of components that is included in the term "power conditioner"*

This definition is complemented by fifteen sub-definitions, which mainly make reference to the different ways in which electricity is conditioned and distributed. To aid an understanding of the different definitions they have been sorted into three broad categories:

- Power conditioning characteristics: Inverters that can be distinguished by the aspect of power supply that they are specified to condition.
- Grid configuration: Inverters that can be distinguished according to how they interact as a component of the interface with the electricity distribution grid.
- Module configuration: Inverters that can be distinguished based on their intended configuration as part of a module array.

The fifteen sub-definitions are presented under these three categories in Table 3.

As can be seen from Table 3 inverters are designed to operate in conjunction with different module configurations. Here, the draft IEC standard 62093 provides a useful common reference point. The standard refers to Power Conversion Equipment (PCE) in the context of design qualification testing for photovoltaic systems with a maximum circuit voltage of 1500 V DC and

connections to systems not exceeding 1000 V AC. The standard groups PCEs into three broad categories based on their size and installation target:

- Category 1: Module-level power electronics (MLPE) – specified to operate at a PV module base level interfacing up to four modules.
- Category 2: String-level power electronics – designed to interface multiple series or parallel connected modules and specified for wall, ceiling or rack mounting.
- Category 3: Large-scale power electronics – also designed to interface multiple series or parallel connected modules, but due to its complexity, size and weight is housed in a free standing electrical enclosure.

(IEC 62093 draft 2017)

Table 3. Categorisation of the IEC inverter definitions. Source: IEC (2016)

Categorisation	IEC term used	IEC definition(s) used
Power conditioning characteristics	Current control	Inverter with an output electric current having a specified sine waveform produced by pulse-width modulated (PWM) control or other similar control system.
	Current stiff	Inverter with an essentially smooth DC input electric current.
	High frequency link	Inverter with a high frequency transformer for electrical isolation between the inverter's input and output circuits.
	Utility frequency link	Inverter with a utility frequency transformer for electrical isolation at the inverter output.
	Transformerless	Inverter without any isolation transformer.
	Voltage control	Inverter with an output voltage having a specified sine waveform produced by pulse-width modulated (PWM) control, etc.
	Voltage stiff	Inverter having an essentially smooth DC input voltage.
Grid configuration characteristics	Grid-connected	Inverter that is able to operate in parallel with the distribution or transmission system of an electrical utility.
	Grid-interactive	A grid-connected inverter that is able to operate in both stand-alone and parallel modes.
	Utility interactive	Inverter used in parallel with the distribution or transmission system of an electrical utility to supply common loads and that may deliver electricity to that distribution or transmission system.
	Non-islanding	Inverter that ceases to energize an electricity distribution system that is out of the normal operating specifications for voltage and/or frequency.
	Stand-alone	Inverter that supplies a load not connected to the distribution or transmission system of an electrical utility (also known as a 'battery-powered' inverter.
Module configuration	Module	Inverter that is integrated to the output of a single PV module. It is usually attached to the rear of a module.
	String	Inverter that is designed to operate with a single PV string. The AC output can be connected in parallel to the output of other string inverters.

The first two categories were already addressed within the general IEC sub-definitions, although Category 1 varies in that it includes for an interface with up to four modules as opposed to only module in the case of an 'AC photovoltaic module'. The latter category 3 is more akin to a standalone substation transformer, being more likely to be used for ground mounted systems such as utility scale solar farms.

1.1.2.5.2 Other non-standardised product category definitions

The U.S. EPA carried out a scoping in 2013 to inform the potential to expand Energy Star to cover inverters. The scoping report provides a further set of definitions[9], but which closely reflect those of draft IEC 62093, with a focus on the conditioning of grid compatible AC power:

[9] *https://www.energystar.gov/sites/default/files/asset/document/Solar_PV_Inverters_Scoping_Report.pdf*

- Central inverter: They are used for installations from 100 kW upwards and, in most cases, are designed for outdoor installation.
- String inverter: In string technology, the photovoltaic generator is subdivided into individual module surfaces and each of these individual "strings" has its own string inverter allocated to it.
- Multi-String inverter: An inverter which, to a large extent, combines the advantages of several string inverters (separate MPP control of individual strings) and a central inverter (low output-related costs).
- Micro-inverter: A micro-inverter is a device that takes the DC output of a single solar module and converts it into grid-compliant AC power.

The scoping report also introduces the concept of smart inverters, providing the following definition:

> 'inverters [are] capable of receiving and responding to grid signals in order to help keep the power grid stable, by for example, disconnecting from the grid in a controlled manner to prevent a sudden change in load when numerous inverters disconnect at once.'

This definition reflects new developments in the market that have introduced inverters that have the potential for a dynamic interaction with the electricity distribution grid.

1.1.2.5.3 Summary of the results from the first stakeholder questionnaire

In this section the scope related questions asked in the first stakeholder questionnaire of December 2018 are reprised and the responses briefly summarised in order to identify the main findings.

Q2.1 Could the inverter scope and definition provided below be appropriate for use in this study?

> The International Electrotechnical Committee (IEC) defines an inverter as '[an] electric energy converter that changes direct electric current to single-phase or polyphase alternating currents' (IEC 61836:2016) The IEC identifies a range of different types of inverters that are used to convert the power output from a solar photovoltaic array. The scope of these inverters can be categorised according to their distinguishing features/properties:
>
> - Power conditioning characteristics: The aspect of power supply that the inverters are specified to condition *e.g. current control, voltage control*.
> - Grid configuration: How the inverters interact as a component of the interface with the electricity distribution grid *e.g. grid connected, grid interactive*.
> - Module configuration: An inverters intended configuration as part of a module array *e.g. central, string, module integrated.*
>
> *Adapted from:* IEC 61836:2016

Of the 14 respondents to this question all responded positively that 'Yes, both the scope and definition are appropriate'. Only one additional comment was made that 'European network codes already set certain criteria for inverters, therefore it is important to avoid any overlaps.'

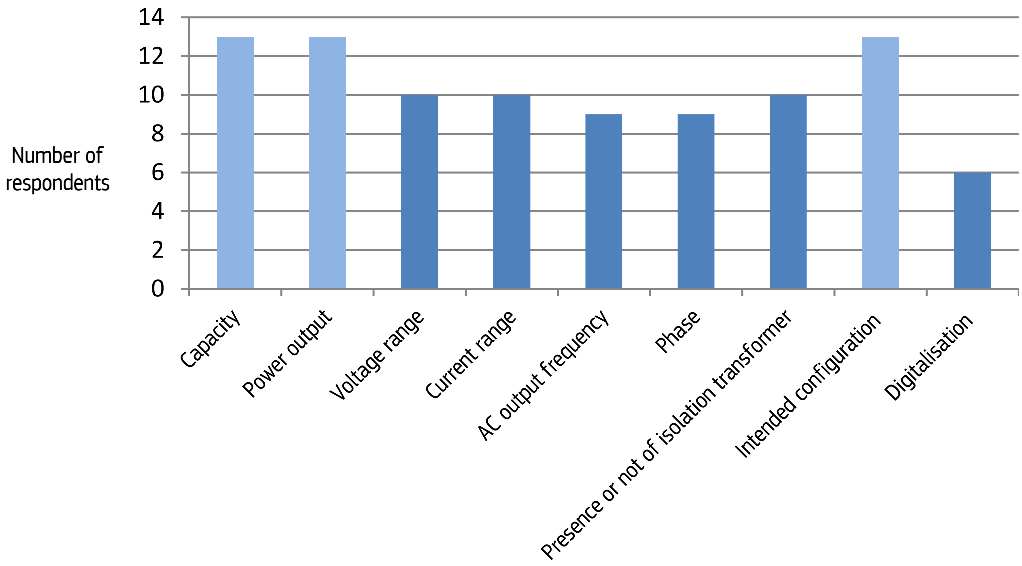
Q2.2 Of the aspects listed below, which do you think should be taken into account in determining the scope and definition of inverters to be analysed? (respondents were invited to choose from a list of nine aspects)

It can be seen in Figure 9 that the three most selected aspects were capacity, power output and intended configuration. In contrast, digitalisation was selected by less than half of the respondents.

Only limited additional comments were made. Two respondents considered that digitalisation is an important future feature. In relation to digitalisation, it was noted by one stakeholder that Maximum Power Point Tracking (MPPT) should be dealt with separately. One respondent pointed out that intended configuration should address the presence of a grid connection or not. Integration with embedded storage was mentioned by one respondent.

It is notable that, with the exception of digitalisation, each aspect was selected by at least 9 respondents, equating to nearly two thirds of the respondents to the inverter part of the questionnaire. This suggests that each of these aspects is of relevance to a specific electrical configuration.

Figure 9. Aspects selected by respondents that should be taken into account in determining the scope and definition of inverters



__Q2.3 Would the three categories of Power Conversion Equipment as defined by draft IEC 62093:2017 be a useful component of the scope and definition?__

> The draft IEC 62093 standard refers to Power Conversion Equipment (PCE) with a maximum circuit voltage of 1500 V DC and connections to systems not exceeding 1000 V AC. Such equipment may include, but is not limited to, grid-tied and off-grid DC-to-AC inverters, DC-to-DC converters and battery charge converters. The IEC standard groups PCEs into three broad categories based on their size and installation target:
>
> Category 1: Module-level power electronics (MLPE) – specified to operate at a PV module base level interfacing up to four modules.
>
> Category 2: String-level power electronics – designed to interface multiple series or parallel connected modules and specified for wall, roof, ceiling or rack mounting.
>
> Category 3: Large-scale power electronics – also designed to interface multiple series or parallel connected modules, but due to its complexity, size and weight is housed in a free- standing electrical enclosure.

Of the 17 respondents to this question 13 responded positively that the three categories would be *'a useful component of the scope and definition'*. Four respondents noted the need for some amendments. These included the observation by two respondents that *'Category 1 may include both micro-inverters and DC optimisers'*. In this respect *'it must be made clear that a DC optimiser does not qualify as an "inverter" but requires an additional string-level device of category 2'*. It was also noted by two respondents that DC-to-DC converters used in storage configurations (battery charge converters) should also be included.

__Q2.4 Should any sizes or types of inverter be excluded from the scope? If so, based on which of the following parameters should this be based?__

Of the 16 respondents to this question all responded that *'all inverters should be included'*.

1.1.2.6 Solar photovoltaic system definitions

A solar photovoltaic system is a broad term that could potentially encompass all types or form of installation in the market, including systems that may supply electronic products. Identification of the target market niches, system scales and end-uses for systems that may be of relevance to the four policy instruments being analysed is therefore of importance in order refine the scope and definition.

Looking at the possible types of photovoltaic systems, the IEA identify a range of possible configurations that exist in the market. The main distinguishing features are whether the end-user is domestic or non-domestic, and whether the system is grid connected or not. The IEA establishes the classification presented in the Table 4.

Table 4. The six broad types of solar photovoltaic systems identified by the IEA

Off-grid domestic	Grid-connected distributed
• Basic electrification: lighting, refrigeration and other low power loads • Off grid networks of households/ villages • Typically up to 5 kW	• Grid-connected customer or directly to the electricity network • Size from kWs to MW scale
Off-grid non-domestic	Grid-connected centralized
• Precious electricity: Telecommunications, water pumping, vaccine refrigeration and navigational aids. • Cost competitive	• Centralized power stations • Typically MW scale • Ground-mounted
Pico systems	Hybrid systems
• Essential electrification: lighting, phone charging and powering a radio or a small computer • Off grid in • Developing countries • PV+ battery + charge controller	• Mini grids: PV + diesel generator • Reliable and cost-effective power source: Mitigate fuel price increases, offer high service quality • Telecom base stations and rural electrification.

Source: IEA, Trends 2016 in photovoltaic applications

Careful consideration of the scope and definition for systems will allow for a better consideration of the environmental and economic implications of aspects such as component selection, installation arrangements and the ongoing operation and maintenance of such systems as are relevant.

System scope definitions used in the market identify a range of possible components that can fall within the scope of a 'system'. A non-exhaustive list of the primary components could include the following:

- Module array
- Power conditioning equipment, including inverters
- Energy storage
- Mounting structures
- System monitoring and (charge) control
- Cables and connectors
- Metering and data transmission
- Transformers

As will be explored in further subsequent sections, these components include a number of sub-systems that are associated with definitions in their own right.

1.1.2.6.1 Standardised product category definitions

For the purpose of the IEC standards series a simple overarching definition of a photovoltaic system is provided as starting point:

'[an] assembly of components that produce and supply electricity by the conversion of solar energy.'

The IEA PVPS programme provides an extended definition which introduces system level concepts relating to how the electricity generated is conditioned and distributed. Their definition includes different potential elements of a system, which may consist of:

'...one or several PV modules, connected to either an electricity network (grid connected PV) or to a series of loads (off-grid). It comprises various electrical devices aiming at adapting the electricity output of the module(s) to the standards of the network or the load: inverters, charge controllers or batteries.'

This definition has some overlaps with the concepts of a solar photovoltaic 'array', which the IEA defines as:

> *'[a] mechanical and electrical assembly of photovoltaic modules, photovoltaic panels, or photovoltaic sub-arrays and its support structure…it includes all components up to the DC input terminals of the inverter or other power conversion equipment or DC loads.'*

Linked to this definition of an 'array' is that of an 'assembly', which the IEA defines as:

> *'PV components that are installed outdoors and remote from its loads, including modules, support structure, foundation, wiring, tracking apparatus, and thermal control (where specified), and including junction boxes, charge controllers and inverters depending on the assemblies installed configuration.'*

The IEA note that the components of an assembly are those parts of a system considered to be those installed in the external environment, as opposed to those that may be installed inside a building.

The simple IEC definition introduced at the beginning of this section is complemented by sixteen sub-definitions, which as well as making reference to the different ways in which electricity is conditioned and distributed, introduce a number of additional system level concepts. To aid an understanding of the different system concepts introduced by the IEC they have been sorted into four broad categories:

- Spatial arrangement: Systems that can be distinguished by the spatial relationship between the different component arrays.
- Electricity end-use: Systems that can be distinguished based on the primary end use that the electricity generated is earmarked for.
- Grid configuration: Systems that can be distinguished according to how they physically interface with the electricity distribution grid.
- Electrical configuration: Systems that can be distinguished based on their modes of operation.

The sixteen system definitions are presented under these four categories in Table 5.

Other types of photovoltaic systems that are not addressed in Table 5 are those where a photovoltaic cell or module form 'part of another device for which it produces electricity where the photovoltaic cell [or module] provides the energy needed to make the electronic product function' (NSF 2017). Examples include street lights with integrated solar modules which charge a battery.

Table 5. Categorisation of IEC solar photovoltaic system definitions

Categorisation	IEC term used	IEC definition(s) used
Spatial arrangement	Centralised	Grid connected PV system that generates bulk electricity.
	Dispersed	Multiple dispersed PV generators or PC systems operating as if they were a single PV generator or system.
	Distributed generation	PV system that is also a distributed generation system
Electricity end-use	Domestic	PV system that electrifies household loads. It may be grid connected or standalone.
	Non-domestic	PV system used for a purpose that is not a domestic purpose. It may be grid connected or standalone.
	Off-grid village	Standalone PV system electrifying a village.
Type of grid configuration	Grid backed-up	PV system that switches over to a utility electricity source when the PV output is less than load requirements.
	Grid-connected	Functions only in a grid connected mode of operation.
	Off-grid standalone	Functions only in an off-grid, standalone mode of operation
	Hybrid	A multi-source PV system operating in parallel with other electricity generators
Type of electrical configuration	Isolated	PV system that only functions in an isolated mode of operation.
	Utility interactive	Functions in an isolated mode or in a parallel mode of operation.

Source: IEC (2016)

1.1.2.6.2 Sub-system definitions of potential relevance

Beyond the concept of a solar photovoltaic 'array', which the IEC defines as comprising the modules, their support structures and all DC cabling up until the input terminals of the inverters, two other important sub-systems are defined in relevant solar photovoltaic standards – Balance of System (BOS) and Power Conversion Equipment (PCE). These two sub-systems describe the power conversion and conditioning equipment that handle the DC electricity generated by the module, so are important in defining relevant components and system configurations for different types of photovoltaic systems.

Balance of System (BOS)

For the purpose of the IEC standards series the Balance of System (BOS) is defined as:

> *'parts of a PV system other than the PV array field, including switches, controls, meters, power conditioning equipment, PV array support structure, and electricity storage components, if any.'*

The IEA makes a further distinction between typical BOS components associated with roof top and ground mounted applications. Ground mounted systems, also sometimes referred to as utility scale systems, require medium voltage grid connections (including transformers), concrete pad foundations and cleaning systems. They may also include tracking equipment as an option to improve performance.

Power Conversion Equipment (PCE)

Also sometimes also referred to as power conditioning, tor the purpose of the IEC standards series Power Conversion Equipment (PCE) forms a sub-system of the Balance of System (BOS) and is defined as:

> *'Electrical devices converting one form of electrical power to another form of electrical power with respect to voltage, current frequency, phase and the number of phases. The definition of PCE covers all active and passive circuitry components and all mechanical components required for operation.'*

The term therefore refers exclusively to electrical equipment. PCE equipment is then further sub-divided into three categories of PCE as reported in section 1.1.2.5.1, reflecting different inverter sizes and configurations. Further sub-divisions recognise environmental conditions to which the PCE may be exposed to during its lifetime.

1.1.2.6.3 Summary of the results from the first stakeholder questionnaire

In this section the scope related questions asked in the first stakeholder questionnaire of December 2018 are reprised and the responses briefly summarised in order to identify the main findings.

Q3.1 Could the photovoltaic system scope and definition provided below be appropriate for use in this study?

> The International Electrotechnical Committee (IEC) defines a photovoltaic system as: '[an] assembly of components that produce and supply electricity based on photovoltaic conversion of solar energy. [This] could also include the following sub-systems: power conditioning, storage, system monitoring and control, and utility grid interface.' (IEC 61836:2016)
>
> The IEC identifies within their scope a range of different system concepts which vary according to how a system is configured, and how the electricity generated is converted and distributed. These can be categorised according to the following distinguishing features/properties:
>
> - Spatial arrangement: Based on the spatial relationship between the different component arrays (e.g. centralised, distributed).
> - Electricity end-use: Based on the primary end use that the electricity generated is earmarked for (e.g. domestic, non-domestic).
> - Grid configuration: Based on the type of physical interface with the electricity distribution grid (e.g. grid connected, off-grid, hybrid).
> - Electrical configuration: Based on the systems modes of operation (e.g. isolated, utility interactive).

16 out of the 24 respondents to this question indicated that *'yes, the scope and definition are appropriate'*.

Of the 8 respondents that considered that an amendment was necessary 3 considered that the scope should be amended. The inclusion of *'interconnections (cabling) between sub-systems, as well as transformers'* and *'the size of the PV system*' were proposed. Reference was also made to *'PV on buildings'* and *'PV farms'*.

6 respondents considered that the definition should be amended. Proposals included more reference to market segmentation ranging from *'individual, residential, tertiary installations to huge utility plants'*, encompassing *'different system sizes (micro,*

residential, commercial, utility scale)' and with a distinction made between ground mounted PV, BAPV and BIPV. Two respondents considered that *'energy storage facilities (mainly batteries) should not be considered as part of a PV system'* as they are *'clearly an optional component'* and *'do not contribute to the renewable energy generation'*.

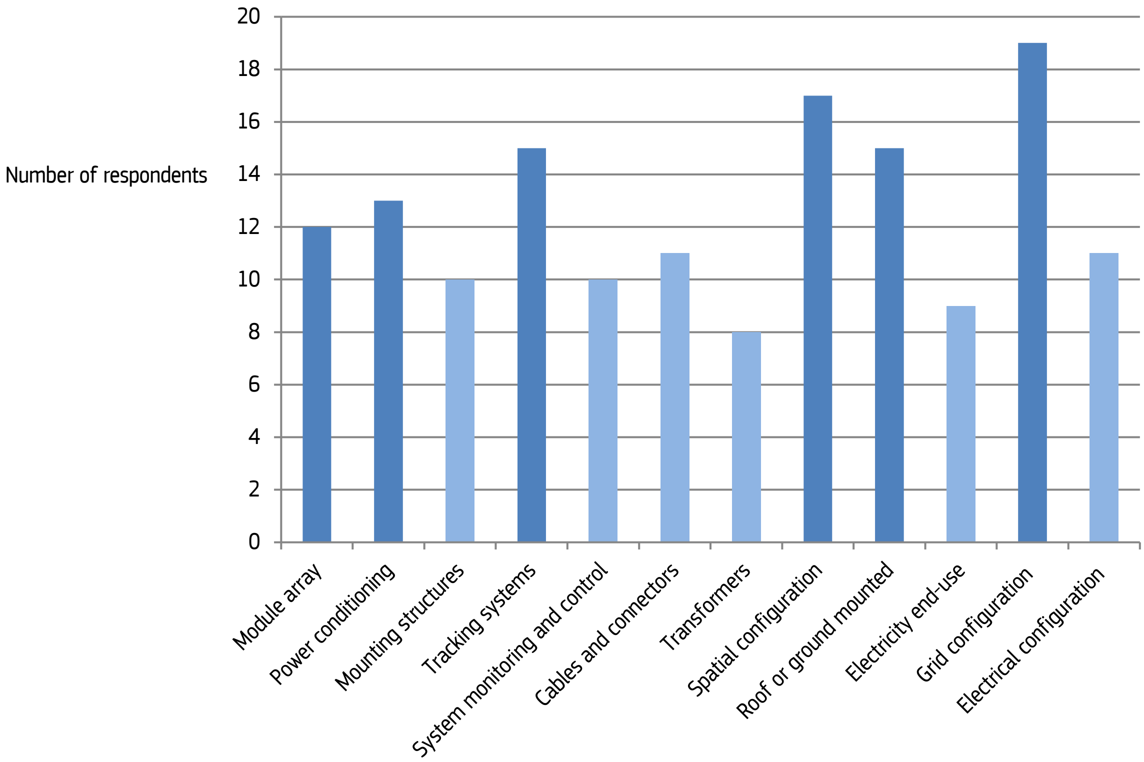
Q3.2 Of the aspects listed below, which do you think should be taken into account in order to determine the scope and definition of the types of photovoltaic systems to be analysed?

It can be seen in Figure 10, the aspects selected by 50% or more of the respondents were *module array, power conditioning, tracking systems, spatial configuration, roof or ground mounted,* and *grid configuration*. It is notable that each aspect was selected by at least 8 respondents, equating to one third of the respondents to the system part of the questionnaire. This suggests that each one is of relevance to a specific system configuration.

In terms of 'any other aspect to the photovoltaic system scope and definition', limited further suggestions were made. One respondent considered that the presence or not of storage should be noted. Three respondents reflected a trade association proposal to differentiate between:

- residential, commercial and utility-scale installations (installation size)
- central, string and microinverters
- ground-mounted vs rooftop installations
- systems with and without storage
- PV systems with tracker (1-2 axes) and without tracker.

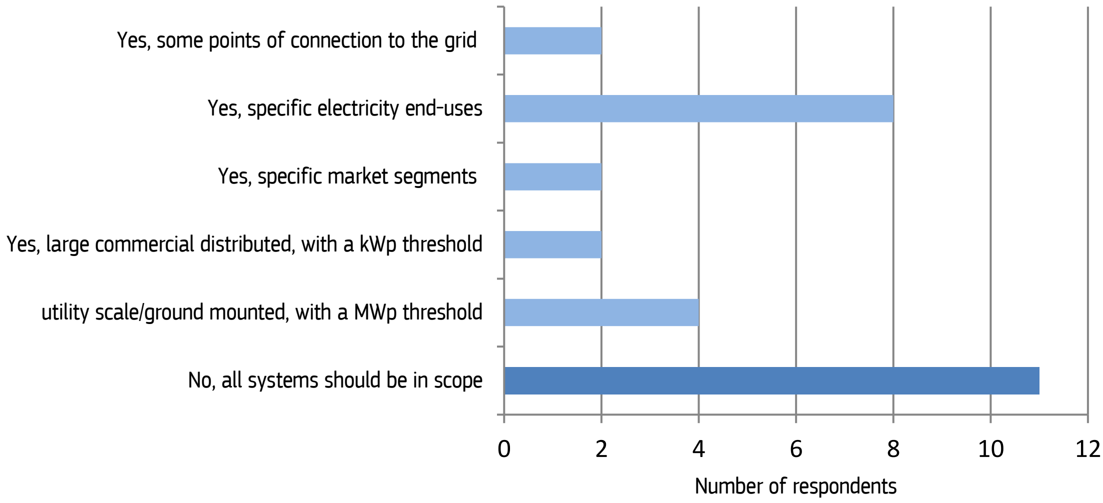
Figure 10. Aspects selected by respondents that should be taken into account in determining the scope and definition of photovoltaic systems



Q3.3 Should any size or type of system be excluded from the scope? If so, based on which of the following aspects?

Of the 24 respondents to this question, 11 considered that all systems sizes and types should be within scope. As can be seen in Figure 11 the main scope exclusion selected by respondents related to *'specific electricity end-uses'*. The questionnaire cited examples as including buildings, street lighting, street furniture and vehicles. .Of those that selected this exclusion, one respondent considered that *'specific end-uses such as street lighting and urban furniture'* were not relevant. Another respondent elaborated further, identifying *'electric vehicles, watches, calculators, power banks and other gadgets'*.

Figure 11. Options selected by respondents for inclusion or exclusion from the scope of different photovoltaic systems



1.1.2.7 Definition of the functional unit and product performance parameters

A review of the commonly used functional units for photovoltaics is made in the following section. At the end of this Task 1, in section 1.4, a first proposal for the solar photovoltaic products functional unit, definition and scope will be presented.

1.1.2.7.1 The primary product performance parameter (functional unit)

In order to carry out meaningful modelling of the life cycle of a product it is important to define the function being provided, and then linked to that a common reference unit of comparison between different products designs or systems – a functional unit of performance. The terms functional unit and reference flow are defined extensively in Life Cycle Assessment (LCA) literature. The ISO 14040[10] defines them as following:

> *Functional unit:* quantified performance of a product system for use as a reference unit
>
> *Reference unit:* measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit

IEA PVPS Task 12[11] highlights the importance of taking into account following fundamental parameters that influence performance along the lifetime of PV systems:

- Life expectancy: life expectancy based on manufacturers guarantee or period of time before the incidence of product or system failures become unacceptable.
- Irradiation: the irradiation collected by modules depends on their location and orientation
- Performance ratio: the performance ratio (PR) (also called derate factor) describes the difference between the modules' (DC) rated performance (the product of irradiation and module rated efficiency) and the actual (AC) electricity generation, taking into account a number of variables.
- Degradation: the level of degradation of a module's efficiency over time.

An additional concept which might differ from the life expectancy is the service lifetime considered either at system or component level. The ISO 15686 'Building and constructed assets – service-life planning' series defines it as:

> *'the period of time after installation during which a component or an assembled system meets or exceeds the technical performance and functional requirements laid down by the end user'.*

[10] ISO 14040:2006 series. Environmental management -- Life cycle assessment -- Principles and frameworkhttps://www.iso.org/standard/37456.html

[11] IEA Task devoted to PV Environmental, Health And Safety (E, H & S) Activities. http://iea-pvps.org/index.php?id=56#c87

The functional unit in an LCA for the analysis of Energy related Products describes the unit of end product to which the energy requirements will be related. The IEA and CEN define it as:

'.... the quantified performance of a product system for use as a reference unit '(ISO 2006a, Clause 3.20).

Related to this definition they also define the reference flow as:

'a measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit' (ISO 2006a, Clause 3.29).'

The best choice for the functional unit will depend on the objectives of the study. Extensively used in literature, functional units in the context of this study are:

- 1 kWh of electricity produced by the PV system;
- 1 Wp of module power or 1 Wac of inverter power;
- 1 m^2 of module area;
- 1 m^2 of cell area;
- 1 module or inverter

Of course the *kWh* and to a lesser extent the *Wp* are the most functional of these units because they are directly related to the end-user service. The disadvantage of the kWh or Wp units is that this choice introduces extra parameters, namely irradiation, PV system performance and module efficiency, which have no or little relation to the energy consumption during module production.

It is obvious that most energy requirements for module production, like energy for material consumption and energy for processing are in the first place area-dependent. Very often the efficiency of a module and thus its power rating may be enhanced by a subtle change in the production process without a significant increase in the production stage energy consumption. An area related unit will be therefore be the most convenient functional unit when the objective is to compare different modules or different energy technologies. The choice between *module area* or *cell area* is less important, although for crystalline silicon technology the unit of cell area has some advantages.

The *module* is considered an inconvenient level to consider the functional unit because modules do not have a standard size or power rating.

A comprehensive analysis of functional unit definitions used in the context of LCA evaluation is presented below. The evaluation is with reference to the following sources:

1. the European Commission's PEF LCA method solar photovoltaic pilot[12]
2. IEA Life cycle Assessment (LCA) recommendations[13]
3. ADEME life cycle environmental impact evaluation guidance (France)[14]
4. CRE solar photovoltaic tender requirements (France)[15]

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[12] Wade et al. (2017) The Product Environmental Footprint (PEF) of photovoltaic modules—Lessons learned from the environmental footprint pilot phase on the way to a single market for green products in the European Union https://onlinelibrary.wiley.com/doi/abs/10.1002/pip.2956

[13] IEA PVPS Task 12, Methodology Guidelines on Life-Cycle Assessment of Photovoltaic Electricity, LCA Report IEA-PVPS T12-03:2011, http://www.iea-pvps.org/fileadmin/dam/public/report/technical/rep12_11.pdf

[14] Methodological framework for assessing the environmental impacts of photovoltaic systems using the life cycle assessment method of the French Environment and Energy Management Agency (ADEME), http://conferences.chalmers.se/index.php/LCM/LCM2013/paper/viewFile/523/124

[15] http://www.cre.fr/documents/appels-d-offres/appel-d-offres-portant-sur-la-realisation-et-l-exploitation-d-installations-de-production-d-electricite-a-partir-de-l-energie-solaire-d-une-puissance-superieure-a-250-kwc3/cahier-des-charges-publie-le-8-avril-2015

The European Commission's PEF LCA method solar photovoltaic pilot

The PEF solar photovoltaic pilot chose to use a unit of analysis in line with ISO 14044:

> *1 kWh (kilo Watt hour) of DC electricity generated by a photovoltaic module.*

The reference flow is the photovoltaic module, measured in kWp (Kilowatt peak), the maximum power output of a module.

The functional unit is then defined according to the following four criteria listed in the PEF Guide.

- The function(s) / service(s) provided ("what"):

DC electrical energy measured in kWh (provided power times unit of time) at the outlet of the DC connector attached to the junction box of the PV module

- The magnitude of the function or service ("how much")

1 kWh of DC electrical energy

- The expected level of quality ("how well")

DC electrical energy at the photovoltaic module at a given voltage level.

- The amount of service provided over the lifetime ("how long")

DC electrical energy generated by the photovoltaic module during the service life of 30 years

IEA Life Cycle Assessment (LCA) recommendations

IEA PVPS Task 12, in the last Methodological guidelines on LCA for PV electricity recommends the following functional unit definition:

> "AC electricity delivered to the grid quantified in kWh is used for comparing PV technologies, module technologies, and electricity-generating technologies in general (goals A to D). For grid-connected systems, use the kWh of alternate current electricity fed into the grid. For PV systems with dedicated transformers (e.g., utility solar farms), use the electricity-output downstream of the transformer."

Alternatively, the reference flows "m^2" or "kW_p (rated power)" may be used. However, these reference flows are not considered suitable for comparisons of PV technologies.

One *m^2* of module is used for quantifying the environmental impacts when PV forms part of a building, or of supporting structures (excluding PV modules and inverters). One square metre is not suited for comparisons of PV technologies because of differences in module and inverter efficiencies and performance ratios.

kWp (rated power, DC) is used for quantifying the environmental impacts of electrical parts, including inverter, transformer, wire, grid connection, and grounding devices. The kW_p may also serve as the reference flow in quantifying the environmental impacts of an individual module technology. However, the comparisons of module technologies shall not be based on nominal power (kW_p) figures because the amount of kWh fed to the grid may differ between the systems analysed."

The location, the module technology used, the voltage level, and whether and how the transmission and distribution losses are accounted for, shall be specified. AC electricity may differ in dispatchability and intermittency. Electricity production with one technology hardly meets all the demand at all times; thus, mixtures of power generating technologies are typically deployed. Aspects of dispatchability or intermittency of AC electricity produced with different technologies shall not be addressed on technology level but on the level of grid mixes provided by utilities (see also Carbajales-Dale et al. 2015).

ADEME life cycle environmental impact evaluation guidance (France)

For ADEME (the French environment agency), the basic function of the PV installations analysed using an LCA methodological framework is electricity production. It is therefore:

1 kWh generated by a photovoltaic system during its lifespan and either exported to the grid (distribution or transmission) or consumed.

Consumed energy in this context means energy consumed on-site by electric appliances, when operating within a contractual arrangement to sell any surplus capacity to the grid. This useable consumed energy does not include losses through the internal electricity network nor any consumption by ancillary functions of the photovoltaic installation (e.g. monitoring).

To carry out the environmental analysis of the technological process characterised by this functional unit it is necessary to estimate the PV systems potential output. This estimate should take into account the technical characteristics of the installation being studied (i.e. module yield, electricity losses, PV system lifespan, etc.) as well as the irradiation at the PV system location.

The environmental impacts of the PV system can be calculated either by using the system's nominal power or the effective surface area of the PV field related to the kWh (the functional unit in the framework).

CRE solar photovoltaic tender requirements (France)

CRE (Commission de régulation de l'énergie) defines the functional unit of the simplified carbon footprint analysis as: *1kWp of PV modules without frame*.

The respective reference flows of included materials in this functional unit are as described as follows:

- Modules in m^2 modules. This value is the module area needed to make 1 kWp whether for crystalline modules or thin film.
- Polysilicon in kg. This value is reduced to the mass of silicon contained in 1 kWp equivalent of module.
- Ingots in kg silicon. This value is reduced to the mass of silicon contained in 1 kWp equivalent of module.
- Wafers in number of wafers. This amount is reduced to the number of wafers needed to make 1 kWp equivalent of module. Losses and breakages are accounted for. (The reference value contribution is based on the actual size and the actual thickness of wafers - wafer reference size: 156 x 156 mm, thickness 190 microns).
- Cells in number of cells. This value is the number of cells required to make 1 kWp equivalent of module. Losses and breakages are neglected. The contribution may be reduced to the actual cell size (reference wafer 156 x 156 mm).
- Glass in kg. This value is the mass of glass needed to make 1 kWp so reduced to the surface and the thickness of glass (reference density of 2700 kg/m^3).
- Tempered glass in kg. This value is the mass of tempered glass to make 1 kWp (so returned to the surface and thickness of the tempered glass, reference density 2700 kg / m^3).
- EVA/PET/PVF in kg. This value is the mass of EVA/PET/PVF needed to make 1 kWp equivalent of module (so reduced to the surface and the thickness of the material, reference density 963 or 1400 kg/m^3).

Further specifications laid down are as follows:

- The calculations are based on the electricity mix of the country regardless of the actually electricity supply contract.
- Savings linked to the recycling of the complete module at the end of life cannot be considered in the carbon footprint calculation.
- Process inefficiencies are neglected. (e.g. breakage and yield loss).

1.1.2.7.2 Secondary product performance parameters

Secondary product performance characteristics are also possible to define based on additional functional performance characteristics required of the products. An initial identification has been made of the most important secondary characteristics related to interactions between the components of an installed PV system and:

- the electricity network to which a system is connected;
- a host building onto which a system may be installed or integrated; or
- users who may wish to maximise self-consumption of the electricity generated by a system.

These three possible forms of functional interaction are each briefly reviewed below and are then analysed in greater technical detail in the Task 3 report of this study:

Electricity network interactions

Interactions take place between the electricity distribution network to which a system is connected, and how components and parameters of the power supplied are managed – for example:

- Power management in order to provide control functions similar to those that have traditionally being provided by fossil fuelled power stations, such as: voltage support, ramping, frequency response, variability smoothing and frequency regulation and the control of reactive power, where beneficial to the system operator or as required by AC distribution network operators,

Host building interactions

Both functional overlaps and performance interactions may arise between a PV system and the host building onto which it may be installed or integrated within the external envelope or façade systems - for example:

- Window replacement provided by glass-glass laminates. The PV glass laminate pane will need to substitute like for like a high performance glass pane's functional characteristics.
- Weather proofing and façade substrate stabilisation or replacement provided by PV integrated into a rain screen cladding system, curtain wall or roofing. The PV cladding solution will need to substitute like for like the conventional construction product's functional characteristics.
- Shading that may be provided by cells or modules integrated into a brise soleil façade or patio shading system. The PV solution will substitute the expected shading characteristics of a metal fin, lamina or louvre.

It is also to be discussed whether potential trade-offs in the PV system performance as a result of integration should be accounted for in the evaluation e.g. higher operating temperatures due to the thermal absorption by building elements or constraints on the back ventilation of modules due to building fabric integration.

User interactions

Interactions may take place between a PV system the electrical systems of the host building and its users. In particular this may be influenced by users who may wish to maximise the self-consumption of the electricity generated, either by instantaneous load matching or by achieving a time shift of several hours between generation and final supply through the use of energy storage – for example:

- Demand-side management: Smart metering and data loggers that enable information about the electricity generated by a system to be consulted by a consumer and/or to be used as part of a smart control system linking appliances and systems within a home or office. In this case the consumer is likely to be interested in the 'smart readiness' of the digital systems.
- Electricity storage: Battery storage in order to supply electricity demands that occur when there is no solar insolation. In this case the consumer is likely to be interested in the characteristics of the battery system, the proportion of the electricity generated that can be stored and also the life cycle performance characteristics of the battery cells.

Thermal storage system components such as heat pump/thermal accumulator combinations are considered outside the scope of the study, because they would suppose remodelling to take into account an additional affected energy system *i.e. a domestic hot water system*. The same would apply to an interface with a grid ready car battery storage system, which would suppose remodelling to take into account displaced vehicle fuel systems.

1.1.3 Product scope for the EU Ecolabel

In this section an initial analysis of the scope, definition and criteria areas of existing ecolabel criteria at EU and international level. Initial feedback gathered from stakeholder questionnaire on the suitability and practicability of using the Ecodesign and/or EU Ecolabel product scope is also analysed.

1.1.3.1 Existing Ecolabel criteria sets at EU and international level

The Global Ecolabelling Network (GEN) identifies the following organisations as having developed ecolabel criteria sets with some relation to the photovoltaic product group at international level:

- TÜV Rheinland: The private body is considering the establishment of criteria for photovoltaic modules under its Green Product Mark ecolabel[16]. These are likely to be adopted from EPEAT, the ecolabel scheme of the US Green Electronics Council (GEC).
- Japan Environment Association (JEA): Criteria have only been developed for consumer products incorporating photovoltaic cells[17].
- Korea Environmental Industry & Technology Institute: Criteria have only been developed for consumer products incorporating photovoltaic cells [18].
- Singapore Environment Council: Criteria have only been developed for consumer products incorporating photovoltaic cells [19].

In addition to those initiatives listed by the GEN there are three further ecolabelling initiatives that may be of significance to this study:

- The German national ecolabel the Blue Angel. The ecolabel has since 2012 maintained a criteria set for inverters, but of potentially broader relevance to this study are their successive attempts to introduce criteria for both systems and modules.
- As referred to by TÜV Rheinland, module criteria are under development by private US organisation NSF International with the support of the US Green Electronics Council (GEC).
- The private US non-profit organisation Cradle to Cradle Products Innovation Institute, which has established a certification for the inherent sustainability of products and their component materials.

Each one of these initiatives is examined in turn in the following sections.

1.1.3.2 Blue Angel criteria for photovoltaic modules, inverters and systems (Germany)

The Blue Angel is an ecolabel established at national level by the German government in 1978. It is a pioneer in the development of product performance criteria for a broad range of consumer products. A criteria set for inverters was published in 2012. Several attempts have been made to develop criteria for modules and also systems. The criteria areas that were identified and the main issues encountered that prevented adoption of the criteria are briefly explained in this section.

Photovoltaic inverters product group (RAL-UZ 163)

The 2012 Blue Angel criteria for inverters apply to string and multi-string inverters with up to an output power of 13.8 kVA that are designed for use in grid-connected PV power systems. They identify maximising inverter efficiency as part of a photovoltaic system and engaging in network management to support grid stability as key challenges that the criteria seek to address. The eight technical criteria areas are listed in Table 6. Excluded from the product group are inverters integrated into a module (micro-inverters) and inverters designed for use in stand-alone systems. The criteria are all pass or fail. There are currently no licenses awarded.

Criteria development for modules and systems

The Blue Angel has made previous attempts to develop criteria sets for systems (2002 and 2008) and modules (2013) [20]. Neither of these criteria sets were adopted, in both cases due to problems reaching agreement on the assessment of energy yield and the restriction of hazardous substances.

The system criteria were to have included a requirement to simulate the performance of a system. However, agreement could not be reached on how to ensure comparability between the results whilst allowing designers a choice of calculation methods and software tools. They were also to have included a criteria on batteries, with cadmium content and the warranty a focus of attention.

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[16] *TÜV Rheinland, Green Product Mark, https://www.tuv.com/world/en/green-product-mark.html*

[17] *Japanese Environment Association, Product categories (certification criteria), https://www.ecomark.jp/english/nintei.html*

[18] *Korea Environmental Industry & Technology Institute, Certification criteria, https://www.ecomark.jp/english/nintei.html*

[19] *Singapore Environment Council, Singapore Green Labelling Scheme directory, https://www.sgls.sec.org.sg/sgl-directory.php*

[20] *Communication with Elke Kreowski, German UBA (2018)*

Table 6. Blue Angel photovoltaic inverters criteria overview (Germany). Source: RAL (2012)

Criteria area	Criteria	Requirement
1. Energy efficiency	Overall efficiency	Overall European weighted efficiency calculated according to EN 50530 of 95%
	No-load loss	No-load loss not exceeding 0.5 watts
2.Reactive power capability	Reactive power capability	In accordance with Guideline VDE-AR-N 4105
3. Longevity	Warranty	Free-of-charge warranty of at least 5 years Extended option of up to 20 years at extra charge
	Service	Defective systems repaired or replaced within a maximum of 48 hours
4. Material requirements	General requirements for plastics	Shall not contain REACH Candidate list substances Shall not contain substance with specific CLP hazard classifications (see the criteria document listing which includes some exemptions)
	Additional requirements for plastics used in housings and housing parts	Halogenated polymers shall not be permitted Halogenated organic compounds may not be used as additives or added to parts (with exemptions)
	Additional requirements for plastics used in Printed Circuit Boards	PBBs, PBDEs, TBBPA or chlorinated paraffins may not be added to the carrier material of the printed circuit boards.
	Requirements for electronic components	Shall not contain lead, mercury, cadmium or hexavalent chromium. Lead-containing solder shall not be used.
5.Recycling and disposal	Recyclability	Shall be designed to allow for easy disassembly for recycling by a specialist firm using ordinary tools.
	Product take-back	Free take back of the product Routing to reuse, recycling or professional disposal
6. Safety	Safety requirements	Meets minimum requirements according to EN 62109 (CE marking) Certificate of non-objection to integrated electronic load break switch Product literature to integrate product into protection systems
7.Electromagnetic capability	Compatibility requirements	Conformity with EN 61000-6-1/6-3 (CE marking)
8. Noise emissions	Maximum level	Maximum sound power level of 55 dB(A)

The module criteria were to have included requirements relating to module quality (with reference to IEC 61215 and IEC 61646[21]), the Energy Payback Time (EPBT) of the product, the marking of components for recycling purposes and a requirement for RoHS compliance which would have excluded certain PV-technologies containing lead or cadmium. Similarly to systems, agreement could not be reached on how to measure performance, with exemplars from the German market, such as PV Test and the Photon Module test, having been studied at the time. It was considered in the end that the development of a test protocol to measure energy performance fell outside the scope of the criteria study.

1.1.3.3 NSF/ANSI 457 Sustainability Leadership Standard for Photovoltaic Modules (USA)

The US organisation NSF International, with the support of the Green Electronics Council (GEC), has been leading since 2015 a process to develop environmental criteria for photovoltaic modules. The starting point for the criteria set has been the US Silicon Valley Toxics Coalition's (SVTC) 'Solar Scorecard' and the aim has been to develop a criteria set that addresses the full life cycle of a module. The final criteria set have been published as ANSI standard 457 and will be qualified to become an EPEAT standard as part of the global ecolabelling scheme for IT products [22]. Given the global success of the EPEAT standards for ICT equipment, this new standard therefore has potentially wider significance than just within the USA.

[21] IEC Standard 61646 is foreseen to become part of IEC 61215-1-x in 2019

[22] NSF International. Joint Committee on Sustainability Leadership Standard for Photovoltaic Modules – NSF/ANSI 457, October 2017, https://standards.nsf.org/apps/group_public/workgroup.php?wg_abbrev=sls_sust_photovoltaic

In terms of the product scope and definition used within the proposed criteria, the final 2017 release version of the NSF/ANSI 457 standard defines a solar photovoltaic module as being for:

'installation on, or integral with buildings, or to be primarily used as components of free-standing power-generation systems…' .

It defines a module as including, but not being limited to the following components:

- photovoltaic cells that generate electric power using solar energy
- interconnects (materials that conduct electricity between cells)
- encapsulant (insulating material enclosing the cells and cell interconnects)
- superstrate (material forming primary light-facing outer surface) and substrate (material forming back outer surface) (e.g., glass, plastic films)
- wires used to interconnect photovoltaic modules and connect junction boxes to the balance of system equipment
- frame or integrated mounting mechanism, if present

Moreover, the product definition then establishes the following exclusions:

- balance of system equipment, such as cabling and mounting structures, equipment intended to accept the electrical output from the array, such as power conditioning units (inverters) and batteries, unless they are contained in the photovoltaic module
- a photovoltaic cell that is a part of another device for which it produces the electricity, such as consumer or industrial electronic products (e.g. calculators, lights, textile) where the photovoltaic cell primarily provides the energy needed to make the electronic product function
- mobile photovoltaic cell where the inverter is so integrated with the photovoltaic cell that the solar cell requires disassembly before recovery

The standard contains product performance criteria and corporate performance metrics and consists of seven performance categories, which are identified together with the required criteria under each category, in Table 7. Like all EPEAT standards three levels of performance can be achieved – bronze, silver and gold. The bronze level is intended to reflect the performance of the top third of the market. Few products are currently anticipated to meet the gold level. The criteria set includes both environmental and social criteria. The criteria documentation contains an extensive set of normative references, which include IEC standards, European legislation (e.g. REACH, CLP). Reference is also made to industry and NGO initiatives, such as those relating to the development of sources of conflict-free minerals.

Table 7. NSF/ANSI 457 Sustainability Leadership Standard for Photovoltaic Modules required criteria overview Source: NSF International (2017)

Criteria area	Required criteria	Requirements for conformity
1. Management of substances	List of declarable substances	– Listing of IEC 62474 declarable substance groups – Processes to manage, maintain, update the listing
	List of declarable substances used in manufacturing	– List of substances from the ECHA database present in the product
	Disclosure of substances on the EU REACH Regulation Candidate List of Substances of Very High Concern	– List of substances from the Candidate List of SVHCs present in the product above 0.1%
	Avoidance or reduction of high Global Warming Potential (GWP) gas emissions resulting from photovoltaic module manufacturing	– Ensure that high GWP gases are not used or emitted – That abatement systems are installed, operated and maintained
2. Preferable materials use	Declaration of recycled content in product	– Declaration of the minimum % by weight of recycled content in the product (by component)
3. Life cycle assessment	Conducting life cycle assessment	– Conduct an LCA in accordance with ISO 14040/14044, EU PEF Guide or IEA PVPS Task 12 guidelines
4. Energy efficiency & water use	Water inventory	– Manufacturing in facilities that compile an inventory of water use and wastewater effluent
5. End of life management & design for recycling	Product take-back service and processing requirements (corporate)	– Provision of a product take-back service in conformance with the requirements
6. Product packaging	Elimination of substances of concern in product packaging	– Product packaging shall not contain lead, mercury, cadmium or hexavalent chromium in total >100ppm
	Elimination of chlorine in processing packaging materials	– Paper based materials shall not be bleached with chlorine compounds
	Enhancing recyclability of packaging materials	– Non-reusable packaging components □25g shall be separable by material type without the use of tools – All plastics □25g shall be clearly marked with their material type according to ISO 11469/1043
7. Corporate responsibility	Environmental Management System (EMS) certification (corporate)	– The product(s) shall be manufactured in facilities certified to either ISO 14001 or EMAS
	Manufacturer conformance with occupational health and safety performance (corporate)	– Manufacturers' operations covered by their EMS shall conform to OHSAS 18001
	Reporting on Key Performance Indicators (corporate)	– Annual public disclosure of information according to 10 Key Performance Indicators (KPIs)
	Committment to environmental and social responsibility (corporate)	– A commitment to continuous improvement in their operations and their suppliers
	Public disclosure of use of conflict minerals in products (corporate)	– Declaration of whether products contain conflict minerals

1.1.3.4 Cradle to Cradle certification (USA)

The Cradle to Cradle programme is a third party verified labelling scheme that aims to determine the extent to which the design and material composition of a product are able to facilitate future recycling. Two major solar PV module manufacturers are currently listed as having products certified according to the US Cradle to Cradle scheme – Sunpower and Jinko Solar [23]. The programme's criteria are grouped according to the following attributes [24] (Table 8)

- Material health: Use of materials that are safe for human health and the environment through all use phases
- Material reutilisation: Product and system design for material reutilisation, such as recycling or composting
- Renewable energy and carbon management: Use of renewable energy in production
- Water stewardship: Efficient use of water, and maintenance of water quality at production sites
- Social fairness: Company strategies for social responsibility.

Certification is in four tiers of attainment - Basic, Silver, Gold, and Platinum levels. The certification program applies to materials, sub-assemblies and finished products.

Table 8. Cradle to Cradle certification 'basic' level criteria overview (USA). Source: Cradle to Cradle Institute (2016)

Attribute	Standard requirements (basic level)
1. Material health	– No Banned List chemicals are present above thresholds. – Materials defined as biological or technical nutrients. – 100% "characterized" (i.e., all generic materials listed).
2. Material reutilisation	– Defined the appropriate cycle (i.e., technical or biological) for the product.
3. Renewable energy and carbon management	– Purchased electricity and direct on-site emissions associated with the final manufacturing stage of the product are quantified.
4. Water stewardship	– The manufacturer has not received a significant violation of their discharge permit related to their product within the last two years. – Local- and business-specific water-related issues are characterized (e.g., the manufacturer will determine if water scarcity is an issue and/or if sensitive ecosystems are at risk due to direct operations). – A statement of water stewardship intentions describing what action is being taken for mitigating identified problems and concerns is provided.
5. Social fairness	– A streamlined self-audit is conducted to assess protection of fundamental human rights. – Management procedures aiming to address any identified issues have been provided.

1.1.3.5 Summary of the results from the first stakeholder questionnaire

1.1.3.5.1 Modules

<u>Q1.8 Do you think that the scope of the study should be broadened or restricted for the specific purpose of the EU Ecolabel?</u>

35 out of the 39 respondents to this question (90%) indicated that the Ecolabel product scope should reflect that used for Ecodesign and Energy Labelling. Those that felt that the scope and definition should be different cited the potential to *'focus more on recyclability and Life cycle than power efficiency'* as well as *'material use, their toxicity for workers and their depletion*'.

<u>Q1.9 Are you aware of any relevant certification schemes or labels for the environmental performance of photovoltaic modules?</u>

In terms of relevant certification schemes or labels, those cited were:

[23] *Cradle to Cradle certified product registry, Listed under 'building supply and materials>electrical' https://www.c2ccertified.org/products/registry*

[24] *Cradle to cradle products innovation institute (2016) Cradle to cradle certified – product standard, version 3.1.*

- NSF/ANSI 457 Sustainability Leadership standard (10 respondents),
- Cradle to cradle (C2C) certification, noted as having been achieved by Sunpower (5 respondents),
- the French photovoltaic national call for tenders (4 respondents),
- the French Ecopassport scheme (4 respondents),
- the French E+C labelling (2 respondents).
- the Ecolabel initiative, piloted by CEA-INES and CERTISOLIS, with the support of Fraunhofer ISE and ENEA. (1 respondent)
- Clean Production Evaluation Index System for PV Cells in China (1 respondent),
- The Silicon Valley Toxics Coalition in the USA (1 respondent),
- 'Climate Savers' Partnership between WWF and Yingli Solar (1 respondent),
- The 'Solar Commitment' voluntary scheme in the USA (1 respondent).

One respondent highlighted that a set of Member State national ecolabel criteria had not been developed further because *'the difference in environmental performance between products was too small'* and that it *'could cause confusion for customers'* which would not be desirable given the overall environmental gain from solar electricity production.

1.1.3.5.2 Inverters

<u>Q2.8 Do you think that the scope of the study should be adapted for the specific purpose of the EU Ecolabel?</u>

12 out of the 14 respondents to this question (86%) indicated that the Ecolabel product scope should reflect that used for Ecodesign and Energy Labelling. The two respondents who felt that the scope should be adapted considered that Ecodesign and Energy Labelling have different scopes –*'efficiency (energy labelling) is [not always] proportional to a lower environmental impact'*.

<u>Q2.9 Are you aware of any relevant certification schemes or labels for the environmental performance of photovoltaic inverters?</u>

In terms of relevant certification schemes and labels, the only one mentioned was the German Blue Angel (1 respondent).

1.1.3.5.3 Systems

<u>Q3.11 Do you think that the scope of the study should be broadened or restricted for the specific purpose of the EU Ecolabel?</u>

Of the 20 respondents to this question all indicated that the Ecolabel product scope should reflect that used for Ecodesign and Energy Labelling.

<u>Q3.12 Are you aware of any relevant schemes or labels for the environmental performance of photovoltaic systems? In terms of relevant certification schemes and labels, those mentioned were:</u>

- the French photovoltaic national call for tenders (4 respondents),
- The German renewable energy law (EEG) which sets a requirement for the type of land to be used for PV projects (3 respondents)
- IEC Renewable Energy conformity assessment scheme for systems (1 respondent)

Under Q3.9 relating to 'existing initiatives or criteria sets used to benchmark or promote an improved quality of installation for solar photovoltaic system' the following were also identified:

- DNV GL (private) certification for power plants, originating from Norway (1 respondent)
- The 'GRTU approved' quality, efficiency and safety inspection scheme for installed PV systems in Malta (1 respondent)
- The Quest scheme in Belgium for installation quality (1 respondent)
- VDE (and Fraunhofer ISE) Technical Bankability certification for PV power plants (1 respondent)

The mandatory schemes for certification of installers resulting from art 14 of the Renewable Energy Directive were highlighted.

1.1.4 Product scope for Green Public Procurement (GPP) criteria

In this section an initial analysis of the scope, definition and criteria areas of existing Green Public Procurement (criteria) used in the EU is made. Initial feedback gathered from stakeholder questionnaire on the suitability and practicability of using the Ecodesign and/or EU Ecolabel product scope is also analysed.

1.1.4.1 Existing GPP criteria sets used in the EU

A EU GPP criteria set for the solar photovoltaic product group does not currently exist. A criteria set for electricity was published in 2012 by DG Environment [25]. The criteria document states part of EU GPP approach shall be to *'increase the share of electricity from renewable energy sources*'. No specific criteria or references to solar photovoltaic technology could be found in the current criteria document. A review of European Commission surveys of Member State GPP criteria [26] and collaborative EU projects such as PRIMES and GPP 2020 did not reveal any national criteria sets to be currently in use [27].

1.1.4.2 Summary of the results from the first stakeholder questionnaire

1.1.4.2.1 Modules

<u>Q1.11 Should the same scope as set out for the whole study also be used for public procurement purposes?</u>

Of the 24 respondents to this question 23 indicated that the Green Public Procurement (GPP) product scope should reflect that used for Ecodesign and Energy Labelling.

<u>Q1.12 Are you aware of any existing initiatives or criteria sets used in public procurement for the environmental performance of modules?</u>

In terms of existing initiatives or criteria sets, those mentioned were:

- the French photovoltaic system national call for tenders, which contain *'a carbon criterion for modules and some additional environmental criteria'* (6 respondents),
- NSF/ANSI 457 Sustainability Leadership standard (1 respondent),
- The German renewable energy law (EEG) which sets a requirement for the type of land to be used for PV projects (1 respondents)
- US EPA GPP webinar entitled 'Improving Solar PV Results through Collaborative Procurement' which covered the Renewable Energy Procurement (REP) Project in California (1 respondent)

Amongst the references to the French national call 'a "simplified carbon evaluation" based on specific emission factors considering material or component manufacturing process' was referred to. One respondent noted that:

> *'the lower the value is, the better the evaluation for the tender is. The purpose of these steps is to bring manufacturers to modify their environmental practices by proposing a gradual improvement throughout the periods and calls for tender.'*

In relation to the NSF/ANSI 475 standard it was noted by the respondent that 'since the EPEAT ecolabel is widely recognized globally and within the EU when it comes to GPP, the [standard] could offer a lot of synergies to the GPP process.'

1.1.4.2.2 Inverters

<u>Q2.11 Should the same scope as set out for the whole study also be used for public procurement purposes?</u>

All 14 respondents to this question indicated that the Green Public Procurement (GPP) product scope should reflect that used for Ecodesign and Energy Labelling.

<u>Q2.12 Are you aware of any existing initiatives or criteria sets used in public procurement for the environmental performance of inverters?</u>

No initiatives were put forward and it was noted by one respondent that *'there are very few public tenders specifically for inverters'*.

1.1.4.2.3 Systems

<u>Q2.11 Should the same scope as set out for the whole study also be used for public procurement purposes?</u>

Of the 14 respondents to this question 13 indicated that the Green Public Procurement (GPP) product scope should reflect that used for Ecodesign and Energy Labelling.

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[25] DG Environment (2012) EU GPP criteria for electricity, http://ec.europa.eu/environment/gpp/pdf/criteria/electricity.pdf

[26] DG Environment, Studies, http://ec.europa.eu/environment/gpp/studies_en.htm

[27] DG Environment, GPP Ongoing projects, http://ec.europa.eu/environment/gpp/projects_en.htm

Q2.12 Are you aware of any existing initiatives or criteria sets used in public procurement for the environmental performance of inverters?

In terms of existing initiatives or criteria sets, those mentioned were:

- the French photovoltaic system national call for tenders (2 respondents),
- The German renewable energy law (EEG) which sets a requirement for the type of land to be used for PV projects (2 respondents)
- US Department of Energy solar procurement guide for Federal Agencies (1 respondent)

1.2 Measurement and test standards

This section represents a summary version of the accompanying draft JRC Technical Report 'Standards for the assessment of the environmental performance of photovoltaic modules, power conditioning components and photovoltaic systems', which has been published as a support of this Preparatory Study[28]. It makes the following analysis of standards that are specific for solar photovoltaic modules, inverters and systems:

- Identification and description relevant standards,
- Comparative analysis of existing standards and their functional parameters,
- New standards under development.

For each sub-product an overview of the identified relevant performance parameters and their supporting standards, when available, is presented – namely: individual PV modules (see 1.2.2), power conditioning and storage components with a focus on inverters and batteries (see 1.2.3), and PV systems including stand-alone. building-added (BaPV) and Building Integrated (BIPV) systems (see 2.2.4 and 2.2.5).

Generic standards that address aspects of environmental performance and which are applicable to solar photovoltaics, such as those establishing methods for Life Cycle Assessment (LCA) and the assessment of material efficiency and circularity aspects such as repairability and disassemblability, are addressed further in the aforementionedJRC report.

1.2.1 Organisational structure of standardisation

The first choice on which to base the European legislation are harmonised standards. As defined by article 2 of the Regulation (EU) 1025/2012, a harmonised standard is a "European standard" that has been adopted by a recognised European Standardisation Organisation (i.e. CEN, CENELEC or ETSI) on the basis of a request made by the European Commission (EC). Such a request is aimed to the application of the requested standard's technical specifications and requirements within the European Union's harmonisation legislation. Manufacturers, other economic operators or conformity assessment bodies can use harmonised standards to demonstrate that products, services or processes comply with the relevant EU legislation that refers to those standards. A "presumption of conformity" is granted for those products that fully comply with harmonised standards.

When harmonised standards are not available, as it is the case of first stages of a new legislation process, other types of (preferably international) standards may be considered to be brought to the level of harmonised standard through the legislative procedure.

The standards considered in this section originate from the different standardisation organisations, depending on the specific topic and on their current availability. Whenever possible, the standards referred to are those published by the European standardisation organisations CEN and CENELEC for the general and the electrotechnical topics, respectively. In absence of relevant standards set in the specific European context, other equivalent and applicable norms were examined within broader international standardisation bodies like the International Standardization Organisation (ISO) and the International Electrotechnical Commission (IEC) for general and electrotechnical topics, respectively. In few cases lack of standardisation is highlighted.

[28] Dunlop E.D., Gracia Amillo A., Salis E., Sample T., Taylor N., Standards for the assessment of the environmental performance of photovoltaic modules, power conversion equipment and photovoltaic systems, EUR 29247 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-86608-1, doi:10.2760/89830, JRC111455

1.2.2 PV Modules

1.2.2.1 Functional parameters and related standards

The following functional parameters currently have a basis in standardisation and can be considered essential as a starting point for supporting the Preparatory Study:

a. **PV module maximum power (P_{max})** according to the EN 60904-1 and reported at specific reference conditions, named Standard Test Conditions (STC) and defined by the Technical Specification CLC/TS;
b. **Module Energy Conversion Efficiency**, as defined in the next edition of the EN 60904-1 under revision;
c. **Module Performance Ratio (MPR)** calculated according to the series of standards EN 61853 partly still in preparation at the IEC (drafts IEC 61853-3 and IEC 61853-4);
d. **Module Energy Yield DC**; the DC energy produced by a single PV module following the method of calculation described in the draft IEC 61853-3 for one or all of the Standard Reference Climatic Profiles tabulated in the draft IEC 61853-4, with measurements of PV module power according to EN 61853-1 and corrections for temperature, spectrum and angle-of-incidence losses as described in EN 61853-2;
e. **Module Energy Yield AC**, derived from Module Energy Yield DC by suitable losses factors (to be defined);
f. Module Annual Degradation Rate.

The PV module maximum power P_{max} is a first measure to compare the performance of different PV modules and is normally defined at STC.

The power measurement, performed according to EN 60904-1, usually requires the support of other standards from the EN 60904 series and of the EN 60891 for appropriate corrections, as the actual test conditions rarely match STC definition.

PV technologies including c-Si modules need to be pre-conditioned or brought to a stable state before an STC measurement can be performed. Therefore, the series of standards EN 61215 is of support to both the power measurement and the module performance ratio.

The comparison of PV modules according to the measurement of their energy conversion efficiency (n) at STC (defined as the ratio between the maximum power at STC in watts (W) and the product of the total reference irradiance of 1000 W/m^2 with the module area in m^2) is useful to compare different PV modules or technologies. Efficiency on its own does not however evaluate directly the capability of electrical power delivery of single modules. The power measurement has to be performed at STC following the requirements set by the standard EN 60904-1 (for single-junction (SJ) PV modules). The present edition of this standard does not define the efficiency, though. The next edition currently under preparation at the IEC TC82 WG2 would likely define it. Therefore, it would be possible to refer directly to it for the definition of module conversion efficiency.

A combined parameter integrating several of the above elements could be defined as:

> *"A PV module functional unit is 1 kWh of DC power output under predefined climatic and installation conditions for 1 year and assuming an intended service life of 25 years"*

This represents the module energy yield, instead, and is based on the measurement of the electrical power delivered by a PV module under several conditions of irradiance and temperature, which better represent the real conditions met in the field. Such a set of power measurements at varying irradiance and temperature defines the power matrix (or performance surface) of the PV module and is subject of the standard EN 61853-1. The power matrix is then used as input to the MPR calculation according to the draft standard IEC 61853-3 together with other parameters defined and required by the standard EN 61853-2.

The MPR calculation is performed considering the climatic conditions that represent the typical location at which the PV module will be installed. A set of six Reference Climatic conditions are defined in the draft standard IEC 61853-4, which covers the most common climatic conditions observed in the world. As far as the European continent is concerned, it is possible to cover the variety of the European climatic regions with three of these six data sets (or define three data sets specifically for Europe), which can be described as subtropical, temperate continental and temperate coastal.

Three possible solutions are proposed to be considered to define the necessary European climatic data sets:

- To use those data sets already included in the draft IEC 61853-4 and representative of the three main European climates;
- To define climatic data sets specifically for the European continent only in addition to those included in the IEC 61853-4 and either include them explicitly in the future policies or refer to a centralised server to host them as downloadable data;
- To make site-specific climatic data available through a geographical information system (GIS), which everyone could download (which may be more appropriate for systems).

These solutions are also discussed in the Task 3 report of this Preparatory Study, in relation to the modelling of 'direct' impacts according to a system expansion approach.

1.2.2.2 Product quality standards

The main pillar of the performance qualification of PV modules is the EN 61215 series of standards, which has replaced and grouped in a single consistent series the qualification requirements prescribed by the previous single standard EN 61215 (applicable only to c-Si PV modules) and by the EN 61646[29] (applicable only to thin-film PV modules). With the latest revision of the standard IEC 61215 (which afterwards went through parallel vote at CENELEC), the IEC TC 82 WG 2 reorganised and rationalised the subject.

The current series EN 61215 consists of two main Parts:

1 *EN 61215-1 Design qualification and type approval - Part 1: Test requirements*, which includes general requirements for testing relevant qualification aspects of PV modules, such as susceptibility to thermal, mechanical and electrical stressors;
2 *EN 61215-2 Design qualification and type approval - Part 2: Test procedures*, which describes the individual tests to be run in order to qualify a PV module type, i.e. the single materials and components chosen for its manufacturing as well as their layout and interconnection that are part of the specific PV module design.

The new holistic approach given to the series EN 61215 "*Design qualification and type approval*" becomes even clearer when the individual material-specific parts in which the EN 61215-1 is split into are considered. Indeed, as listed in the following, they individually address specific requirements for the qualification of PV modules (with higher priority than the general Parts 1 and 2) depending on the active PV material (i.e. the PV technology) that is used in their production:

- EN 61215-1-1 Design qualification and type approval - Part 1-1: Special requirements for testing of crystalline silicon photovoltaic (PV) modules;
- EN 61215-1-2 Design qualification and type approval - Part 1-2: Special requirements for testing of thin-film Cadmium Telluride (CdTe) based photovoltaic (PV) modules;
- EN 61215-1-3 Design qualification and type approval - Part 1-3: Special requirements for testing of thin-film amorphous silicon based photovoltaic (PV) modules;
- EN 61215-1-4 Design qualification and type approval - Part 1-4: Special requirements for testing of thin-film Cu(In,Ga)(S,Se)2 based photovoltaic (PV) modules.

The testing required by the EN 61215 series for qualification of PV modules consists of a specific sequence of accelerated tests. These tests aim to simulate, in a much shorter time, the degradation process to which PV modules are likely to be subjected when mounted in real installations and exposed to a foreseeable range of environmental conditions. However, it has to be highlighted that the acceleration factors, which would give a quantitative correspondence between the stressor as applied in the laboratory and the degradation achieved in the field due to exposure to specific environmental conditions, are not yet available, as they indeed depend on climatic conditions to which the PV module is exposed as well as on the specific design of the PV module and the actual installation.

Some accelerated tests are explicitly included in the EN 61215. These are:

[29] *IEC Standard 61646 is foreseen to become part of IEC 61215-1-x in 2019*

- Thermal cycle test, which considers only temperature as stressor;
- Damp heat test, which considers the combination of effects due to temperature and humidity. This test is addressed by the individual sub-parts EN 61215-1-X with parameters specific for each PV technology;
- Humidity freeze test, which aims to causing and revealing possible failures of the sealing materials and components of the PV modules;
- UV test, which can precondition the polymeric components of the PV module;
- Static mechanical load test, which simulates the effect of prolonged continuous mechanical loads on the surface of the PV module, such as those caused by constant wind or homogeneous snow accumulation;
- Hot spot test. It deals with safety issues due to local partial shading on thin-film modules, which can cause the creation of very hot small areas in the PV material and produce failure of the PV module;
- Hail test.

In addition to these, other accelerated tests are available as separate standards, some of which are being considered to be included in the future within the EN 61215 series.

Further information on the acceleration factors to be used for quantitative analysis of the degradation process might be derived by means of extensive testing applying measurement procedures like those required by the series of standards EN 62788, which deals with accelerated weathering testing procedures on a wide variety of materials and components for PV modules. In this sense, an increased availability of feedback from the field in terms of information on (known or new) failure modes and the environmental conditions at which they occur would also be extremely valuable.

Furthermore, there is ongoing work to submit a proposal for a new work item on extended testing, which would include longer or more intense test for a specific stressor in order to further improve PV module qualification beyond the basic requirements. This could be used by manufacturers as well as by PV installation designers to check whether the PV products meet specific more aggressive or prolonged stressing conditions.

Today, in addition to qualification testing (IEC 61215 for measurements and IEC 61730 for safety) most PV companies require a robust quality management system that controls many aspects of the manufacturing process (incoming materials, processes, etc.) as well as testing beyond IEC 61215. As the PV industry matures, the methods used for quality control (QC) are evolving to utilize new knowledge and to be more consistent, enabling lower QC costs, as with IEC TS 62941.

Series EN 62788 could also be used in the framework of quality controls recommended by the IEC TS 62941, in order to improve confidence in PV module design qualification and testing at production sites. Indeed, the series EN 62788 gives guidelines on many measurement procedures that, for example, could be implemented at the manufacturer factory as quality check of the incoming material/component or of the PV module production process itself and as feedback from the production to the design and engineering stage within the overall quality system of the manufacturer.

Additionally, the standards series IEC 60068 "Environmental testing" contains environmental testing procedures for electrical, electro-mechanical and electronic equipment and devices. Some of these testing may be applicable to PCEs for testing degradation due to corrosion, or failure due shock, vibration, or deposition of dust and sand. The same testing conditions could be applicable to PV modules.

An evolution in the standardisation process might be anticipated, whereby there could be a move from "pass-fail" qualification testing to more sophisticated analyses, which instead provide more quantitative assessment of risks specific to a particular location, or type of location, and thus enable more quantitative assessments to be made of the value of high-quality components, both in terms of degradation rates and failure rates. One proposed approach to completing a quantitative assessment assigns a Cost Priority Number (CPN) that reflects the cost of repair or loss of revenue associated with a problem [30]. Assignment of a CPN or other rating methodologies [31] relies on being able to link knowledge about the components and system with the anticipated outcomes. The industry has not yet agreed upon the best approaches for gathering and using the information needed for quantifying overall risk.

[30] Moser D, Del Buono M, Jahn U, Herz M, Richter M and De Brabandere K 2017 *Identification of technical risks in the photovoltaic value chain and quantification of the economic impact* Prog Photovoltaics Res Appl 25 592-604

[31] Shrestha S M, Mallineni J K, Yedidi K R, Knisely B, Tatapudi S, Kuitche J and TamizhMani G 2015 *Determination of Dominant Failure Modes Using FMECA on the Field Deployed c-Si Modules Under Hot-Dry Desert Climate* IEEE J. Photovoltaics 5 174-82

1.2.2.3 Lifetime, failure modes and performance degradation

The lifetime of a PV module is not precisely defined yet in any international standard or other official document. Some suggestions or common practices are available, which are reported in both this section and in section 1.2.2.2.

In particular the subject of degradation of PV modules is still subject to debate within the PV community and all the standardisation bodies. The available standards, published or in draft as first edition, dealing with degradation issues are tabulated in the main standards report.

The lack of extended standardisation work on this topic is due mainly to the fact that, although some tests for qualification were developed to set some pass/fail criteria according to which to discard the most probable failing modules, new and different failure modes of PV modules appear in the field over time. Also, alternative materials or different environment (climatic) conditions are explored. The previous IEC 61215 (now IEC 61215 series) standard has demonstrated its value for rapidly uncovering well-known failure mechanisms. However, it is insufficient for assessing long-term risks, for evaluating newer or less common materials and designs, or for establishing field performance degradation[32].

The issue of failure modes and performance degradation for PV modules (and therefore systems) must still be considered as belonging to the learning curve of the PV scientific community. As a consequence, the operational service life of PV modules may have to be defined by the co-legislators instead, according to best criteria still to be determined. This opens the possibility for wider involvement of the PV community in a feedback process that could be the basis for building a European dataset of failure modes; these could then be used as input to new and improved standardisation activities, e.g., for the prEN 45552 work.

Today's rapidly changing PV technology requires many companies to launch new versions of their products every few months while requiring warranties that are decades long (typically 80% of power after 25 years). In the absence of a standardised method to determine the durability of PV modules, one can use compiled field data, in order to obtain educated (scientifically observed) estimates for degradation rates for different technologies.

1.2.3 Inverters and other power conversion and conditioning components

The product category of power conversion equipment (PCE) comprises the electrical and electronic equipment used to convert the electrical power from a PV modules array into a form suitable for subsequent use by a downstream consumer and with the required quality in order to be delivered to the connected electrical appliances. It therefore includes equipment to transform from DC to AC, like inverters, but also other instruments to modify the voltage or frequency like transformers or converters. Other electrical equipment such as batteries, battery-charge regulators, optimisers and blocking diodes are also considered in this category.

1.2.3.1 Functional Parameters and related standards

With a focus on inverters as being the most important PCE for most solar PV installations, there are several parameters that could be considered as the main functional unit.

In accordance with the standard IEC 62894 "Photovoltaic Inverters - Data Sheet and Name Plate" or the withdrawn equivalent EN 50524 "Data sheet and name plate for photovoltaic inverters" there are different variables that could be considered as primary functional parameter like the maximum or minimum input voltage, maximum or minimum grid voltage, the start-up voltage at which the inverters starts energising the utility grid or load, the maximum power point voltage, the frequency or the rated input power or rated grid power.

In addition to these parameters, for commercial purposes, PV manufacturers tend to classify different inverters by the recommended PV array power range (i.e. input power to the inverter), by the maximum efficiency or by the "European efficiency". Inverters and power converters in general do not constantly operate at their maximum efficiency possible, but rather at an efficiency that depends on the input power level. The "European Efficiency" is a parameter that corresponds to an

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[32] *Kurtz S et al. 2017 Qualification Testing versus Quantitative Reliability Testing of PV – Gaining Confidence in a Rapidly Changing Technology. In: 33rd European Photovoltaic Solar Energy Conference and Exhibition, (Amsterdam) pp 1302 - 11*

operating efficiency averaged over a year of operation in a middle-European climate. This parameter, defined in Annex D of the standard EN 50530, is at present referenced by most manufacturers. The California Energy Commission (CEC) proposed other weighting factors, which are also included in the above-mentioned EN 50530. The CEC efficiency considers, for example, less likely that the real working conditions of the inverter would make it work at its maximum efficiency, contrary to the European Efficiency definition.

The efficiency could be an adequate primary functional parameter as it can be applied to all PCEs. In addition to EN 50530 for grid-connected inverters, the IEC standard 61683 "Photovoltaic systems – Power conditioners – Procedure for measuring efficiency" describes the guidelines for measuring the efficiency of power conditioners used both in stand-alone and utility-interactive PV systems where the output is a stable AC voltage of constant frequency or a stable DC voltage. Focusing on grid-connected inverters, the standard EN 50530 would apply providing the procedure for the measurement of the accuracy of the maximum power point tracking (MPPT). Both the static and the dynamic MPPT efficiency are considered in order to calculate the overall inverter efficiency, in addition to defining both the European and CEC efficiencies.

In order to apply some of the previously mentioned standards, others need to be considered as supporting standards. Amongst them, for example, standard EN 50160 describes the main characteristics of line voltages at the supply terminals of a network used in public low, medium and high voltage AC electricity networks.

If considered as primary functional unit, the "European efficiency" could be calculated from these efficiency values obtained according to these standards.

An alternative performance–related functional parameter for inverters would be AC energy from a reference PV system consisting of the inverter model under consideration i.e. an integration of the AC energy output in relation to the DC power from the reference modules under fixed climatic conditions for 1 year.

A further elaboration of this approach is to include an assumed service life of 10 to 15 years depending on the size of the inverter (residential PV system or large PV plant). Such a parameter is derived from IEA report references, together with EN 61724. However, in order to estimate such parameter several assumptions should be adopted so as to model both PV array power output and inverter performance including the effects of degradation.

Besides these parameters, there are others not directly related to the electrical characteristics of the PCEs that could be used as secondary functional parameters to further segment and classify inverters and other PCEs. For example, parameters related to physical characteristics, such as number of DC connectors or the cooling principle used, or aspects related to safety or grid integration, such as stand-by consumption, time to start-up, harmonic distortion or different protection techniques like islanding prevention.

A combined parameter integrating several of the above could be defined as:

> *"PV Inverter functional unit is 1 kWh of AC power output from a reference photovoltaic system (excluding the efficiency of the inverter) under predefined climatic and installation conditions for 1 year and assuming a service life of 10 years"*

However, in the case of PCEs we would suggest that this requires the inclusion of the European Inverter Efficiencies to be complete.

1.2.3.2 Lifetime, reliability and failure modes

Various reports conclude that the inverter is the element of the PV system which is responsible for the highest number of operation and maintenance events with the subsequent cost burden and loss of power production. In order to reduce these impacts, some standards are being developed in order to improve the inverter's reliability from quality and testing points of view. In parallel, industry already applies various accelerated tests so as to detect infant failures that would result in premature failure and degradation of the inverter. Some examples are given in Hacke et al (2018) [33].

[33] Hacke P, Lokanath S, Williams P, Vasan A, Sochor P, TamizhMani G, Shinohara H and Kurtz S 2018 A status review of photovoltaic power conversion equipment reliability, safety, and quality assurance protocols Renewable and Sustainable Energy Reviews 82 1097-112

The draft IEC 62093 "*Balance-of-system components for photovoltaic systems- Design qualification natural environment*" defines several tests applicable to the BOS equipment of terrestrial PV systems including batteries, inverters, charge controllers or protectors, maximum power-point trackers, etc. Tests include visual inspection, functioning tests, insulation test, protection against dust or water or UV test among others. However, this standard was minimally adopted by the industry.

The renamed draft second edition IEC 62093 "*Power conversion equipment for photovoltaic systems - Design qualification testing*" has a narrower scope, being just for inverters and DC/DC optimisers. It contains clauses to perform accelerated life testing including both low and high temperature levels, rapid thermal cycling, vibration and combination of these sequences.

A draft standard (IEC 63157) is under development for quality assurance of PCE equipment. However, the quantitative impact that the possible defects will have on the performance of the PCEs is not defined in the standards.

1.2.3.3 Complementary Standards

There are several complementary standards applicable to PCEs regarding aspects of safety as well as grid-connection requirements from different regulatory levels such as EN, IEC but also country specific regulation that PCEs should comply with in order to operate in certain national networks. As an example, we can cite the RD1699/2011 which regulates the connection of generating plants at low voltage to the Spanish distribution network. Similar regulations exist in other countries with which PCEs installed there should comply.

IEC TS 62910 provides a test procedure for evaluating the performance of Low Voltage Ride-Through (LVRT) functions in inverters used in utility-interconnected PV systems. It is applicable to large systems where PV inverters are connected to utility high-voltage (HV) distribution systems, although it may also be used for low voltage (LV) installations. The measurement procedures are designed to be as non-site-specific as possible, so that LVRT characteristics measured at one test site can also be considered valid at other sites. This technical specification is for testing PV inverters, although it may also be useful for testing a complete PV power plant consisting of multiple inverters connected at a single point to the utility grid. It further provides a basis for utility-interconnected PV inverter numerical simulation and model validation.

Regarding safety requirements, the standard EN 62477-1 applies to all PCEs and can be used as reference for adjustable speed electric power drive systems (PDS), stand-alone uninterruptible power systems (UPS) or LV stabilized DC power supplies. It provides minimum requirements for their control, protection, monitoring and measurement. It also establishes minimum requirements for the coordination of safety aspects and specifies requirements to reduce risks of fire, electric shock, thermal, energy and mechanical hazards, during use and operation. Also, the standard series EN 62109 with its different parts defines the minimum safety requirements for PCEs used in PV systems.

EN 62909 specifies general aspects of bi-directional grid-connected power converters linking inverters with DC power converters.

Other standards related to safety or grid-connection requirements have been adopted at EN and IEC level simultaneously, while in some cases they exist solely at IEC level.

Although not directly related to their technical performance, but however possibly applicable to durability, degradation and lifetime analyses, the IEC standard series 60068 constitutes a set of documents containing information on environmental testing procedures for electrical, electro-mechanical and electronic equipment and devices. Some of these testing may be applicable to PCEs for testing degradation due to corrosion or failure due shock, vibration or deposition of dust and sand. The IEC standard 60529 provides test methods and ratings of casing ingress protection from, for example, water and sand.

1.2.3.4 Batteries

The batteries used in PV systems, whether grid-connected or stand-alone, are mainly of two types: lead-acid and lithium-ion. They can be both described by a series of parameters like the capacity or the nominal voltage. The capacity can be defined in two ways: (i) the current capacity in ampere-hour (Ah) that can be drawn from the battery fully charged; (ii) the power capacity in watt-hour (Wh), which would be calculated as the product of the current capacity and the nominal voltage.

Battery performance is subject to degradation over time, expressed in terms of the number of charge and discharge cycles after which a battery will maintain a notional level of capacity, usually 80%. IEC EN 61960 is the reference standard for the

measurement of battery cycle endurance. It specifies both a standard endurance in cycles test at 0.2 It A and an accelerated endurance in cycles test routine based on increased charge of 0.5 It A within the tolerance of the battery.

1.2.4 PV Systems

1.2.4.1 Functional Parameters and related standards

Given that the purpose of a PV system is to provide electrical energy with an adequate quality to a downstream user by converting the received solar radiation into electricity, the following functional parameters can be considered to describe the PV system electrical performance:

- System Power Output;
- System Energy Output/Yield;
- System Performance Ratio, i.e. the ratio of the system energy yield to a reference energy yield, and taking account of losses due to PV array operating temperature and system inefficiencies;
- System Energy Efficiency.

The following describes the normative approaches available to calculate the above parameters.

System Power output: EN 61724-1 defines the system nominal or rated DC power (labelled Wp) as the arithmetic sum of the power values at STC of the installed PV modules (see section 1.1.2.4). The AC rated power on the other hand is determined in EN 61724-1 as the lesser of the sum of the array DC power and the sum of the inverter maximum power ratings.

System Energy output/yield: They relate to AC power output, E_o, typically for a one-year reference period [34], and energy yield, which is the energy output normalised by the rated DC power as defined above.

There is currently no dedicated standard for calculating the expected [35] energy output for PV systems. IEC TS 61724-3 provides a framework for a generic model that would combine a set of fixed parameters describing a PV system with environmental parameters, but it also explicitly notes that the definition of the model itself is outside its scope. Nonetheless, some concepts and parameters can be useful in the present context.

Several PV system energy models are available as online tools, and these generally combine the following elements:

- DC power delivered by the PV module array(s), as a function of its design and environmental parameters (irradiance, ambient temperature, wind speed). Here, the procedure for determining PV module energy yield as per IEC 61853-3 can provide a basis;
- Inverter efficiency, also a function of the power factor if data are available;
- Factor(s) to account for other losses (wiring, connections).

The environmental data can be a Standard Reference Climatic profile (as discussed in section 1.2.2.1 or a location specific dataset, such as the Typical Meteorological Year (TMY) data foreseen under the Energy Performance of Buildings Directive, and compliant with the INSPIRE Directive. In the latter case, the resulting energy output value will be specific to a given system configuration and the assumed location/environment.

EN 15316-4-3 standard “Energy performance of buildings – Method for calculation of system energy requirements and system efficiencies” provides a simple methodology to estimate the energy yield of building integrated PV system, but it is in principle applicable to any kind of PV system.

System performance ratio: EN 61724-1 applies the definition

$$PR = \frac{Y_f}{Y_{ref}}$$

[34] It is also possible to consider the energy output over the service life, including any progressive degradation of the performance of the components (see section 3.2.5).

[35] In IEC terminology “expected” indicates an ex -ante design calculation using an appropriate system model and historical or reference environment input, “predicted” refers to the theoretical output for given environmental conditions, and “actual” refers to measured values.

Where:

Y_f is final energy yield, defined as net energy output E_o normalised by the DC rated power, P_o.

Y_{ref} is the reference energy yield, defined as the in-plane irradiation for the reference period normalised by the reference irradiance $G_{i,ref}$. The latter corresponds to the irradiance condition used to define the nominal DC power, P_o.

One feature of the performance ratio (PR) parameter is that it is sensitive to thermal losses in the PV array, which implies that in hotter climates it will be smaller as the modules operate at a higher temperature. To address this, the EN 61724-1 includes the possibility to calculate a temperature-corrected PR.

System (AC) Efficiency: Another possible functional parameter for PV systems could be its general efficiency, obtained as the ratio of the produced electricity yield and the received solar irradiation. EN 61724-1 defines the system efficiency as:

$$\eta_f = \frac{E_{out}}{H_i . A_a} = \eta_{A,0} \; x \; PR$$

Where: E_{out} is the system energy output, H_i is the irradiation received, A_a is the total module area and $\eta_{A,0}$ is the rated array efficiency. However, as for the PR parameter, the calculation of an expected value is not straightforward as it implicitly requires a system energy output model. Again, a way of circumventing this would be to rely on a limited number of on-site measurements made during the system commissioning.

Alternatively, if the value of the PR can be assumed or if it has been measured (EN 61724-1), the above equation can be used to specify the AC power output, the energy output E_o and also the energy yield. For instance, the IEA Life Cycle Assessment guidelines [2] uses this approach, proposing either site-specific PR values or a default value of 0.75 for roof-top systems and 0.80 for ground-mounted utility installations.

The EN 61724-1 also defines a power performance index, which is the ratio of the actual power output to the expected power output. Likewise an energy performance index relates the actual or predicted energy to the expected energy.

However, EN 61724-1 does not present a method of predicting the System Final Energy Yield, rather it was intended to provide a common post-installation verification standard to perform contractual tests such as the capacity test (61724-1) and the annual energy test (61724-3). It is therefore necessary to define a prediction method for the energy yield. This could be based on the approach for the Module Energy Yield DC (IEC 61853-3) with the additional input of system considerations.

A combined parameter integrating several of the above could be defined as:

> "*PV System functional unit is 1 kWh of AC power output supplied under fixed climatic conditions for 1 year (with reference to IEC 61853-4) and assuming a service life of 25 years*"

1.2.4.2 System design, installation and maintenance standards

The draft EN 62548 "*Design requirements for Photovoltaic (PV) arrays*" defines the design requirements for PV arrays including DC wiring, electrical protection devices, switching and earthing provisions. The standard covers all parts of the PV array but excludes the energy storage devices, the power conversion equipment and the loads.

EN 62446-1 "*Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 1: Grid connected systems - Documentation, commissioning tests and inspection*" contains the information and documentation that should be provided to the customer when the PV grid system is installed, and the requirements of inspection and testing that should be done during the system lifetime in order to verify the safe installation and correct operation of the system.

IEC 61724-3 defines steps to report the actual measured energy, outlining the required steps to report the actual annual energy generation and can therefore be utilised as a consistent measure of the system output.

IEC TS 62738 "Design guidelines and recommendations for Photovoltaic power plants" defines design of utility scale ground mounted PV power plants. The standard covers all part of the PV power plant up to the Medium voltage connection.

IEC 62446-2 (Requirements for testing, documentation and maintenance – Part 2: Grid connected systems – Maintenance of PV systems)" is currently in its final draft and lays out best practices and recommendations for PV plant maintainance.

It should be noted that additional quality standards for the PV system may be necessary to consider.

1.2.4.3 Lifetime, failure modes and performance degradation

To the knowledge of the research team there are no standards currently available for modelling the performance degradation rates of PV systems, and even though there are publications on fault detection and the monitoring of PV systems[36] [37] [38], there are no clear degradation rates for PV systems as there are for PV modules.

Degradation in performance may derive from the modules, wiring, the inverter's maximum power-point tracking system or even other factors, like soiling or presence of shadows. The combined impact of these possible effects is difficult to model and are referred to in the EN 61724 standards series as derate factors with respect to a systems nameplate DC power rating. Even if the performance and power output of a PV system had been monitored over long periods of time, the source of the performance degradation would be difficult to clearly identify. In addition to this, the measurement uncertainty is not negligible in these cases, making the performance degradation rate difficult to measure and quantify. IEC 63019 "Information Model for Availability of PV power plants" is being developed to identify best practices for data gathering, analysis and calculation of the availability of PV power plants. The standard will also provide a generic information model to better characterize system issues and arrive at estimates of lost availability or capacity at all necessary points of the system This standard can be utilized in conjunction with IEC 61724-3 to calculate the actual annual energy yield of the plant

1.2.4.4 Supporting Standards

There exist several standards that could be applied for the PV systems analysis as a whole, like the standard EN 61724-1. Those standards that relate to single components behaviour could also be used, e.g., those mentioned previously in the sections on PV modules and PCEs which were linked to their power performance and efficiency.

Not applicable so much for single modules, but rather for the whole PV arrays, standard EN 61829 presents a procedure for on-site measurement of flat-plate PV arrays. It addresses also field uncertainties because on-site measuring capabilities can differ substantially from what available at indoor laboratory measurements.

Some parts of the harmonised standard HD 60364 regarding low-voltage installations apply to PV systems, including those with storage elements (EN 60364-7-712), and to aspects like their energy efficiency.

Other standards for specific PV systems, like stand-alone (EN 61194) or for pumping systems (EN 61702), could be useful to define a methodology for the analysis of the performance of PV systems in general. Regarding grid-connected PV systems, standards like the draft prEN 61727 and the EN 62446-1 define the conditions and requirements that they must comply with when connected to the grid.

The IECRE conformity assessment system has been launched to establish a system to evaluate the performance of PV systems against design requirements including performance and lifecycle costs. It utilizes established IEC standards and a set of rules and operating documents as well as a peer assessment system for certifying/inspection bodies and auditors for quality control. The certificates should always be associated with performance data that over time can be utilized for benchmarking and also aid in developing models for the lifecycle costs of the system inclusive of degradation, outage, failure, repair and remediation.

[36] *Madeti S R and Singh S N 2017 A comprehensive study on different types of faults and detection techniques for solar photovoltaic system Sol. Energy 158 161-85*

[37] *Villarini M, Cesarotti V, Alfonsi L and Introna V 2017 Optimization of photovoltaic maintenance plan by means of a FMEA approach based on real data Energy Conversion and Management 152 1-12*

[38] *Triki-Lahiani A, Bennani-Ben Abdelghani A and Slama-Belkhodja I 2018 Fault detection and monitoring systems for photovoltaic installations: A review Renewable and Sustainable Energy Reviews 82 2680-92*

1.2.5 Building-Integrated PV Modules or Systems

The term building-integrated photovoltaics (BIPV) covers all photovoltaic modules and components that are used with the dual function of producing PV energy (primary function) while also replacing conventional construction products maintaining the function of the latter, for example in parts of the building envelope such as the roof, skylights, or facades (secondary function).

1.2.5.1 Supporting standards

At present, only the series EN 50583 (2016) addresses specifically the building-integration of PV modules (EN 50583-1) and systems (EN 50583-2). An IEC project team is now further developing the EN concepts in two standards IEC 63092-1 (for BIPV modules) and IEC 63092-2 (for BIPV systems), currently scheduled to be published in 2019.

For structural performance, which is covered by EN 50583-2 and specifically addressed by normative references included in it, compliance is required with Eurocodes under the Construction Product Regulation No. 305/2011. In regard to this, we highlight a possible inconsistency of the EN 50583-2 with the currently valid European legislation, as the European standard EN 50583-2 refers to the Directive 89/106/EEC, which was in fact repealed in 2011 and replaced by the (European Construction Product) Regulation (EU) No. 305/2011. The latter is also the legislative reference of the EN 50583-1, which however deals only with modules as construction products and not for their structural function.

As earlier noted, the Energy Performance of Buildings Directive (EPBD) 2010/31/EC includes standards for assessing the output of energy generating systems. Specifically the calculation of PV energy contribution to the building performance is covered by EN-15316-4-3. It is noted that the application of the method requires location specific data, and that responsibility for reference climatic data is given to the Member States. Overall, while the EPBD requirements establish a framework, many details need to be clearly defined (e.g. system performance factors and degradation effects).

There are specific documents related to safety in building installations that are currently under development/revision, e.g. prEN 50331-1 “Photovoltaic systems in buildings - Part 1: Safety requirements”, or already available as technical reports, e.g. the CLC/TR 50670 “External fire exposure to roofs in combination with photovoltaic (PV) arrays - Test method(s)”.

1.2.5.2 Lifetime and performance degradation

In the case of BIPV systems, the level of degradation is expected to be even more pronounced than in a ventilated open mounting structure. This is mainly due to the higher temperatures reached by the PV modules and components because of the reduced air circulation around them. Some of the standards included in section 1.2.1 address these issues.

1.2.5.3 Functional parameters

With reference to a combined energy parameter for cells or modules integrated into a building fabric the already proposed definition for modules could be used as a starting point:

> “*PV System functional unit is 1 kWh of AC power output supplied under fixed climatic conditions for 1 year (with reference to IEC 61853-4) and assuming a service life of 25 years*”

However, this would require a reflection regarding the higher ambient temperatures that are reached in BIPV installations.

1.3 Existing legislation

1.3.1 Legislation and agreements at European Union level

In this section European Union legislation and agreements of relevance to the product scope are briefly described and analysed for their potential implications. To aid an understanding of how they may influence the EU solar photovoltaic market – both in terms of technical performance and deployment potential - they have been grouped under the following broad themes:

- Energy Union and reshaping of the EU electricity market
- Driving the market for renewable electricity generation
- Driving the market for building renovation and near zero energy buildings
- Improving information on construction product performance
- Improving material efficiency and creating a Circular Economy
- Product policy and consumer information

In some cases legislation has been highlighted that is still under discussion, in which case a level of uncertainty must be accepted in relation to the final implications.

1.3.1.1 Energy Union and reshaping of the EU electricity market

1.3.1.1.1 The role of citizens in the 'Energy Transition'

In 2015 the Commission set out under the title of 'Energy Union' a new strategy for *'more secure, affordable and sustainable energy'* in the EU. This strategy is of relevance to solar photovoltaics because it has a central focus on the role of citizens, including the potential of renewable energy and in particular self-generation. To illustrate this, the Energy Union Framework Strategy of 2015 set out a vision of an Energy Union with:

> '... citizens at its core, where citizens take ownership of the energy transition, benefit from new technologies to reduce their bills, participate actively in the market, and where vulnerable consumers are protected'.

This vision informed a green paper published in 2015 which in turn led in 2016 to a proposal for a new Directive that will lay down new common rules that will empower citizens. This proposal formed part of the 'Clean energy transition' Package of measures that was presented by the Commission in 2016.

1.3.1.1.2 Proposed new common rules for the EU electricity market

In 2016 proposals were put forward for a new Directive which would lay down new common rules for the functioning of the EU's internal electricity market. Its proposed provisions would include guaranteeing consumers rights to the self-consumption of electricity and the establishment of legal frameworks for 'local energy communities' to engage in generation, distribution and supply. The proposed Article 15 on 'Active consumers' states that:

> *1. Member States shall ensure that final customers:*
>
> *(a) are entitled to generate, store, consume and sell self-generated electricity in all organised markets either individually or through aggregators without being subject to disproportionately burdensome procedures and charges that are not cost reflective;*
>
> *(b) are subject to cost reflective, transparent and non-discriminatory network charges, accounting separately for the electricity fed into the grid and the electricity consumed from the grid, in line with Article 59.*

Article 16 would additionally require that non-discriminatory legal frameworks are laid down for local energy communities. In addition, Article 31 makes general provision for a Member State to require distribution system operators, when dispatching generating installations, to give priority to generating installations using renewable energy sources.

1.3.1.2 Driving the market for renewable electricity generation

1.3.1.2.1 The Renewable Energy Directive (2009)

The Renewable Energy Directive 2009/28/EC recast the general regulatory framework for increasing the share of renewable energy in the EU. A number of specific articles are of potential relevance to this study. These include a number of references to renewables in the context of buildings and the establishment of installer certification schemes in Member States.

Article 4 states that *'Member States shall, in their building regulations and codes or by other means with equivalent effect, where appropriate, require the use of minimum levels of energy from renewable sources in new buildings and in existing buildings that are subject to major renovation'*. Moreover, Article 13 states that Member States shall also that new public buildings and existing buildings subject to major renovation *'fulfill an exemplary role*' and that this obligation may be fulfilled by either:

- complying with standards for zero energy housing, or
- by providing that the roofs of public or mixed private-public buildings are used by third parties for installations that produce energy from renewable sources.

Article 14 is of relevance to photovoltaic system installations as it requires Member States make available certification schemes or equivalent qualification schemes for installers. Criteria intended to ensure consistent establishment of schemes and associated requirements are then laid down in Annex IV of the Directive, although there is some evidence of inconsistent implementation by Member States [39]. Annex IV states that *'accredited training programmes should be offered to installers with work experience, who have undergone, or are undergoing, the following types of training'* and that in the case of a solar photovoltaic installer:

> *'training as a plumber or electrician and have plumbing, electrical and roofing skills, including knowledge of soldering pipe joints, gluing pipe joints, sealing fittings, testing for plumbing leaks, ability to connect wiring, familiar with basic roof materials, flashing and sealing methods as a prerequisite' or 'a vocational training scheme to provide an installer with adequate skills corresponding to a three years education in the skills referred to in point (a), (b) or (c) including both classroom and workplace learning'.*

Moreover, the installer shall demonstrate the following 'key competencies':

(i) the ability to work safely using the required tools and equipment and implementing safety codes and standards and identify plumbing, electrical and other hazards associated with solar installations;

(ii) the ability to identify systems and their components specific to active and passive systems, including the mechanical design, and determine the components' location and system layout and configuration;

(iii) the ability to determine the required installation area, orientation and tilt for the solar photovoltaic and solar water heater, taking account of shading, solar access, structural integrity, the appropriateness of the installation for the building or the climate and identify different installation methods suitable for roof types and the balance of system equipment required for the installation; and

(iv) for solar photovoltaic systems in particular, the ability to adapt the electrical design, including determining design currents, selecting appropriate conductor types and ratings for each electrical circuit, determining appropriate size, ratings and locations for all associated equipment and subsystems and selecting an appropriate interconnection point.

1.3.1.2.2 Recasting of the Renewables Directive

Proposals were put forward in 2016 for a further recast of the Renewables Directive to better reflect the new priorities under the Energy Union strategy. These proposal formed part of the 'Clean energy transition' Package of measures that was presented by the Commission in 2016.

The proposals include a policy option to focus on *'empowering citizens to self-consume and store renewable* electricity'. This option is preferred because it:

- maximises consumer's empowerment and their potential participation,
- mitigates grid deployment costs and grid costs distributional issues, and
- enhances the contribution of rooftop solar PV to the renewable energy target.

A number of proposed modifications and new Articles are of potential relevance to the scale and type of solar photovoltaic systems that may be promoted as a result:

[39] T. Tsoutsosetal et al, *Training and certification of PV installers in Europe - A transnational need for PV industry's competitive growth,* Energy Policy 55(2013)593–601

- Article 15 includes a new calculation methodology (anchored on the Energy Performance of Buildings Directive) of minimum levels of energy from renewable sources in new and existing buildings that are subject to renovation.
- Article 17 introduces a simple notification to Distribution System Operators for small scale projects and a specific provision on accelerating permit granting process for repowering existing renewable plants;
- Article 21 empowers consumers by enabling them to self-consume without undue restrictions, being remunerated for the electricity they feed into the grid.
- Article 22 sets forth new provisions on energy communities to empower them to participate in the market.

1.3.1.2.3 Network code requirements for grid connection

A new network code for the grid connection of power generators was adopted in 2016. Regulation (EU) 2016/631 includes the intention to support the integration of renewable electricity sources, however increasing grid penetration of distributed renewable generation means that the potential impacts on the overall stability, reliability, and efficiency of grids require addressing. Bruendlinger (2016) highlights the case of Germany where the simultaneous tripping of several gigawatts of distributed wind or solar capacity could lead to an undersupply that could not be compensated by reserves[40]. The new code is applicable to all new generators >0.8 kW, and adopts a proportional approach with smaller generators of up to 1MW having to meet basic requirements to ensure system stability (type A generators) and with larger generators of >1MW having to fulfil an extended responsibility (type B, C and D generators) – see the summary in Table 9. The code is supported by standards developed by CENELEC TC8X.

Table 9. Overview of system aspects and requirements addressed by the European network codes

System aspect	***Requirement***	***Generator type***		
		A	***B***	***C/D***
Frequency stability	Operating frequency ranges	x	x	x
	RoCoF withstand capability	x	x	x
	Limited Frequency Sensitive Mode – overfrequency	x	x	x
	Constant active power output regardless of changes in frequency	x	x	x
	Limitation of power reduction at under frequency	x	x	x
	Automatic connection	x	x	x
	Remote on/off	x	x	
	Active power reduction remote control		x	
	Additional requirements relating to frequency control			x
	Provision of synthetic inertia			x
Robustness of power generating modules	Fault ride-through		x	x
	Post-fault active power recovery		x	x
System restoration	Co-ordinate reconnection		x	x
General system management	Control schemes and settings		x	x
	Electrical protection and control schemes and settings		x	x
	Priority ranking of protection and control		x	x
	Information exchange		x	x
	Additional requirements to monitoring			x
Voltage stability	Reactive power capability		x	x
	Fast reacting reactive power injection		x	x
	Additional requirements for reactive power capability and control modes			x

[40] Bruendlinger, R (2016) Review and Assessment of Latest Grid Code Developments in Europe and Selected International Markets with Respect to High Penetration PV, Austrian Institute of Technology, Paper presented at the 6th Solar Integration Workshop.

Source: Bruendlinger (2016)

1.3.1.3 Driving the market for building renovation and near zero energy buildings

1.3.1.3.1 Energy Performance of Buildings Directive (2010)

The construction and refurbishment of buildings in such a way as they reduce energy use and CO_2 emissions is a central environmental policy objective for Europe. The recast *Energy Performance of Buildings Directive 2010/31/EU (EPBD)* [41] requires Member States to prepare national plans to ensure that all new buildings are 'nearly zero energy' by 2020. This is defined in Article 2(2) of the EPBD as:

'...a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources,'

Annex I of the Directive lays down a common framework for calculation of a buildings energy performance. The reference to renewable energy within the definition of Nearly Zero Energy Buildings (NZEB) is of relevance to solar photovoltaic systems. Moreover, the Commission Recommendation (EU) 2016/1318 of 29 July 2016 on nearly zero-energy buildings noted that solar PV has been one of the most frequently applied technologies in order to fulfil Member States' NZEB requirements [42].

The recast EPBD states that reporting on the energy performance of a building shall include *'an energy performance indicator and a numeric indicator of primary energy use*' and that the methodology should take into account European (EPB) standards. Within the frame of CEN Mandate M/480 the EN standards providing a harmonised calculation method have been comprehensively updated by the CEN ISO/TR 52000 series. This series is intended to support harmonisation of the National Calculation Methodologies (NCMs) for assessment of the overall energy use of a building.

The contribution of solar photovoltaics is calculated within the Technical Building System calculation module M11 *'Electricity production'*. This module supports calculation of the delivered energy and exported energy from a solar photovoltaic system installed on or integrated into a building. The EN ISO 52000 series and the calculation method provided in EN 15316-4-3 are discussed further in section 1.2 of this Task report.

1.3.1.3.2 Proposed further amendment of the Energy Performance of Buildings Directive (2017)

A proposal for a further amendment of the EPBD formed part of the 'Clean energy transition' package of measures that was presented by the Commission in 2016. Agreement was reached in December 2017 on the content of this further amendment[43]. It is proposed as including a stronger focus on the renovation and decarbonisation of the existing building stock. Also proposed is the introduction of a 'smartness indicator' intended to:

> *'...enhance the ability of occupants and the building itself to react to comfort or operational requirements, take part in demand response and contribute to the optimum, smooth and safe operation of the various energy systems and district infrastructures to which the building is connected.'*

In particular it is understood that it would measure a buildings' capacity to use new technologies and electronic systems to optimise operation and interact with the grid.

1.3.1.4 Improving information on construction product performance

1.3.1.4.1 The Construction Products Regulation (2011)

The Construction Products Regulation (EU) No 305/2011 seeks to ensure that reliable information on the environmental performance of products is provided in the EU market. It lays down in Annex I a set of seven *'basic requirements for construction works'* stating that:

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[41] *Directive 2010/31/EC of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)*

[42] *https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016H1318&from=EN*

[43] *Proposal for a Directive of the European Parliament and of the Council amending Directive 2010/31/EU on the energy performance of buildings, COM(2016) 765 final, Brussels, 30.11.2016*

'Construction works as a whole and in their separate parts must be fit for their intended use, taking into account in particular the health and safety of persons involved throughout the life cycle of the works. Subject to normal maintenance, construction works must satisfy these basic requirements for construction works for an economically reasonable working life.'

To this end, the regulation seeks to harmonise Declarations of Performance for the essential characteristics of building products, and hence any associated CE marking requirements, under each of these seven 'basic requirements for construction works'. The main instrument for achieving this is through the application of new and existing harmonised European standards. The seven requirements are described in Table 10.

With the advent of the European single market for construction products, there was a concern that national Environmental Product Declaration (EPD) schemes and building level assessment schemes based on LCA principles would represent a barrier to trade across Europe. As a result, two standards were developed and published by CEN/TC 350:

- EN 15978 (2011) This standard deals with the aggregation of the information at the building level, describing the rules for applying EPDs in a building assessment. The identification of boundary conditions and the setting up of scenarios are major parts of the standard.
- EN 15804 (2012) This standard provides the Product Category Rules for construction products and services, with the aim to ensure that EPDs for construction products are derived, verified and presented in a harmonised way.

These standards provide a harmonised set of environmental and resource use indicators for use in the assessment and reporting of performance as well as a modular schematic of the life cycle stages (see . EN 15804 in particular is assuming an increasing important in the EU as the sector moves towards greater use of life cycle assessment, with an accompanying need for data on the performance of individual building products. The major building assessment schemes that are currently used in the EU, together with Member State governments such as France and the Netherlands, are actively aligning EPDs and building assessment methods with the EN series.

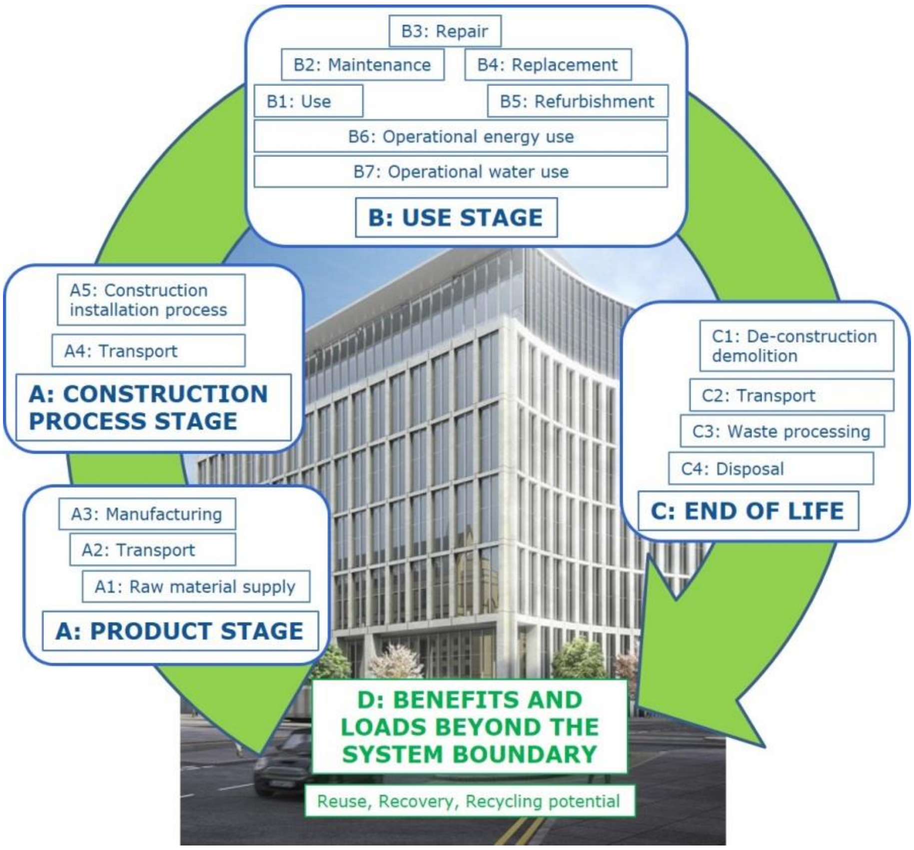
Table 10. Basic requirements for construction works according to the Construction Products Regulation (EU) No 305/2011

1. Mechanical resistance and stability	The construction works must be designed and built in such a way that the loadings that are liable to act on them during their constructions and use will not lead to any of the following: (a) collapse of the whole or part of the work; (b) major deformations to an inadmissible degree; (c) damage to other parts of the construction works or to fittings or installed equipment as a result of major deformation of the load-bearing construction; (d) damage by an event to an extent disproportionate to the original cause.
2. Safety in case of fire	The construction works must be designed and built in such a way that in the event of an outbreak of fire: (a) the load-bearing capacity of the construction can be assumed for a specific period of time; (b) the generation and spread of fire and smoke within the construction works are limited; (c) the spread of fire to neighbouring construction works is limited; (d) occupants can leave the construction works or be rescued by other means; (e) the safety of rescue teams is taken into consideration.
3. Hygiene, health and the environment	The construction works must be designed and built in such a way that they will, throughout their life cycle, not be a threat to the hygiene or health and safety of workers, occupants or neighbours, nor have an exceedingly high impact, over their entire life cycle, on the environmental quality or on the climate during their construction, use and demolition, in particular as a result of any of the following: (a) the giving-off of toxic gas; (b) the emissions of dangerous substances, volatile organic compounds (VOC), greenhouse gases or dangerous particles into indoor or outdoor air; (c) the emission of dangerous radiation; (d) the release of dangerous substances into ground water, marine waters, surface waters or soil; (e) the release of dangerous substances into drinking water or substances which have an otherwise negative impact on drinking water; (f) faulty discharge of waste water, emission of flue gases or faulty disposal of solid or liquid waste; (g) dampness in parts of the construction works or on surfaces within the construction works.EN 4.4.2011 Official Journal of the European Union L 88/33
4. Safety and accessibility in use	The construction works must be designed and built in such a way that they do not present unacceptable risks of accidents or damage in service or in operation such as slipping, falling, collision, burns, electrocution, injury from explosion and burglaries. In particular, construction works must be designed and built taking into consideration accessibility and use for disabled persons.
5. Protection against noise	The construction works must be designed and built in such a way that noise perceived by the occupants or people nearby is kept to a level that will not threaten their health and will allow them to sleep, rest and work in satisfactory conditions.
6. Energy economy and heat retention	The construction works and their heating, cooling, lighting and ventilation installations must be designed and built in such a way that the amount of energy they require in use shall be low, when account is taken of the occupants and of the climatic conditions of the location. Construction works must also be energy-efficient, using as little energy as possible during their construction and dismantling.
7. Sustainable use of natural resources	The construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following: (a) reuse or recyclability of the construction works, their materials and parts after demolition; (b) durability of the construction works; (c) use of environmentally compatible raw and secondary materials in the construction works.EN L 88/34 Official Journal of the European Union 4.4.2011

Source: European Commission (2011)

During the recent development of the common EU framework of building environmental performance indicators by the JRC for DG Environment it was identified that life cycle information for energy technologies such as solar photovoltaics is limited in its availability to building designers. It is anticipated that with the onset of the EU framework, now referred to by the Commission as Level(s), there will be increasing demand for this type of life cycle data at product level.

Figure 12 Modular schematic of building life cycle stages



Source: Based on CEN (2011)

1.3.1.4.2 Piloting of the Product Environmental Footprint (PEF) method

The pilot phase of the European Commission's Product Environmental Footprint (PEF) method for Life Cycle Assessment (LCA) ran during 2014 -2017. It tested the technical basis for establishing Product Environmental Footprint Product Category Rules (PEFCRs) for a series of products [44]. The pilot included a number of building related products, one of which was solar photovoltaic modules.

The PEF method has as its basis a more extensive set of environmental and resource use indicators than the EN standards series described in section 1.3.1.4.1. The potential influence of the PEF on future standards and category rules for building product environmental assessment will, to a great extent, depend on deliberations by the Commission on the way forward following this pilot, which are ongoing at the time of writing.

1.3.1.5 Improving material efficiency and creating a Circular Economy

The Roadmap to a Resource-Efficient Europe COM(2011) 571 highlighted the need for a more sustainable and productive use of natural resources [45]. There have subsequently been a number of related policy initiatives that have aimed to drive a

[44] European Commission, The Environmental Footprint pilots, DG Environment, http://ec.europa.eu/environment/eussd/smgp/ef_pilots.htm

[45] COM (2011) 571 Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Roadmap to a Resource Efficient Europe

transformation in how materials are obtained and used. Two initiatives of particular relevance to solar photovoltaics are briefly reviewed in this section.

In addition to a focus on processes upstream of producers, European waste legislation has extended producer responsibility for the take back and subsequent handling, treatment and/or disposal of solar photovoltaics. The implications are briefly summarised in this section.

1.3.1.5.1 Battery directive

Directive 2006/66/EC regulates the manufacture and disposal of batteries in the European Union with the aim of improving the environmental performance of batteries and accumulators. The directive, apart from restating the content limits of cadmium and prohibiting mercury in all batteries, it no longer restricts the lead content of batteries. The Directive aims to prevent batteries from being incinerated or dumped in landfills.

The Battery directive was amended in 2013 to ensure that batteries and accumulators can be easily removed from the electrical or electronic equipment they are attached. This means that it should be possible to remove them without delay or difficulty and at a reasonable cost, where needed using the instructions provided.

Batteries and accumulators used in electrical and electronic equipment (EEE) fall within the scope of the Batteries Directive unless there are specific provisions in the WEEE Directive. When they are in waste electrical and electronic equipment (WEEE) can be collected on the basis of the WEEE Directive. However, after collection, they must be removed from the appliance (electronic equipment) in accordance with Article 8(2) and Annex VII of the Battery Directive (as well as Article 3 (l)) of the WEEE Directive and they count towards the collection targets laid down in the Batteries Directive. These batteries and accumulators must be recycled as required by the Batteries Directive.

1.3.1.5.2 The Raw Materials Initiative

The Commission is implementing the Raw Materials Initiative [46], which sets out a strategy for tackling the issue of access to raw materials in the EU. This strategy has three pillars which aim to ensure:

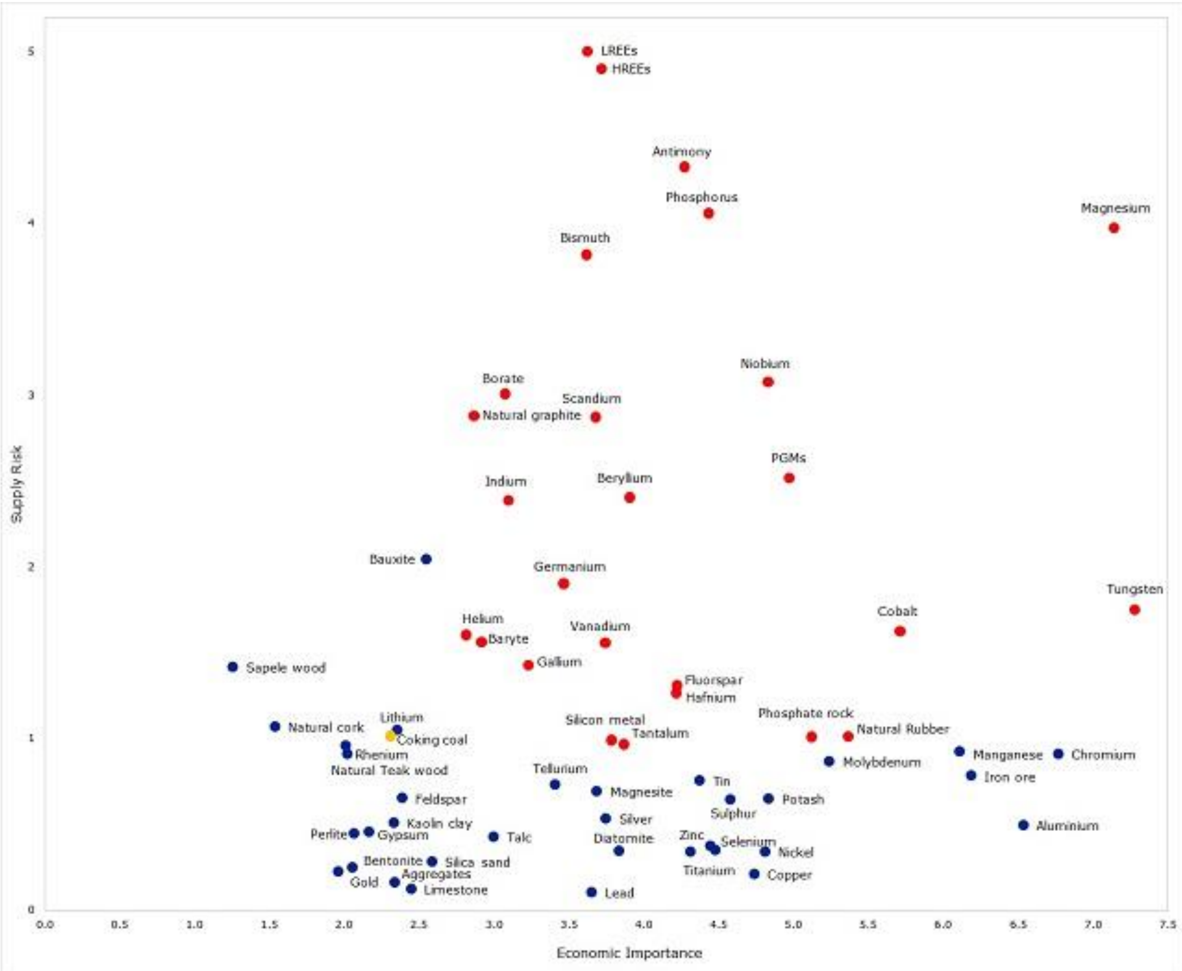
1. Fair and sustainable supply of raw materials from global markets: The EU has committed to pursue a Raw Materials Diplomacy reaching out to third countries through strategic partnerships and policy dialogues.
2. Sustainable supply of raw materials within the EU: The EU is dependent on the imports of many raw materials. To facilitate the sustainable supply of raw materials from European deposits, the European Commission aims to secure the right legal and regulatory conditions.
3. Resource efficiency and supply of 'secondary raw materials' through recycling: Production using recycled materials contributes to the supply of raw materials and is often much less energy intensive than manufacturing goods from primary materials. Recycling can thus improve supply conditions and reduce production costs and GHG emissions.

Related initiatives include the assessment of the criticality of raw materials and a package of measures to tackle the sourcing of certain minerals sourced from areas of conflict.

Critical Raw Materials are described by the European Commission as *'raw materials of high importance to the economy of the EU and whose supply is associated with high risk'*. Their criticality is assessed according to two main parameters - economic importance (EI) and supply risk (SR). A list of raw materials assessed as being critical is revised every three years to reflect changes in the market. The third revision of the list was published in 2017 and the materials listed as CRMs are identified with red/yellow points in Figure 13. Of broad relevance to the solar photovoltaic product group the following CRMs can be provisionally identified - cobalt, borate, indium, gallium, silicon metal and tantalum.

[46] COM(2011)25 Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Tackling the challenges in commodity markets and on raw materials

Figure 13 The 2017 list of Critical Raw Materials (in red) to the EU. (HREEs = Heavy Rare Earth Elements, LREEs = Light Rare Earth Elements, PGMs = Platinum Group Metals)



Source: European Commission (2018)

1.3.1.5.3 The recast Waste Electrical Equipment (WEEE) Directive (2012)

The WEEE Directive requires the establishment at Member State level of schemes to ensure the separate collection and 'proper treatment' of Electrical and Electronic Equipment (EEE). From the 15th August 2018 the scope of EEE will be extended to included solar photovoltaic modules and they are also identified in the Directive as a priority for separate collection.

Annexes I - IV of the Directive specifically identifies solar photovoltaic 'panels' (modules) under EEE category 4(b). No specific collection rate for modules is specified, instead an overall collection rate for EEE is stipulated which shall rise from 45% in 2016 to 85% in 2019. From the 15th August 2018 for EEE category 4 products an 85% recovery rate and an 80% re-use and recycling rate shall be achieved.

Other system components such as inverters are not specifically identified in the existing EEE categories but could be interpreted to fall under the new EEE category 5 *'Small equipment (no external dimension more than 50 cm)'* which refers to equipment *'for the generation of electric currents'*. The new EEE categories shall apply from 15th August 2018.

In terms of whether inverters fall within the general scope of the Directive the Commission clarified in 2014 in response to a Frequently Asked Question that inverters [47]:

[47] *Frequently Asked Questions on Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE), April 2014.*

'...fall[s] under the definition of EEE given in Article 3(1)(a) and thus fall[s] within the scope of the Directive. An example of an inverter that falls within the scope of the Directive is one used in a photovoltaic installation. However, an inverter does not fall within the scope of the Directive in the following cases:

- when it is designed and placed on the market as a component to be integrated into another EEE,

- when it benefits from an exclusion on the basis of Article 2: e.g. it is specifically designed and

- installed as part of another type of equipment that is excluded from or does not fall within the scope of the Directive, and the inverter can fulfil its function only if it is part of that equipment. '

Based on this interpretation micro-inverters integrated with a photovoltaic module would be treated as a specific product.

To support data collection and tracking the Commission published in 2017 a new WEEE Calculation Tool which compiles stock Placed on the Market (POM) and waste data [48]. The default disposal rate used is based on a product lifespan that is determined using a Weibull distribution. 'Photovoltaic panels (including inverters)' are assigned UNU (United Nations University) code 0002 and preliminary data can be obtained that has been pre-loaded in the individual Member State calculator spreadsheets. The data obtained for this category should, however, be treated with caution because the inclusion or not of system components such as inverters is not clear from the metadata specification [49].

Beyond the separate collection and subsequent preparation for the purposes of re-use, recovery or recycling, *'proper treatment'* of EEE shall include the removal of fluids from and selective treatment for the following components which may be of relevance to solar photovoltaic systems, dependent on their configuration and scale:

- Batteries,
- Printed circuit boards with a surface are greater than 10 square centimetres,
- Plastic containing brominated flame retardants,
- Chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC) or hydrofluorocarbons (HFC), hydrocarbons (HC),
- External electric cables,
- Electrolyte capacitors containing substances of concern (height > 25 mm, diameter > 25 mm or proportionately similar volume).

Verification of proper treatment and depollution is supported by the EN 50625 series which, informed by the approach developed by the EU LIFE funded WEEElabex project [50] which ran during 2009-2012, defines WEEE collection logistics and treatment requirements. Annex A of EN 50625-1 identifies specific components of equipment that shall be removed for depollution purposes. Parts 2-4 and 3-5 focussing on treatment requirements and a specification for depollution for 'photovoltaic panels' are in the final stages of development.

The Directive also states that Member States shall encourage co-operation between product manufacturers and recyclers in order to facilitate the re-use, dismantling and recycling of WEEE at product, component and material level. It is understood that some MS are considering specific references in legislation to the treatment of photovoltaic modules.

1.3.1.5.4 An EU action plan for the Circular Economy (2015)

A Circular Economy package was published in late 2015. The Package contains measures to address the whole materials cycle, from production and consumption through to waste management and the use of recycled (secondary) raw materials, with the aim of contributing to 'closing the loop' of product lifecycles through greater recycling and re-use.

The action plan seeks to make links to other EU priorities, including creating jobs and growth, industrial innovation and tackling climate change. A direct link is made to product policy, in which it states that the Commission will:

[48] DG Environment, Statistical data – WEEE calculation tools, http://ec.europa.eu/environment/waste/weee/data_en.htm

[49] ProSum, 0002 Basic metadata catalogue - photovoltaic Panels (incl. inverters),http://prosum.geology.cz/records/5a0ee62e-9fc0-46ae-8e18-6cda0a010854

[50] WEEElabex, http://www.weeelabex.org/

'...promote the reparability, upgradability, durability, and recyclability of products by developing product requirements relevant to the circular economy in its future work under the Ecodesign Directive, as appropriate and taking into account the specificities of different product groups.'

And that it will also:

'specifically consider proportionate requirements on durability and the availability of repair information and spare parts in its work on Ecodesign, as well as durability information in future Energy Labelling measures'.

The need for an efficient use and recycling of Critical Raw Materials was highlighted within the action plan.

1.3.1.5.5 Critical Raw Materials and circular economy report (2018)

Solar photovoltaics receive specific attention in a Commission Staff Working Document on CRMs published early 2018 which analyses the link between CRM management and circular economy objectives. The CRMs indium, gallium and silicon metal are identified in the report as being of particular relevance. A high potential (95%) for economically feasible recycling is identified.

Figure 14 illustrates the proportion of material flows that are estimated to be associated with these CRMs.

1.3.1.6 Product policy and consumer information

1.3.1.6.1 Climate dependant Ecodesign and Energy labelling requirements

Two product group lots that have been developed under the Ecodesign Working Plan for 2009-2011 are of potential relevance to solar photovoltaics. This is because calculations made in support of the performance requirements and/or the information requirements must, in addition to being based on average test conditions, also reflect two other distinct European climate zones. The lots and associated sub-products of potential relevance are:

- Reversible and heating-only air conditioners under Lot 10 [51] [52]
- Heat pump water heaters and solar water heaters provided as part of a package *'offered to the end-user containing one or more water heaters and one or more solar devices'* under Lot 2 [53] [54]

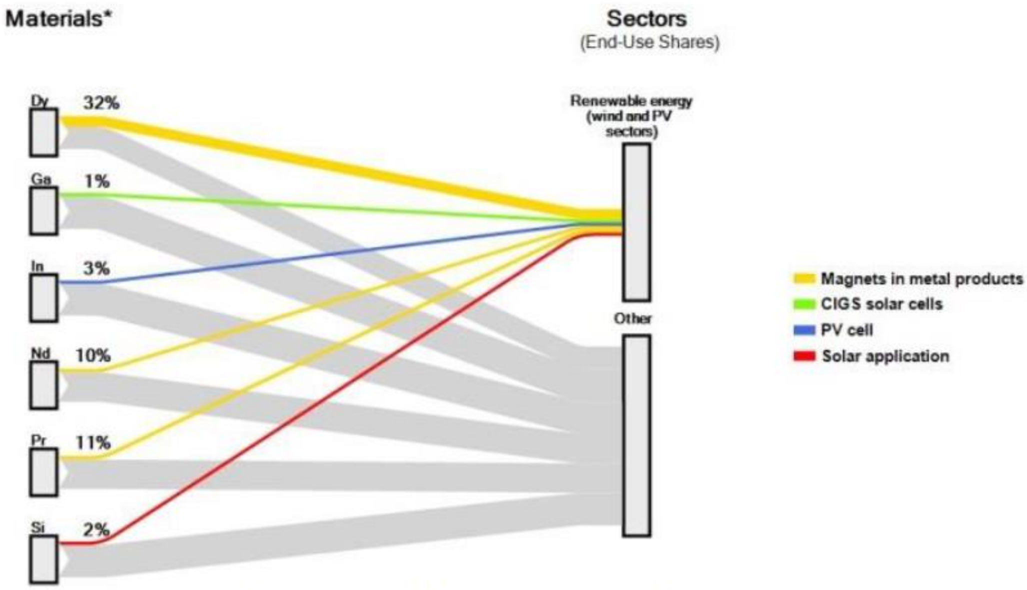
[51] Commission regulation (EU) No 206/2012 of 6 March 2012 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for air conditioners and comfort fans OJ L 72, 10.3.2012

[52] Commission Delegated Regulation (EU) No 626/2011 of 4 May 2011 supplementing Directive 2010/30/EU of European Parliament and of the Council with regard to energy labelling of air conditioners OJ L 178, 6.7.2011

[53] Commission Regulation (EU) No 814/2013 of 2 August 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for water heaters and hot water storage tanks OJ L 239, 6.9.2013

[54] Commission Delegated Regulation (EU) No 812/2013 of 18 February 2013 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of water heaters, hot water storage tanks and packages of water heater and solar device OJ L 239, 6.9.2013

Figure 14 Share of CRMs used in wind and solar PV cell production



* Only a subset of all CRMs used in renewable energy sector is included.

Source: European Commission (2018) The lag time before large amounts of solar PV waste are generated is discussed and based on likely future waste arisings forward projections of the EU CRM demand are made.

In both cases an approach has been adopted to Ecodesign information requirements and Energy Labelling that is, in part, based on the communication of performance under pre-defined conditions in three different geographical locations in Europe.

In the case of reversible and heating-only air conditioners three designated European heating seasons representing average, cooler and warmer conditions are specified. In the context of these two Lots these three conditions are defined as *'the temperatures and global solar irradiance conditions characteristic for the cities of Strasbourg, Helsinki and Athens, respectively'*. Manufacturers placing products on the EU market shall present:

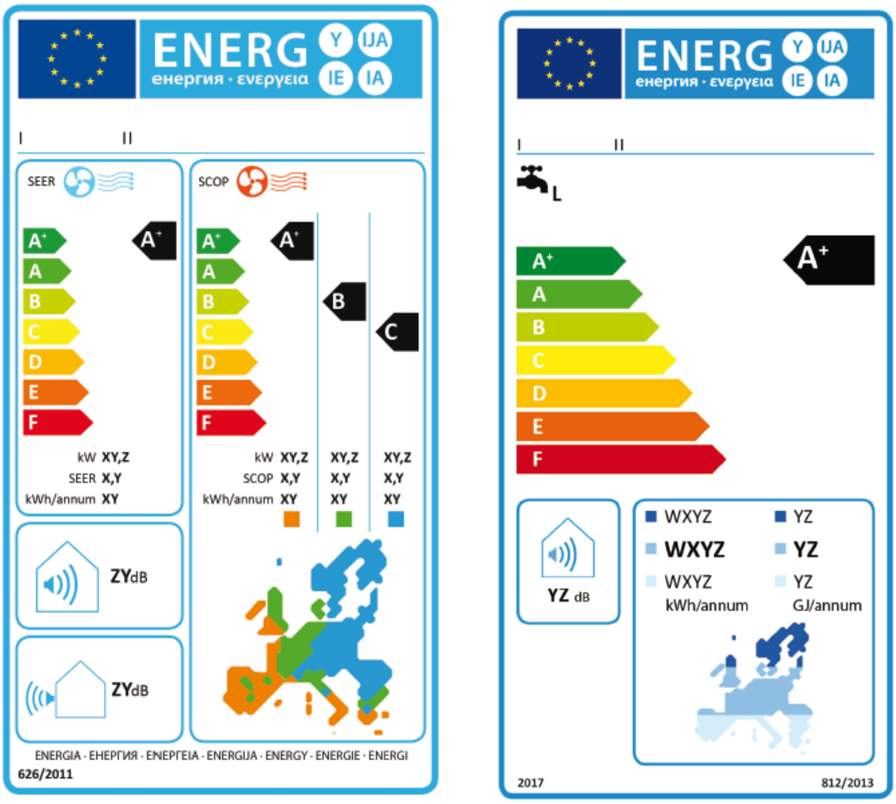
- the cooling energy efficiency class and the *Seasonal Energy Efficiency Ratio (SEER)* under average climate conditions.
- the heating mode energy efficiency class and the related *Seasonal Coefficient of Performance (SCoP)* for each of the three designated European heating seasons (see Figure 15).

For the purposes of measurement and calculation the heating seasons, together with reference design conditions, are defined in Annex VII of the Ecodesign implementing Regulation No 206/2012 and of the Energy Labelling delegated Regulation No 626/2011.

In the case of heat pump water heaters and solar water heaters, three geographically defined zones representing average, cooler and warmer conditions are specified. For the purpose of product testing the Ecodesign minimum requirements specify only the average conditions. For energy labelling purposes manufacturers placing products on the EU market shall present:

- foremost on the label the energy efficiency class based on the performance under *average climate conditions*.
- Inset on the label electricity and fuel consumption estimates for the *three European climate conditions* (see Figure 15).

Figure 15. European climate zones used by the air conditioner and solar water heaters labelling schemes.



a. Reversible air conditioners: three heating seasons

b. Solar water heaters: three temperature zones

Source: European Commission (2018). Note that the recent EL framework regulation (2017/1369) will lead to a rescaling from A to G, which neither for air conditioners nor solar heaters has happened yet and in the latter case is planned for 2025.

For the purposes of measurement and calculation the climate conditions are defined in Annex III of the Ecodesign implementing Regulation No 814/2013 and of Annex VII of the Energy Labelling delegated Regulation No 812/2013.[55]

Dealers of packages shall ensure that the labelling for each component - which may include a solar water heater, a water heater and/or a hot water storage tank - is displayed at the point of sale. Moreover an additional step is specified that provides the purchaser of a package with an assessment of the water heating efficiency class for a combination of components. The calculation method is specified in an information fiche in Annex IV of the delegated Regulation, but it is important to note that it includes a disclaimer for possible losses in performance due to *'factors such as heat loss in the distribution system and the dimensioning of the products in relation to building size and characteristics'*.

Dealers of water heater packages shall ensure that the labelling for each component - which may include a solar water heater, a water heater and/or a hot water storage tank - is displayed at the point of sale. Moreover an additional step is specified that provides the purchaser of a package with an assessment of the water heating efficiency class for a combination of components.

The calculation method for the water heater package consumer information fiche is provided in section 4 of Annex IV of the delegated Regulation. It is important to note, however, that it includes a disclaimer for possible losses in performance due to

[55] Note that the recent EL framework regulation (2017/1369) will lead to a rescaling from A to G, which neither for air conditioners nor for solar heaters has happened yet - and in the latter case is planned for 2025. Moreover, what it is meant to be shown here is an example of how a differentiation of climatic zones has been dealt in the energy label.

'factors such as heat loss in the distribution system and the dimensioning of the products in relation to building size and characteristics'. This means in practice that it does not provide information on the efficiency of the system as a whole.

1.3.1.6.2 Ecodesign requirements that address battery performance

Batteries on products have been object of Ecodesign regulations of other product categories. In the ecodesign regulation for computers EU 617/2013, specific requirements for batteries included to give information on the minimum number of loading cycles and battery replacement issues (e.g. in the case the battery was not accessible it has to be stated in the external packaging).

For the revision of this regulation an analysis of material efficiency aspects of personal computers product group has been made in 2018 by JRC[56]. Battery durability aspects were looked at, since the lifetime of batteries could be extended by up tp 50% by preventing the battery remaining at full load when the notebook is in grid operation. The study concludes that implementing a preinstalled functionality on notebooks would make possible to optimise the state of charge (SoC) of the battery. Information to users in that regard is seen as a valuable measure.

A focus on the content of CRMs (especially cobalt in batteries) is also made in this JRC report. To improve the material efficiency during the recycling, the identification of the chemistry type of batteries in computers is necessary for an efficient and sorting.

1.3.1.6.3 Preparatory study on smart appliances

The lot 33 preparatory study on smart appliances has a wide scope [57]. This study is not analysing all communication-enabled appliances, but the appliances that support *Demand Side Flexibility*. Those smart appliances that are relevant for the present solar preparatory study are:

- Home energy management systems: they are systems using the same language/semantics that the smart home appliances to exchange information. They are also referred to as energy boxes. Some appliances at home are considered to have flexibility potential to store electricity coming for example from solar photovoltaics (smart radiators or electric water heaters).
- Residential energy storage system: they mainly work for storing cheaper (renewable) electric energy to avoid buying expensive electricity at a later period. Distinctions are made between different implementations, such as:
  - residential energy storage systems combined with a separate PV installation,
  - fully integrated residential energy storage systems with PV, or
  - electric vehicles to home, where the vehicles will be used as (mobile) Battery Storage Systems

In the Follow up study for lot 33, chargers for electric cars have been included. Smart charging involves the intelligent charging of the batteries in electric vehicles: charging them in a way that avoids excessive and costly spikes in power demand and also – in the years to come – using the batteries of the cars as storage to deliver valuable services to the electricity system, as well as maximising local integration of renewable energy sources (RES). Standards in grid interconnection for battery electric cars are currently being developed by JRC.

1.3.2 Legislation and requirements at Member State level

Intervention to improve market conditions for solar photovoltaics at Member State level has historically played an important role in the support of growth in the deployment of the technology. Legislation designed to improve the market conditions and incentivise investment has been pivotal in the growth of the European market and the policy instruments used continue to evolve in response to policy priorities.

In this section an overview of legislation and agreements for thirteen selected Member States is provided. The Member States have been selected based on the significance of their solar photovoltaic markets, in terms of combination of historical, present and projected market penetration. The Member States that have been selected are identified in **Table 11**.

[56] *Tecchio, Ardente et al. Analysis of material efficiency aspects of personal computers product group, JRC 2018.*

[57] *Ecodesign Preparatory study on Smart Appliances (Lot 33) MEErP Tasks 1-6, http://www.eco-smartappliances.eu/Documents/Ecodesign%20Preparatory%20Study%20on%20Smart%20Appliances%20_Tasks%201%20to%206.pdf*

The Member State overviews have been developed based on the JRC's *'PV Status Report'* (2016), the IEA-PVPS publications *'Trends 2016'* and *'Review and analysis of PV self-consumption policies'*, the Horizon 2020 funded PV Financing initiative database [58] and consultation of Member State legislation. For each Member State the most important instruments are then characterised and briefly analysed for their relevance to the study. Qualification requirements for equipment, systems and installers in order to receive subsidies and contracts are also identified, where relevant.

1.3.2.1 Pioneers, high market penetration

1.3.2.1.1 Germany

PV system support: The main price support instrument driving growth of the market has been the Renewable Energy Sources Act (Erneuerbare Energien Gesetz EEG) introduced in 2000. This piece of legislation introduced a feed-in tariff with 20 year contracts. This mechanism is credited with creating Europe's largest solar PV market. The tariffs are adjusted in function of growth in the market and reductions in system costs. The tariffs are currently weighted to provide greater support to residential building and sound barrier mounted systems of <10kWp and <40kWp respectively. Since 2016 only systems <100 kWp have been eligible for the feed-in tariff.

Table 11 Clustering of the Member States analysed based on their market evolution and penetration

Pioneers (pre 2008)	High market penetration – Germany
	Medium market penetration – Austria - Spain – Netherlands - Denmark –
Late starters (post 2008)	High market penetration – Italy – United Kingdom
	Medium market penetration – Belgium – Czech Republic – France – Greece
	Low market penetration – Bulgaria – Romania
Key to electricity market penetration levels High = >5.0% Medium = 1.0 – 5.0% Low = <1.0%	

Utility scale system support: Since 2015 new systems must win in an auction of new capacity by the Federal electricity network agency. The first auction called on 500 MW of new capacity. The auction follows the 'market integration model' which provides a feed-in premium on top of the market electricity prices.

Self-consumption support: Systems <10 kWp are exempt from a 40% levy on electricity. The feed-in tariff rates are now below those for consumer electricity, providing an incentive for self-consumption. A maximum of 90% of the electricity generated is eligible for price support, thereby incentivising self-consumption.

Product environmental criteria: The federal ecolabel scheme the Blue Angel has had since 2012 a set of environmental criteria for inverters. A number of attempts have been made to establish criteria sets for both solar PV modules and solar PV systems, but consensus could not be reached in both cases (see section 1.1.3).

Grid integration support: The high numbers of installations in some areas has driven the introduction of new regulations in 2015. These have focussed on frequency disconnection settings for inverters in order to avoid a 'cascade' disconnection in the case of frequency deviations and the peak shaving of the maximum power output for systems <30 kWp at 70% for systems not remotely controlled by the grid operator.

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[58] PV Financing, Database, Accessed in March 2018, http://database.pv-financing.eu/database.html

Electricity storage support: A market support programme was introduced in 2013 and targets storage that is installed in conjunction with systems of <30 kWp. A 30% rebate is complemented by low interest loans available from the Kreditanstalt für Wiederaufbau (KfW) [59]. Loans are subject to a cap on the capacity of the storage relative to the nominal rating of the accompanying PV system. Funding is only provided for products that meet technical quality requirements. Furthermore, systems must reduce pressure on the local grid by reducing peak load exports of the electricity generated.

Table 12 Germany: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017

2016	*2017E*	*2018E*	*2019E*	*2020E*
41111	43111	45411	47911	50611

1.3.2.2 Pioneers, medium market penetration

1.3.2.2.1 Austria

PV system support: The most important national policy instrument is the Ökostrom-Einspeisetarifverordnung 2012 (Eco-Electricity Act) which establishes a feed-in tariff with 13 year contracts for renewable electricity. Only PV systems >5kWp are currently supported and ground mounted systems of >200 kWp are no longer supported. The tariff is adjusted annually and is currently capped at a level that constrains growth. Federal investment support programmes also support PV system installations up to 30 kWp but have limited funds available. In addition, five provinces are reported as having their own PV support programmes.

BIPV support: Building integrated systems of a size up to 5 kWp currently receive an upfront investment subsidy on a kWp basis.

Self-consumption support: Self-consumption is legal unless the system owner is in receipt of a feed-in tariff. Self-consumed electricity is exempt from tax up to an annual threshold of 25,000 kWh electricity generation.

Electricity storage support: Six Federal States are reported to have subsidy programmes supporting electricity storage. The subsidies range from 200-500 €/kWh storage.

Table 13 Austria: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017

2016	*2017E*	*2018E*	*2019E*	*2020E*
1077	1277	1577	1977	2577

1.3.2.2.2 Netherlands

PV system support: The main price support instrument has been a net metering scheme that was introduced in 2011. This has targeted residential systems of up to 15 kWp and a cap of 5,000 kWh/yr electricity generation. This arrangement is to be retained until 2020. New systems with a capacity ≥ 15 kWp may benefit from the SDE+ auction process. Contracts for subsidy of the difference between the cost price and the market price of electricity are allocated for periods of 8, 12 or 15 years. Three bands of capacity are supported < 1 MWp and ≥ 1 MWp. A maximum number of 950 full load hours is specified and systems must have a large scale grid connection.

Table 14 Netherlands: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017

2016	*2017E*	*2018E*	*2019E*	*2020E*
1911	3099	4091	5391	6591

[59] *kfW Bank, KfW and Federal Environment Ministry launch programme to promote use of energy storage in solar PV installations, 18th April 2013, https://www.kfw.de/KfW-Group/Newsroom/Aktuelles/Pressemitteilungen/Pressemitteilungen-Details_107136.html*

Self-consumption support: A net-metering scheme was initiated in 2011 with modifications in 2014. Below 15 kWp excess electricity that is not consumed on site is remunerated with a lower feed-in tariff rate. Self-consumption is permitted above 15 kWp but not incentivised. High electricity prices further incentivise self-consumption.

1.3.2.2.3 Denmark

PV system support: A feed-in tariff introduced in 2012 was suspended in 2016 due to an oversubscription of the scheme and a total cap on installed capacity of 800 MW was imposed until 2020. The results has been a significant decline in the annual installed capacity, particularly at the smaller end of the market.

Utility scale system support: Since 2015 new systems must compete in a competitive auction of new capacity based on electricity price bids for 20 years contracts. This auction process is open to bids from Germany and signals the first use of a provision within the Renewables Directive that allows for cross border auctions.

BIPV support: There are currently no support mechanisms but BIPV is promoted by the building codes for new and refurbished Near Zero Energy Buildings.

Self-consumption support: Self-consumption is legal but the original system of annual net metering compensation was modified in 2012 to allow for compensation for one hour daily only. Where the hourly threshold is exceeded a price below market value is paid. A system size limitation of 6 kW exists in order to access this net metering arrangements with a preferential electricity tariff. Time of Use tariffs are available as an incentive for self-consumption.

Table 15 Denmark: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017

2016	*2017E*	*2018E*	*2019E*	*2020E*
862	1002	1152	1332	1530

1.3.2.2.4 Spain

PV system support: A feed-in tariff scheme was first introduced in 2004 but it was not until a further revision of this scheme in 2007 that there was a rapid expansion of the market. A moratorium and a 500 MW cap on support was introduced in 2008 because the scheme was oversubscribed, contributing to an existing electricity market budget deficit. The scheme was subsequently stopped in 2012 and replaced by an auction process for investment subsidy based on system size instead of the electricity generated. It now seems that investors frustrated with the subsidy regime but recognising the good investment fundamentals in Spain are moving to prepare utility scale system proposals without subsidy, with a pipeline of up to 29 GW claimed to be under approval, as of April 2018 [60].

Self-consumption support: A new regulatory framework for self-consumption was introduced in 2015. Two types of self-consumers are defined in the legislation, with the framework being different in each case:

- Type 1 self-consumers are defined as those with systems of up to 100 kW and which use all of the electricity generated on site. The consumer and the owner of the system must be the same entity. No compensation is permitted for electricity export to the grid. Type 1 systems of a size up to 10 kW which impede the export of electricity are exempted from grid connection and access studies.
- Type 2 self-consumers are defined as those that export surplus electricity at the wholesale electricity market rate or via an aggregator. The installation of net metering is required. Grid charges are applied to all electricity generated. An additional 'grid backup toll' is applied to surplus electricity exported from systems with a capacity > 10 kW.

Where the system size is less than the contracted electricity supply capacity of the consumer then a system can be connected at the same point of supply and according to a simpler procedure. Self-consumption by several end-consumers or communities of consumers is not currently permitted. Battery storage is permitted but the electricity is still subject to grid tariffs.

BAPV/BIPV support: The building regulations include a requirement for new and major renovations of commercial buildings to install photovoltaic systems with a minimum capacity of 6.25 kW [61]. A calculation must be made to determine the capacity

[60] PV-Tech, Economics not tenders driving Spain's solar resurgence, 23rd April 2018, https://www.pv-tech.org/news/economics-not-tenders-driving-spains-solar-resurgence

[61] El Código Técnico de Edificación (2013) Sección HE 5: Contribución fotovoltaica mínima de energía eléctrica, Documento Básico de Ahorro de Energía

that shall be installed. The calculation is based on the buildings floor area and additional coefficients related to the building use and the climate zone.

Table 16. Spain: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017

2016	*2017E*	*2018E*	*2019E*	*2020E*
5491	5571	5721	5971	6271

1.3.2.3 Late starters, high market penetration

1.3.2.3.1 Italy

PV system support: Following the end of successive legislation that mandated a feed-in tariff there now only exists an investment tax credit. The tax credit is available for residential systems of up to 20 kW. Financial support under the Conto Energia was subject to specific quality and performance requirements which may be of relevance to this study (*see the box below*).

Self-consumption support: Self-consumption is supported for all system sizes under the 'Scambio Sul Posto' system. For systems below 500 kW real-time self-consumption based on a net metering arrangement apply. In the case of self-consumption, the avoided grid costs are compensated for, either fully or partially (systems >20kW). Above 500 kW real-time self-consumption is supported. A combination of grid electricity market prices ('energy quota') and a grid service quota apply ('grid quota') are applied. Multiple systems can be connected to a single customer by private distribution cables.*Electricity storage support:* Tax credit measures are foreseen, but have not been brought forward yet due to the low number of installations.

Table 17 Italy: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017

2016	*2017E*	*2018E*	*2019E*	*2020E*
18983	19418	19940	20575	21275

Product and system qualification requirements

Conto Energia feed-in tariff 2005-2016 (Italy)

In order to receive the feed-in tariff for solar photovoltaic installations made available under successive Energy Bills between 2005 and 2016, systems as well as their component modules and inverters, were required to comply with a series of standards and requirements laid down in legislation.

Before owners of systems could be in receipt of the feed-in-tariff, the Performance Ratio (PR) of systems had to be tested in accordance with EN 61724. The PR achieved had to be greater than 0.78 in the case of systems with inverter ratings <20kW and greater than 0.80 in the case of systems with inverter ratings >20 kW. The system performance was to be tested under minimum light conditions of 600 W/m^2.

In addition, a series of requirements are stipulated for modules which comprise the following product quality standards:

- IEC standards
- - IEC 61215 for crystalline modules
- - IEC 61646 for thin film modules
- A warranty for 10 years against manufacturing defects
- Adherence of the manufacturer to a system or a consortium that will ensure the recycling of the modules at the end of life
- Confirmation of the execution of periodic factory inspections and product verifications in support of compliance with the above technical standards (IEC 61215/61646/62108)

In addition inverters shall be certified to be in compliance with EN 45011.

1.3.2.3.2 United Kingdom

PV system support: The feed-in tariff previously used to support systems of up to 5 MW was closed in 2016, resulting in a substantial fall in the installed capacity. A new scheme started in 2017 and has restricted the number of installations in specified capacity bands. The support is split into two tariffs – a generation tariff (applicable to all electricity generated) and an export tariff (applicable to all electricity exported). The export tariff is only available to systems below 30 kWp. The tariffs are adjusted on a quarterly basis and in accordance with the subscription rate for each capacity band. Larger systems can be supported under Contracts for Difference capacity auction rounds, whereby bids are selected based on the lowest prices tendered, but to date only one round has taken place in 2015.

An important feature of the subsidy regime in the UK is that those in receipt of price support must ensure that quality requirements for PV systems and their components laid down by the Microgeneration Certification Scheme are met. More details are provided in the box below.

Self-consumption support: Self-consumption is supported by a generation tariff which applies to up to 50% of the electricity generated which is not consumed on site. For systems below 30 kWp the differential between the retail price of electricity and the export tariff is an incentive to self-consumption.

Product and system qualification requirements

Microgeneration Certification Scheme (UK)

Photovoltaic modules that will be used in systems in receipt of feed-in tariff support must be selected from a pre-approved list that is maintained under the Microgeneration Certification Scheme (MCS). Systems are also subject to checking in accordance with the guidance and requirements under the MCS scheme.

The module pre-approval scheme provides independent third party assessment of compliance with the standards EN 61215 (crystalline modules) and EN 61646 (thin film modules). Tolerances applying to the module maximum power rating are also laid down as follows:

- tolerances as declared on the data sheet and label shall be either a value either side of zero (e.g. +/- 5%) or a value relative to zero (e.g. 0% to +3%)
- tolerance brackets above zero are not permitted (e.g. +5% to +10%).
- a variation of more than 10% between the upper and lower figures is not permitted.

Building Integrated PV products are the subject of separate MCS requirements. The scheme uses the concept of a BIPV product family in order to facilitate the approval process via test samples. The main standards tested are the same as for modules, but more detailed instructions are provided on how to test material or product samples e.g. the number of cells, the glass or coating type. In addition, the following are specified:

– a measurement of the deflection of the sample,
– application of relevant glazing quality standards from a listing,
– consideration of imposed, static and live loads that the product may be exposed to in the field, and
– application of factory methods to achieve correct lamination in accordance with EN ISO 12543.

All manufacturers shall operate a certified documented factory quality control system, in accordance with specific MCS 'Generic Factory Production Control Requirements'.

System supply, design, installation, commissioning and handover are subject to requirements. These include the professional competence of the contractor carrying out the installation, the extent to which they have followed MCS installation technical guidance and that an estimate of annual energy performance has been made in accordance with the MCS methodology.

Products and installers must be accredited under the Microgeneration Certification Scheme (MCS) to be eligible for payments under the FITs scheme.

Table 18. UK: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017

2016	*2017E*	*2018E*	*2019E*	*2020E*
11547	12397	13047	13722	14722

1.3.2.4 Late starters, medium market penetration

1.3.2.4.1 Belgium

PV system support: A system of green certificates has been chosen by each of the three regions. Owners of systems are entitled to an allocation of green certificates per MWh generated which in turn have a market value. Since 2015 an electricity price subsidy scheme called Qualiwatt has been operated in Wallonia. The first 3 kW of up to 10 kW systems is eligible for a subsidy. Quality requirements are laid down in the contract to receive the subsidy (*see the box below*).

Product and system qualification requirements

Qualiwatt feed-in tariff (Belgium)

In order to receive the electricity subsidy available under the Qualiwatt programme the following quality related requirements must be fulfilled:

- a copy of the certificate of competence for the installer of the solar photovoltaic systems issued by the RESCERT body;
- a copy of a Factory Inspection Certificate (FIC) which identifies the site of the photovoltaic modules used were produced;
- evidence that photovoltaic modules used are certified according to:
  - IEC 61215 for crystalline modules
  - IEC 61646 for thin film modules
  - IEC 61730 when panels are integrated or superimposed on a building.
- The certifications must be carried out by an accredited testing laboratory according to ISO 17025 by BELAC or another national accreditation body enjoying mutual recognition with BELAC.

Source: CWaPE (2017)

Self-consumption support: Net metering is supported for residential systems of up to 5 kW (Brussels) and 10 kW (Flanders and Wallonia). The electricity generated by a system must not exceed the consumers annual demand. Capacity based grid utilisation fees apply in Flanders. Time of Use electricity tariffs are also available.

Table 19. Belgium: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017.

2016	*2017E*	*2018E*	*2019E*	*2020E*
3423	3623	3873	4073	4283

1.3.2.4.2 Czech Republic

PV system support: A feed-in tariff was introduced in 2009 which led to a boom in installations through to 2014/15. The capacity installed mainly consists of utility scale systems (86%). The confidence of investors was damaged by the retroactive reduction in tariffs and the application of a 10% tax from 2014. Feed-in tariff support for PV systems was withdrawn completely in 2014.

A new 'Green Savings' programme running from 2015-2021 provides investment subsidy for new system installations on residential roofs of up to 10 kW. Systems may be installed in conjunction with electricity and hot water storage.

Table 20. Czech Republic: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017.

2016	*2017E*	*2018E*	*2019E*	*2020E*
2078	2088	2103	2123	2148

1.3.2.4.3 France

PV system support: Following the Paris COP21 in 2015 the government decided to give a new impetus to market development. National targets for installation are set through to 2023 under the Energy Transition for Green Growth Act (2015). Market support is provided by a combination of feed-in tariffs and capacity auctions to drive down market prices. Feed-in tariffs are available for all sizes of systems but those below 100 kWp are favoured by the pricing structure. The tariffs are adjusted in

function of growth in the market and reductions in system costs. A calendar for tenders for new capacity with the combined aim of contracting 4.350 MW between 2016 and 2019 was published in 2015. The tender process targets systems of greater than 100 kWp.

Green procurement requirements: Calls for tender for Power Purchase Agreements let under the national scheme are run by the Commission de régulation de l'énergie (CRE). The calls are notable for each containing an award criteria that rewards modules with a lower estimated production stage CO_2 emissions. The most recent calls for tender include a specific award threshold expressed in kg eq CO_2/kWp. To ensure comparability the boundaries and calculation method are laid down in the tender documentation (see Section 1.1.2.7 for more details). Moreover the call for tender also stipulates that owners shall make provision for the recycling of system components upon replacement or dismantling.

BIPV support: Building integrated systems up to 100 kWp currently receive a 10% increase in the feed-in tariff rate. Purchasers of BIPV systems shall be provided with a 10 year warranty for the performance of the integrated system and a guarantee that the installation works comply with current building regulations. In order to provide such a warranty insurers will expect the main components to comply with French product quality standards. For solar photovoltaics the national Technical Assessments (ATecs) are understood to be an important reference point (*see the box below*). *Self-consumption support:* Market electricity prices are currently low relative to the feed-in tariffs available, thereby dis-incentivising self-consumption. This is particularly the case for building integrated systems, which are eligible for a feed-in tariff approximately double the value of rooftop (building added) systems. A new law on self-consumption of renewable energy was introduced in 2016. This law applies to systems of less than 100 kWp and establishes a new network usage tariff together with tax exemptions for self-consumed electricity and a reduction in, and in some case the elimination, of network connection costs. Those choosing to maximise self-consumption can opt to receive investment support but in exchange receive a lower remuneration compared to the feed-in tariff for any electricity sold to the grid.

Table 21. France: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017.

2016	*2017E*	*2018E*	*2019E*	*2020E*
7134	8134	9734	11394	13220

Product and system qualification requirements

BAPV and BIPV product warranties (France)

National Technical Assessments (ATecs) of innovative construction products .are made by CSTB. The ATec GS21 'Photovoltaic systems' evaluation was developed in 2008 to provide assurance to insurers of solar photovoltaic systems.

GS21 has as a pre-requisite the conformity of modules with the performance standards EN 61215 (crystalline modules) and EN 61646 (thin film modules). Non-standard modules with no rear protection such as those specified for façades, glass roofs or shading applications must then be subjected to additional durability, strength and safety tests. Where PV modules are intended as like for like replacements for building systems (e.g. glass products, waterproof membranes, etc.), they must be tested to demonstrate equivalent minimum performances and behaviour as described in National or European standards.

Moreover, GS21 also makes reference to a number of system components. *In the 'construction data form' submitted to CRE for a solar PV system the following information and certifications of conformity (as relevant to this study) shall be provided:*

- *A calculation note on the mechanical resistance of the component parts of the mounting system (fixing clips, rails, screws, etc.) and on the climatic loads that may be applied to the modules.*
- *Justifications based on test results of the waterproofing of the main system components.*
- *Justifications based on test results of the resistance and durability of the component parts and their materials according to their ageing under environmental conditions (e.g. temperature, UV, humidity).*
- *Junction boxes according to EN 50548, which covers a range of environmental protection aspects, including water ingress and ambient temperature range, as well as resistance to ageing and corrosion.*
- *Classification of fire cables according to national standard NF C 32-070 which contains the need for reporting on halogen content in conformance with IEC 60754-1.*

Source: CSTB (2008) CC FAT (2017)

1.3.2.4.4 Greece

PV system support: A feed-in tariff scheme was introduced in 2009 but the rapid increase in system deployment was curtailed in 2013, with a particular impact on systems larger than 100 kW. This reduction in support was in part called for by electricity network operators in order to maintain normal grid operation.

Table 22. Greece: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017.

2016	*2017E*	*2018E*	*2019E*	*2020E*
2611	2641	2731	2950	3250

1.3.2.5 Late starters, low market penetration

1.3.2.5.1 Bulgaria

PV system support: A feed-in tariff was introduced in 2011 which led to a boom in installations during 2011/12, prompting concerns about grid stability. Retroactive reductions in tariffs and the application of new grid access charges have since depressed the market. Feed-in tariff support for PV systems was withdrawn completely in 2014. During the daytime renewable energy plant are also requested by the grid operator to limit their output to between 40% and 60% of their capacity. Significant administrative barriers exist to the installation, commissioning and grid connection of a system.

Table 23. Bulgaria: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017.

2016	*2017E*	*2018E*	*2019E*	*2020E*
1024	1025	1026	1031	1046

1.3.2.5.2 Romania

PV system support: A Renewable Portfolio Standard (RPS) based price support for systems was introduced in 2011 and led to rapid market growth. The majority of systems are of a multi MW utility scale. A reduction in the number of green certificates issued was imposed in the period 2014-2017 in order to sustain market prices.

In 2017 a new source of investment support for residential systems - the Green Economy Financing facility (GEFF) - was introduced by the European Bank for Reconstruction and Development (EBRD) [62]. Modules that form part of a financed system must be selected from a pre-approved 'GEFF technology selector' list. The products in this list must meet a requirement to demonstrate an efficiency of at least ≥14%. Module and battery combinations also figure in the list.

Self-consumption support: A new law supporting net metering for systems up to 100 kW will come into force in 2018 [63].

Table 24. Romania: historical and projected cumulative installed capacity (MW). E by the year stands for estimated in a medium scenario. Source: Solar Power Europe, 2017.

2016	*2017E*	*2018E*	*2019E*	*2020E*
1372	1459	1599	1749	1899

[62] PV Magazine, EBRD launches loan scheme for rooftop solar in Romania, July 2017, www.pv-magazine.com/2017/07/06/ebrd-launches-loan-scheme-for-rooftop-solar-in-romania/

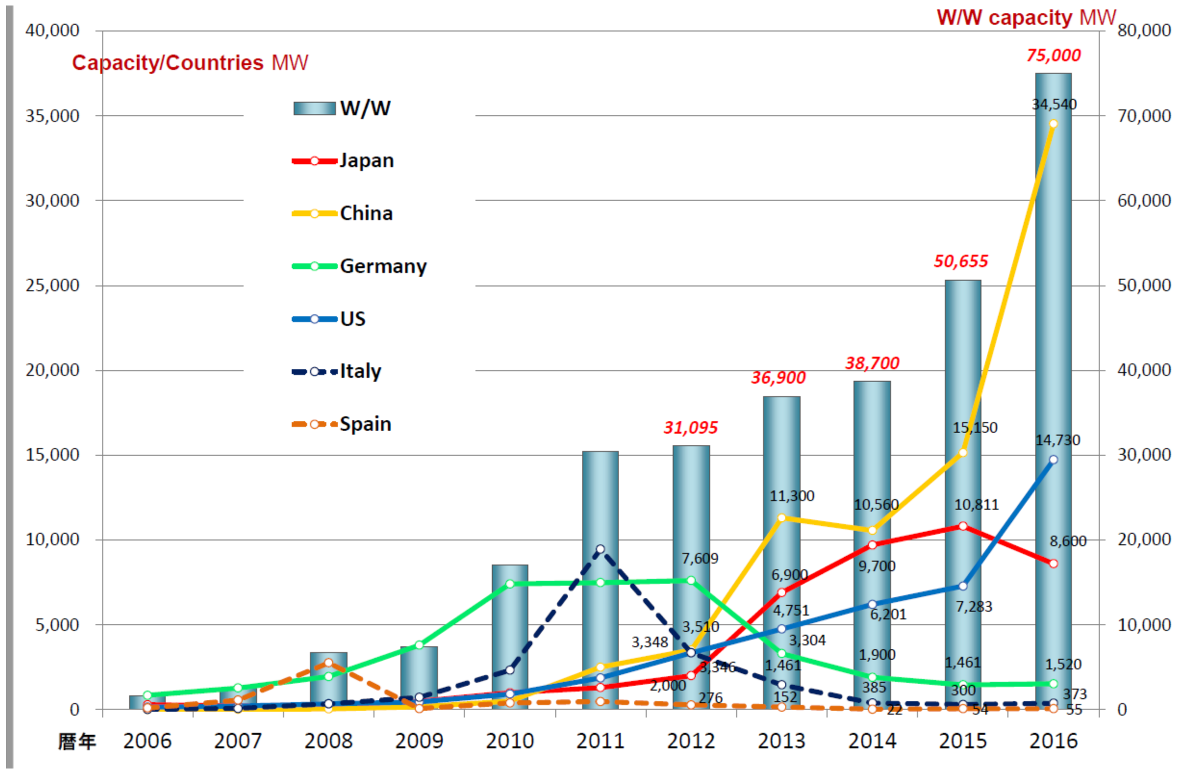
[63] PV Magazine, Romania to introduce net metering for solar up to 100 kW, January 2018, https://www.pv-magazine.com/2018/01/02/romania-to-introduce-net-metering-for-solar-up-to-100-kw/

1.3.3 Third country legislation and requirements

China is globally the country with the largest photovoltaic capacity installed (25% in 2016[64]). It continues to lead growth followed by Japan and the United States. The cumulative installed capacity of solar power in Japan reached almost 43 GW in 2016, with a 2,5 times growth projected up to reaching 100 GW in 2030. US occupies the third place in capacity installed though in 2016 has overtaken Japan in installed power p.a. This can been in **Figure 16**

In this section an overview of legislation and agreements for third countries outside the EU zone is provided. The countries have been selected based on the significance of their solar photovoltaic markets, in terms of combination of historical, present and projected deployment (Table 25). An analysis of the currently in place policies addressing regulatory framework and grid integration, and their effects in the PV market has been made.

Figure 16. Annual capacity in the major PV players in the world.



Source: JPEA, 2017[65]

[64] *JRC PV Status report 2016*

[65] *PV in Japan, current status and the way to go, the Japan Photovoltaic Energy Association (JPEA) 2017. www.nedo.go.jp/content/100866173.pdf*

Table 25. Overview of PV policy instruments in the selected countries. Source: Trinomics study 2016 and own elaboration; marks in red to be implemented by governments in the near future

Policy instruments	US	China	Japan	India	
FiT ($/kWh)	✓ (some states)	✓	✓		Market
Direct capital subsidy	✓ (some states)		✓	✓ (for residential and off-grid)	
Renewable portfolio standards	✓ (most states)	✓		✓	
PV RPS	✓ (some states)	✓		✓	
Green electricity scheme[1]	✓[2]		✓		
Financing schemes PV	✓		✓	✓	
Tax credits	✓ (30%)				
Net metering	✓ (most states)		✓	✓ (most states)	
Depreciation scheme	✓			✓	
Tax incentives	✓		✓	✓	
Local component requirement				✓	Manufacturing
Financing manufacturing		✓		✓	
Tax incentives manufacturing		✓		✓	
Subsidies/refunds		✓			
RD&I programmes	✓	✓	✓	✓	Research & innovation

Notes: 1: Allows the consumers to purchase RE electricity; 2: In the US, this exists even for PV specific electricity; 3: It is not explicitly called net metering in any official document but PV owners do receive payment for excess electricity exported back to the grid

1.3.3.1 China

PV system support: one of the diversity of on-going mechanisms to promote solar photovoltaics in China are feed in tariff mechanisms (FiT). The FIT program provided the strongest support when the price of solar was still significantly higher than other energy resources – but is still the main incentive for solar power, though now at much lower levels which are adapted annually. They do have different tariffs paid in 3 different regions - from sun-rich to sun-poor and geographically from northwest to the east coast. In December 2016, China reduced the FIT for utility scale plants by 19%, 15%, 13% respectively to 0.65/0.75/0.85 CNY per kWh[66]. At the same time, the FIT for distributed solar has remained the same. The Chinese government has revealed its new feed-in tariffs (FIT) for different types of PV projects, with rates set to fall by as much as 15% from the start of 2018[67]. Such adjustments are intended to shift the market segmentation towards distributed generation, which is expected to grow strongly to about 5 GW in 2017. Based on the Photovoltaic Industry Roadmap (PVIR),

[66] *1 EUR= 7.77 CNY (April 2018)*

[67] *https://www.pv-magazine.com/2017/12/22/china-sets-lower-solar-fit-rates-for-2018/*

the Chinese market is supposed to shrink between 2018 and 2020 to a level of 20 to 30 GW due to FIT cuts, but resume at an even higher installation rate in the first part of the following decade.

Self-consumption support: self-consumption is allowed in China. Self-consumed electricity gets a bonus (0.42 CNY/kWh) on top of the saved retail price. PV system owners can choose whether they want to use the FiT policy or opt for self-consumption with the bonus. Excess PV electricity injected into the grid is remunerated at wholesale price of electricity (based on coal-fired power plants' electricity prices) plus a bonus on top of it (0.42 CNY/kWh).

Ground mounted systems: "PV + agriculture" is becoming popular. Crops, flowers and herbs that prefer shady ambience are now being planted underneath solar power plants to use precious farming land as efficiently as possible. (Solar Power Europe, Global Market Outlook, 2017).

Product and system qualification requirements

Top Runner Program (China)

The so-called "top runner program" was developed by the Ministry of Industry and Information Technology (MIIT), the national Energy Administration, and the Certification and Accreditation Administration in 2015. It is an auction based tender program for projects using high efficiency modules and advanced technologies The idea is to guide project developers to adopt the latest technology, increase system efficiency and reduce LCOE. Results have been encouraging: by the end of 2016, the average cell efficiency of mono Si produced in Mainland China increased to 20.5%, the LCOE in sun-rich areas was below 0.65 CNY/kWh, and the record auction price reached was as low as 0.45 CNY/kWh (due in 2017).

There are two programs within the main one, the application and the technology:

- The application top runner program requires that modules fulfill a particular conversion efficiency requirement (e.g. poly module≥17%/mono module ≥17.8%)
- The efficiency requirements of the technology program are stricter. Any new tech such as PERC/MCT/HC which can improve module conversion efficiency would get higher score based on the aforementioned 17%/18%

Other requirements of top runner program are for PV project developers. Investors are selected depending on enterprise investment ability, performance level, technology available, offered electricity price etc. The threshold for business bidding requires a price of 10% lower than the local electricity price

1.3.3.2 Japan

PV system support: Feed-in tariff (FiT) introduced in Japan from July 2012 to promote the renewable energy, particularly after the nuclear accident of Fukushima Nuclear Power Plant in March 2011. PV systems rapidly increased and have a monopoly on renewable energy with 99.9% of the accredited system numbers. PV domestic shipments expand 2.7 times from the previous year. The 2013 FiT price was reduced 10 % of solar energy, but others were deferred. Thus, it is clear that FiT is expanding PV market in Japan. Over 80 GW have been approved since the FiT started in 2012, from where only 30 GW have been commissioned but around 50 GW were not operated up to the end of 2016[68]. FiT scheme is most attractive in the commercial segment, where 34.4 GW FiT are in the pipeline. Under FiT, many new comers start to install 10~50kW PV systems in the residential sector, where FIT accounts for 4.1 GW. Grid parity has been achieved in the residential sector and probably in the commercial where in 2016 was imminent. For the utility scale, grid parity will not be reached in foreseeable future. FiT scheme for same as for commercial sector (43.2 GW in the pipeline, Trinomics, 2016), is therefore less attractive. FiT have started to decline, which together with competition and Yen depreciation is expected to cause a cost reduction (**Table 26**).

Table 26. FIT cuts for Japanese installations for 2017 and 2018 and the projected FIT for 2019, in Japanese yen[69]

Energy Source	Procurement Category		Price per 1kWh		
			2017	2018	2019
Solar power	10kW or less	Output control equipment not required	28 yen	26 yen	24 yen
		Output control equipment required	30 yen	28 yen	26 yen
	10kW or less ("double generation")	Output control equipment not required	25 yen		24 yen
		Output control equipment required	27 yen		26 yen
	10kW or more, but less than 2,000kW		21 yen + tax	-	

For owner, constructer, and investor of such systems, the Japan Photovoltaic Energy Association has published the check list of design/construction of foundation and cradle (mounting base) for more than 10kW.

[68] *PV in Japan 2017. RTS Corporation. https://unef.es/wp-content/uploads/dlm_uploads/2017/05/japan-pv-market_apr-2017.pdf*

[69] *1 EUR= 132 JPY (April 2018)*

Since the FiT law revision in June 2016, maintenance and periodic inspections are obliged to the PV system owners, as they are considered important key roles for long life operation. Guidelines have been published but only in Japanese[70].

PV auctions framework: From October 2017, a FiT auction process has been launched for 10 kW to 2 MW with a ceiling price (21 JPY/kWh) which is intended to minimise the amount of subsidy given and make PV more competitive[71].

PV Storage: subsidy is available for home storage from national and local governments for year 2018: Zero Energy Building program promotion subsidy: 10 billion JPY. The subsidy is: 50,000Yen/W (442 USD/kWh) and the Typical price : 1500 – 1750 USD/KWh. This opens opportunities for residential storage in 2019. Moreover, FIT projects with storages are ongoing to address grid connection issues.

1.3.3.3 United States

The state of California is notable for already accounting for 23.738 GW of PV installed capacity[72]. The Go Solar California! Campaign is a joint effort of the California Energy Commission and the California Public Utilities Commission[73]. The solar incentives and rebates for self-consumption were launched in California in 2006 with ambitious goals - 3,000 megawatts of solar energy systems on homes and businesses by the end of 2016 – funded with $3,351 million between 2007-2016[74]. The ultimate goal is to establish a self-sufficient solar industry in 10 years so that solar energy systems are a viable mainstream option for homes and commercial buildings, and in 13 years to put solar energy systems on 50 percent of new homes.

PV system support: the rebates are tax credits in effect through 2021. The 30% of the cost is subject to the return (including installation costs), with no upper limit (Credit decreases to 26% for tax year 2020; drops to 22% for tax year 2021) It must be installed in a private home used as a residence - no rentals, but second homes qualify).

Self-consumption support: it has been mentioned above the program from the state of California. The incentive structures shall promote high-quality designs and installations.

Table 27. US: historical and projected cumulative installed capacity (MW) GTM research 2017

	2016	**2017**	**2018**	**2019**	**2020**	**2022**
Residential	2500	2642	3000	3270	3650	4750
Non –residential	800	900	950	1000	1050	2775
Utility-scale	10975	8300	6600	8000	9400	10000

At country level there are two programs currently to refund PV systems providing electricity for the residences:

- New Solar Homes Partnership (NSHP): financial incentives and other support to home builders, encouraging the construction of new, energy efficient solar homes that save homeowners money on their electric bills and protect the environment.
- Multifamily Affordable Solar Housing (MASH) is another program administrated by the Pacific Gas and Electric Company, funded with $162 million to encourage building owners to install solar panels on low-income, multifamily dwellings like apartment buildings, and tenants receive incentives.

Thee 3 major pricing or "tariff" options for solar customers are:

[70] PV in Japan, Current status and The way to go, 2017. Japan Photovoltaic Energy Association

[71] PV in Japan, 2017. RTS Corporation

[72] Tracking Progress. California's Installed Electric Power Capacity and Generation California Energy Commission August 2017, http://www.energy.ca.gov/renewables/tracking_progress/documents/installed_capacity.pdf

[73] Go solar campaign: http://www.gosolarcalifornia.org/about/index.php

[74] 1 EUR= 1.24 USD (April 2018)

- Net Energy Metering, which will include net surplus compensation by 2011 where customers can receive compensation at the end of the year if they produce more electricity with their solar system than they consume from the grid.
- Virtual Net Metering, which allows the electricity produced by a single solar installation to be credited toward multiple tenant accounts in a multifamily building without requiring the solar system to be physically connected to each tenant's meter. For now, this program is only available as a pilot program to multifamily affordable housing, but the CPUC is currently considering expanding the program in the future.
- Renewable Energy Self-Generation - Bill Credit Transfer (RES-BCT), which enables solar customers transfer excess credits to another account. This works similar to net metering, but any production credits that normally would be received by the consumer can be transferred to another account.

The formula varies from program to program but applicants must pay a minimum percentage of eligible project costs after the Federal Investment Tax Credit (ITC) is subtracted from the project costs (within certain limits).

Grid integration support: The high numbers of installations in some areas has driven the introduction of new regulations. Interconnection data on California Solar Statistics fully captures solar PV net energy metering (NEM) participation in IOU territories (PG&E, SCE and SDG&E)

Electricity storage support: The California Energy Commission (CEC) proposed its own weighting factors for calculating the efficiency. It considers, for example, less likely that the real working conditions of the inverter make it work at its maximum efficiency in comparison to the Euro Efficiency definition (see section 1.2)

Product and system qualification requirements

Eligibility requirements for equipment from the California Energy Commission

In order for an installation to be eligible to receive the FIT, PV modules and inverters must be listed on the California Energy Commission's Eligible Equipment Lists. Moreover, all solar energy equipment for electricity generation (e.g. PV modules, inverters, tracking mechanisms, etc.) shall have a minimum 10-year manufacturer performance warranty to protect against degradation of electrical generation output of more than 15% from their originally rated electrical output.

Modules

For incentive eligibility in the California program all flat-plate PV modules shall have certification conducted by an NRTL73 to UL 1703. Additional testing shall be conducted to specific subsections of IEC Standard 61215, *Crystalline Silicon Terrestrial Photovoltaic (PV) Modules Design Qualification and Type Approval, Edition 2.0, 2005-04* or IEC Standard 61646, *Thin-Film Terrestrial Photovoltaic (PV) Modules – Design Qualification and Type Approval, Edition 2.0, 2008-05.*

Inverters

All inverters shall have certification conducted by an NRTL76 to UL 1741. Each model of inverter shall also be tested by a NRTL for performance ratings according to sections of the test protocol titled Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems[75]. The CEC provides a list of currently certified eligible equipment on the Go Solar California site at http://www.gosolarcalifornia.ca.gov/equipment/

Systems

There are three approaches: flexible installation incentive (FII) approach, the performance-based incentive (PBI) approach, and the expected performance-based incentive (EPBI) approach.

- In the flexible approach, systems shall be installed with an azimuth and tilt angle within a designated range as determined by the program administrator. The performance based is the preferred way to promote high-performing systems since the solar energy systems receive incentives based on the actual production (kWh) over the period during which the incentives are being paid.
- The PBI incentive payment is calculated by multiplying the incentive rate ($/kWh) by the measured kWh output. The expected performance-based incentive (EPBI) approach pays an upfront incentive based on calculated expected performance, taking into account all major factors that affect performance of the particular installation in a given location.
- The EPBI calculation shall be based on hourly modelling of the interactive performance of solar energy systems using the third-party tested performance characteristics of the specific modules and the inverter over the range of conditions that affect component performance.

[75] *Sandia National Laboratories, Endecon Engineering, BEW Engineering, and Institute for Sustainable Technology, October 14, 2004,*

1.3.3.4 India

India was one of major countries that accounted for the highest cumulative installations at the end of 2017 almost reaching 17 GW[76] (13 GW having been installed in the last three and a half years, with a production of around 13 TWh in 2017). India is the third country in the world that has added more PV capacity (India solar handbook 2017).

PV system support: The National Solar Mission (NSM) contains an elaborate set of policies and incentives capturing accelerated depreciation, capital subsidies, renewable portfolio obligations and more. The government has set an ambitious target of achieving 40% cumulative electric power through renewable energy sources by 2030, and an installation of 175 GW of renewable energy source by 2022, 100 of which are allocated to solar technology.

The government has issued guidelines for the procurement of solar and wind power through a tariff-based competitive bidding process, and has expanded Renewable Purchase Obligation (RPO) up to the year 2018-19 while notifying standards for deployment of solar photovoltaic systems/devices.

PV modules and equipment: there is no formal information relating to any specific solar equipment or component being of low quality and sold in the Indian market. To impose strict quality norms for solar equipment and components, and to restrict low quality solar PV equipment in the Indian market, the central government, after consulting the Bureau of Indian Standards, has issued the "Solar Photovoltaics, Systems, Devices and Components Goods (Requirements for Compulsory Registration) Order, 2017" dated September 5, 2017, for the quality control of solar photovoltaic systems, devices and components. In a second phase India recently allocated 7.5GW of local content tenders to Central Public Sector Undertakings (CPSUs), which provides for installation of entire capacity of solar projects based on domestically manufactured solar PV cells and modules. However, analysts in the solar sector have noted this measure is not competitive due to the price of the modules. Their quality may be as well an issue in a country with many obsolete manufacturing lines[77].

NSM includes specific targets for manufacturing: a capacity of PV module production of 4-5 GW by 2020 and the necessary manufacturing capacity of poly silicon material to produce 2 GW of solar cells. Policy instruments are special incentive packages to set up manufacturing plants and access to low interest loans amongst others.

Grid integration support: the majority of the capacity in India is in utility scale, which may create some issues. Current PPAs being signed for new schemes are around 0.045 $/kWh (0.066 €/kWh) and even reaching a lowest winning bid of 0.037 $/kWh (0.058 €/kWh) (MNRE 9, 2016). Every new auction is hitting a new low, which is worrying developers and manufacturers according to Mercom Capital[78]. The result of aggressive bidding is that projects below the 0.045 $/kWh mark are considered extremely risky and difficult to finance. Local lenders are avoiding funding these as some of the companies with similar awarded projects are in financial trouble. With these low PPAs being reached, the utility segment is about to reach grid parity in the near future.

Self-consumption support: India has foreseen up to 2 GW of off-grid installations by 2017, including 20 million solar lights in its National Solar Mission. (IEA Trends in PV applications 2016) PV is perceived as a way to provide electricity without first building complex and costly grids. The challenge of providing electricity for lighting and communication, including access to the Internet, will see the progress of PV as one of the most reliable and promising sources of electricity in developing countries in the coming years.

1.3.3.5 Australia

Each state in the country has different laws regarding feed-in tariffs. The Clean Energy Council (CEC) has established an exhaustive accreditation program that covers installations, equipment and installers. The solar accreditation program for solar PV installations is meant for installations to be eligible for government rebates such as

[76] https://www.pv-magazine.com/2018/01/04/indias-impressive-solar-achievements-in-2017/

[77] https://www.pv-tech.org/news/problems-with-indias-newest-domestic-pv-manufacturing-support-idea

[78] Trinomics, 2016

Product and system qualification requirements

Approval for equipment listing to be eligible for FiTs and rebates

Modules

All crystalline and thin film PV module listing applications must demonstrate compliance with new versions of IEC 61215 and application class 2 of IEC 61730, plus the following:

- PV modules are Fire Class C per UL790 under IEC 61730 certification.
- PV systems above 50 volts (open circuit) or 240 watts rated power must meet Application Class A of IEC 61730.
- PV modules installed on buildings must also be certified as meeting Fire Safety Class C or better per UL 790.
- Roof integrated modules may have additional requirements under the Building Code of Australia (BCA).
- For PV systems with total power of less than 240W and open circuit voltage less than 50 volts, modules do not need to meet IEC 61730 Class A, however they should meet 61730 Class C. Class B modules are not to be used in Australia.
- Certificates are a type that requires periodic factory inspections, and identifies all factories which are covered by the certification

Inverters

Apart from fulfilling the relevant Australian standard (e.g. for a Multiple Mode Inverter - PV and Battery, AS/NZS 4777.2:2015, or for a grid connected AS/NZS 4777.2:2015) inverters shall fulfil the IEC 62109-1 and IEC 62109-2 and the isolation of the PV array, must be of at least IP 55.

For microinverters, in addition to the requirements for all inverters, the following has to be fulfilled:

- Each input of the micro inverter is limited to 350W PV power at STC and at ELV.
- DC cable length is less than 1.5m (including any adaptor cables)
- The method of cable support for the interconnecting AC cable and DC panel cables shall have a life as long as the system.
- Cable support shall ensure that there is no stress placed on connectors.
- Plugs, sockets and connectors shall only be mated with those of the same type from the same manufacturer
- A PV array disconnection device is not required for PV modules connected to micro inverters (AS/NZS5033:2014 clause 4.4.1.2)

PV array installation

Among others related to safety conditions, the following particular requirements for the PV array were found worth to mention here:

- There is an specific Australian standard (AS/NZS 5033) for the installation of photovoltaic (PV) arrays.
- Unless specified by the CEC system designer, the installer shall not install two parallel strings, connected to the same MPPT input at the inverter, installed on different orientations (e.g. east and west).
- the array structure meets AS1170.2 certification
- PV wiring losses are less than 3% at the maximum current output of the array

Specific earthing, wiring instructions, insulation levels of the wiring cables between array and inverters are as well listed with a great level of detail

Small-scale Technology Certificates and feed-in tariffs. The CEC has also launched a Solar Retailer Code of Conduct in 2013 on behalf of the solar industry to improve customer service and industry standards, and an accredited installer process with clear steps. Accredited installation guidelines are published and summarized below.

PV modules and equipment: modules and inverters have to be in Clean Energy Council's approved lists to be eligible. See the table below

PV systems installations: To ensure the high quality of solar installations by accredited installers, the Clean Energy Council produces both design guidelines and install and supervise guidelines for grid-connect systems. A system of demerit points is also in place with the aim of addressing instances of continued non-compliant work that can result in direct suspension (e.g. a possible safety hazard which poses an imminent risk of damage to property or persons could be that the DC isolator enclosure or cable junction boxes are not suitably installed to prevent water ingress. It would be categorized as serious non-compliance and unsafe and would incur in 10 demerit points).

1.4 Conclusions and recommendations

1.4.1 General conclusions and recommendations

1.4.1.1 Product definition according to statistical and legislative references

Consultation of the EU's industrial production statistics as compiled under Eurostat PRODCOM codes and activities has revealed that whilst divisions and activities can be identified that are likely to contain data on module, inverter, system equipment and system installation data, there are currently no specific divisions or classes that correspond exactly to photovoltaic modules or inverters, or to the installation of systems.

The same is true for CE marking, where there exist relevant marking requirements for construction products, the electromagnetic compatibility of electrical equipment, safety requirements for low voltage electrical equipment and the restrictions on hazardous substances in electrical equipment, but no specific conformity requirements that contain a product definition.

1.4.1.2 Establishing a basis for product system comparisons

1.4.1.2.1 Defining the life cycle stages

In order to adopt a life cycle approach to the identification of improvements in the environmental performance of a product it is important to analyse the environmental impacts associated with the different life cycle stages. Emulating the approach adopted in the criteria developed for the French national PV capacity auction process and by NSF International for the Green Electronics Council (GEC), it is proposed to refer to a schematic of the life cycle stages.

Pending conclusion of the European Commission's Product Environmental Footprint (PEF) the most suitable standardised reference point is considered to be the life cycle modules and stages laid down in the EN standards 15804 and 15978. These provide a standardised approach to the life cycle assessment of construction works. Reference to these modules and stages would have the advantage of allowing for the narrowing or broadening of the life cycle scope depending on the opportunities of constraints of each policy instrument. So, for example, the boundary for Ecodesign implementing measures would normally be limited to addressing the use stage performance, whereas Ecolabel criteria could also address aspects of the production stage. The reference to project stages can therefore be adjusted to the policy context under study.

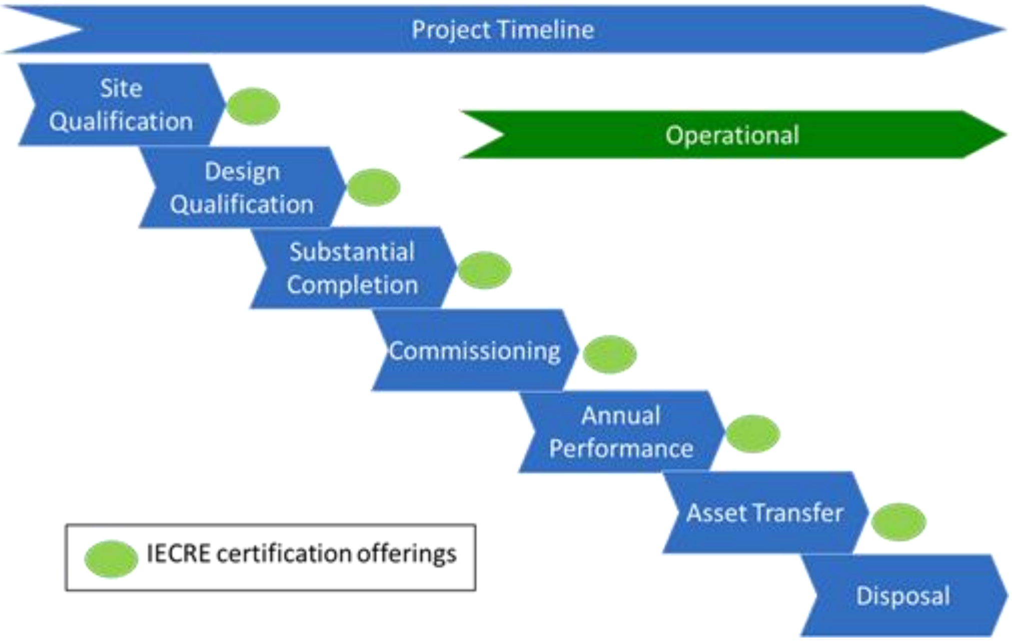
1.4.1.2.2 Defining generic project stages

Moreover, in order to support a practical understanding of when performance criteria can be applied to products or systems – for example, in Green Public Procurement (GPP) - it is proposed to also refer to a schematic of common project stages. The following generic stages can be identified as relating to project activities and can be mapped onto the IEC's Renewable Energy (RE) system project timeline (see also **Figure 17**):

- Design stage: system design/specification and performance assessment based on calculations and simulations
- Implementation stage: construction and installation of a system based on drawings and specifications
- Commissioning stage: functional commissioning and testing based on defined routines
- Operational stage: monitoring and maintenance of performance according to agreed parameters
- Decommissioning stage: based on the potential for recovery of products or materials from a product or system

The reference to project stages can therefore be adjusted to the policy context under study.

Figure 17. IEC RE system project timeline Gantt



Source: IEC (2017)

1.4.1.2.3 Defining functional units of performance

In order to carry out meaningful modelling of the life cycle of a product it is important to define the function being provided, and linked to that a common reference unit of comparison between different products designs or systems – a functional unit of performance.

Proposed approach to defining solar PV functional units of performance

The following parameters and conditions shall be taken into account when modelling the performance of modules, inverters and systems:

- Climatic conditions: the irradiation collected by modules depends on the climate, their orientation and how they are installed.
- Performance ratio: the system Performance Ratio (PR) (also called *derate factor*) takes into account the modules' (DC) rated performance, the inverters' rated performance and other operational variables in order to estimate the actual (AC) electricity generation.
- Service life expectancy: based on a manufacturers performance guarantee or the period of time before the combined probability of failures and the level of degradation in performance become unacceptable.

In accordance with the definition contained in the ISO standards series 'Building and constructed assets – service-life planning' it is proposed to use the following definition of the (first) intended service lifetime of a product or system:

> *'the period of time after installation during which a component or an assembled system meets or exceeds the technical performance and functional requirements according to market expectations and/or as laid down by the end user'.*

Moreover, based on the recommendations of the IEA PVPS programme in relation to the life cycle environmental performance of PV technology, it is proposed to define the functional units for modules, inverters and systems according to the following fundamental parameters and conditions that influence performance during a product or systems service lifetime (see the box below). The proposal would allow for a combination of the location, design decisions and lifetime estimations at component and system level to be taken into account. Additional analysis is to be carried out to determine the levelised cost of electricity (LCOE) generated via PV system according to the parameters and conditions included within the functional unit.

1.4.1.3 Lessons and potential implications of existing legislation

1.4.1.3.1 European Union policy level

The review of relevant European Union level legislation and agreements in section 1.3 has revealed a number of important potential short to medium term influences on the EU solar photovoltaic market. They are briefly summarised in **Table 28**. These influences can later be taken into account in the selection of base cases, introduction of sensitivities into the modelling and into considerations as to how policy instruments could act within the market.

1.4.1.3.2 Market leaders at Member State level

A review of the current legislation for thirteen Member States, as well as four examples of component and system requirements, has identified a number of important actions that are influencing the deployment, quality and performance of solar photovoltaic systems. They are briefly summarised in **Table 29**. These influences can later be taken into account in the description of representative base cases and further identification of accepted performance metrics and standards.

1.4.1.3.3 Market leaders at International level

A review of the third country countries China, Japan, United States, India and Australia has identified a number of policy actions and programmes that are influencing the deployment, quality and performance of solar photovoltaic systems. They are briefly summarised in **Table 30**. Possibly, the policy instrument of greatest potential significance to this study is China's Top Runner programme. The programme forms part of the capacity auction process and establishes criteria for module performance and the PV technology to be deployed. This programme has been successfully used to drive manufacturers to progressively increase the performance of modules and to accelerate new technologies such as PERC, black silicon and bifacial cells into full-scale production phase.

Table 28. Potential influence of EU policy instruments on the EU solar PV market

Thematic policy area	**Possible influence on the EU solar PV market**
Energy Union and reshaping of the EU electricity market	• The proposed new common rules for the electricity market will impose more favourable market conditions for self-consumption and local energy communities • Provisions for non-discriminatory handling of grid connections, including associated charges and procedures, will support 'active consumers'
Driving the market for renewable electricity generation	• The proposed recast Directive will support self-consumption and storage by simplifying permitting and removing restrictions. • A new calculation methodology for the minimum contribution of renewable sources in new buildings and major renovations will further support rooftop solar PV
Driving the market for building renovation and near zero energy buildings	• Targets for all new buildings and major renovations to achieve Nearly Zero Energy performance by 2020 will further drive BAPV and BIPV, which are already favoured options. • A renewed focus on the large scale renovation and decarbonisation of the existing building stock could further drive BAPV deployment. • Buildings will increasing need to demonstrate their 'smart readiness' and this will include energy systems • The EN ISO 52000 series calculation method for BAPV/BIPV performance will be widely used
Improving information on construction product performance	• The EN 15804 and EN 15978 LCA standards, together with the Commission's Level(s) framework will drive an increased focus on the life cycle performance of building components. • Circular thinking will increasingly need to form part of building design and operation.
Improving material efficiency and creating a Circular Economy	• The Critical Raw Materials indium, gallium and silicon metal will be the focus of actions to foster material efficient solutions • Member State reporting on rising solar PV waste streams will increase the focus on end of life routes
Product policy and consumer information	• Products will need to be smart ready, with the potential to interact with home management systems and appliances.

Table 29. Effect of Member State policies and requirements on solar PV deployment

Policy or requirement	**Influence on solar PV deployment**
PV system support	• Feed-in tariffs are progressively being scaled back and are increasingly being weighted to support smaller, largely residential systems of <5-30kW . • Auctions of electricity price contracts are increasingly being used for larger systems (>100-200kW), but tend to support larger utility scale systems with greater potential to reduce bid LCOE
BIPV support	• Only two large Member States give BIPV preferential subsidy, either in the form of investment subsidy or an increased feed-in tariff rate. • BIPV is in some Member States required according to building permits and codes.
Self-consumption support	• Net-metering is in permitted in most Member States whereas net-billing is a newer concept • A variety of adjustments have been made to legislation and support schemes in order to incentivise self-consumption at <5-100 kW. These include: – Reducing feed-in tariffs to below consumer electricity prices – Waving grid connection study and connection costs
Electricity storage support	• At least two Member States have established investment subsidies that support the installation of battery storages in small systems (<30 kW).
Module qualification	• In some Member States modules and inverters must pre-qualify whilst in others qualification must be shown the point of bidding/contract award • The IEC standards 61215 and 61646[79] are specified in all of the requirements analysed. • Other performance aspects include: – Performance tolerances, including for specific types of BIPV products – minimum warranty periods, – factory quality inspections and – coverage by a compliant WEEE take back scheme • Residential investment support available in former ascension states is linked to a requirement to use products from a pre-approved list
System qualification	• In at least one Member State a system Performance Ratio target with field testing requirement has driven a focus on installed performance. • In one Member State an award criteria for the embodied GWP the modules to be used in a system is included in auction requirements. • In one Member State performance criteria have been set in support of product and system warranties. These include coverage of: – The durability of the mounting system – Waterproofing of the main system components *e.g. junction boxes* – The halogen content of cables

[79] *IEC Standard 61646 is foreseen to become part of IEC 61215-1-x in 2019*

Table 30. Selected third country policies and requirements for solar PV deployment

Policy or requirement	Influence on solar PV deployment
Demand side targets	• China and US have clear and ambitious targets defined for near future electricity generation from RES and explicitly for PV. • The Chinese government's official 2020 installation target is 105 GW (despite they have reached almost 120 GW[80] at the end of 2017) India on the other hand has a PV capacity target for 2022.
PV system support	• China has repeatedly reduced the FIT for utility scale plants by 15% as an average since 2016. The Chinese market is expected to shrink between 2018 and 2020 to a level of 20 to 30 GW due to FIT cuts according to IRENA Roadmap . • Remaining FiTs are focused on small and residential. Self-consumption is being incentivised, and this starts to include storage. PV system owners in China can choose whether they want to use the FiTs policy or opt for self-consumption with the bonus. The threshold to get the FiTs has as well a tendency to decrease in the majority of the third countries analysed. • More price based auctions seem to exist in those countries. This is resulting in large systems to have a predominant role. Japan has a tender for 500MW with the right to apply for FiTs. China has launched the Top runner program, an auction based tender program for projects using high efficiency modules and advanced technologies.
System and component qualification	• The Top runner program in China is a leading example, which has introduced module efficiency criteria into an auction process in order to drive improvements in performance. • The most complete set of criteria from the analysed ones are the California (Go Solar!) and the Australian program. Both programs state the tests and standards that must be met by modules, inverters and other components, in order to be part of a list of eligible equipment, but also requirements for their installation.

1.4.2 Photovoltaic modules: recommendations and proposals

1.4.2.1 Product definition and scope

Product definitions developed by the IEC and IEA, as well for UL, NSF International and the PEF pilot, were consulted in order to develop a definition for the Preparatory Study. Stakeholders were consulted on an example definition and possible scope delimitations from December 2017 to January 2018. The headline results were a follows, and are reflected in the first formal proposal to stakeholders:

- The majority of respondents supported an output power cut off of less than 50 Watts.
- The encapsulant and junction box should be included in the product definition and scope.
- The number of cells, the module area or the form factor should not form part of the product definition and scope.

In addition, the majority of respondents considered that Building Integrated PV should be included within the scope, but will need to be handled separately from standard modules so as not to hinder innovation and growth of what is currently a relatively small niche in the market.

Examples of feed-in tariff qualification criteria for BIPV modules, such as those of the UK Micro Generation Scheme, suggest that one option for managing this could be to focus on the performance of cells, rather than the diversity of different construction product form factors into which they may be integrated.

For the purpose of modelling module level power electronic components such as micro-inverters and power optimisers are proposed to be excluded from the scope of PV modules. Instead it is proposed that the potential benefits are analysed within the PV systems scope.

[80] *https://www.pv-magazine.com/2017/11/22/bnef-china-to-install-54-gw-in-2017/*

The first proposal for the solar photovoltaic module product definition and scope are presented below.

Proposed solar photovoltaic module definition and scope

A photovoltaic module is a framed or unframed assembly of solar photovoltaic cells designed to generate DC power. A photovoltaic module consists of:

- strings of photovoltaic cells (crystalline technology) and/or semiconductor layers (thin film technology),
- a substrate, encapsulation and cover materials,
- the interconnections of the cells,
- the junction box and associated cabling, and
- the framing material (where applicable).

The scope shall correspond to photovoltaic modules produced for use in photovoltaic systems for electricity generation. The scope shall include Building Integrated Photovoltaic (BIPV) modules that incorporate solar photovoltaic cells and form a construction product providing a function as defined in the European Construction Product Regulation CPR 305/2011. The scope shall include street furniture that incorporates solar photovoltaic cells, but it does not include street lighting equipment.

Specifically excluded from this scope are:

- Module level power electronics, containing micro-inverters and power optimisers
- Modules with a DC output power of less than 50 Watts under Standard Test Conditions (STC),
- Modules intended for mobile applications or integration into consumer electronic products.

1.4.2.2 Measurement and test standards

Photovoltaic modules have been found to be well covered by existing standards for production, design qualification and type approval, power and energy yield. An extensive collection of operational data and correlation with laboratory testing results give confidence in building an appropriate definition of failure modes and degradation effects, although an intermediate method may be required for quantifying them.

A definition of technical lifetime and operational service life is still not clarified; however, following the future IEC TS 62994, the IEC/TR 62635 and the guidelines in the ISO 15686 series an agreed method is considered to be achievable. The issues of recyclability, repairability and durability will be covered by the general framework of standards being developed under the Mandate M/543 but PV-specific standards deriving from the horizontal ones will be necessary.

1.4.2.3 Product functional unit

In addition, a proposal has been formulated for definition of the primary product performance parameter (functional unit) for solar photovoltaic modules. This definition would limit the scope to DC generating modules without module level power electronics, so as to ensure comparability at product level.

The definition has been aligned with the proposed IEC 61853-3 method for calculating a Module Performance Ratio and then estimating the energy yield according to irradiance and temperature conditions. This method is considered the most suitable for making estimates of the primary function provided by a module, which is to generate DC power for a determined period of time.

To ensure that performance along the life cycle of a module is taken into account, the proposal supposes that the yield is modelled for a reference service life. To be representative the impact on energy yield of degradation and fault mechanisms would therefore also need to be taken into account.

Proposed solar photovoltaic module functional unit

The functional unit shall be 1 kWh of DC power output under predefined climatic and installation conditions as defined for a typical year and for a service life of 30 years.

1.4.3 Inverters for photovoltaic applications: recommendations and proposals

1.4.3.1 Product definition and scope

Product definitions developed by the IEC and the US EPA addressing both inverters and more broadly power conditioning equipment were consulted in order to develop a definition for the Preparatory Study. Stakeholders were consulted on an example definition and possible scope delimitations from December 2017 to January 2018. The headline results were as follows, and are partly reflected in the first formal proposal to stakeholders:

- The majority of respondents considered that:
  - All types of inverters should be included in the scope
  - Power output and intended configuration should be addressed in the scope and definition
- Power Conversion Equipment categories in the draft IEC 62093 standard should form a component of the scope and definition
- It shall be made clear that DC optimisers shall not quality as inverters

The comments have largely been addressed by redrafting the proposal to incorporate the thresholds and categories of draft IEC 62093 standard. However, upon further consideration of the possible grid and module configurations that may need to be modelled, the following new proposals are presented for discussion:

- That the scope shall encompass those that are able to function in a utility interactive mode. The rationale is that the majority of inverters will be connected to distribution grids and this configuration is specifically covered in testing standards.
- That 'central solution' inverters combining a transformer connected to a distribution network are proposed as being excluded. The rationale is to ensure comparability and to avoid an overlap with existing Ecodesign Regulations.
- That inverters falling within draft IEC 62093 Category 1[81] should be excluded from this scope, but shall be within the scope of photovoltaic systems. The rationale is the potential difficulty in making a meaningful comparison between standalone and module-integrated functions. Moreover, this approach would reflect that adopted by Germany's Blue Angel ecolabel inverter criteria.

The first proposal for the product definition and scope of inverters for photovoltaic applications is presented below.

Proposed definition and scope of inverters for photovoltaic applications

An inverter is as an electric energy converter that changes the direct electric current (DC) output from a solar photovoltaic array to single-phase or polyphase alternating current (AC). The scope shall correspond to:

- Utility interactive inverters that are designed to operate grid connected in stand-alone and parallel modes.
- Inverters with a maximum circuit voltage of 1500 V DC and connections to systems not exceeding 1000 V AC. Hybrid inverters and micro-inverters sold separately are falling within this category.
- String inverters falling within category 2 as defined in draft IEC 62093 ('String-level power electronics') and designed to interface multiple series or parallel connected modules and specified for wall, roof, ceiling or rack mounting.
- Central inverters falling within Category 3 as defined in IEC 62093 ('Large-scale power electronics') and designed to interface multiple series or parallel connected modules, but due to its complexity, size and weight are housed in a free-standing electrical enclosure.

Specifically excluded from this scope are:

- Central inverters that are packaged with transformers (sometimes referred to as central solutions) as defined in Commission Regulation (EU) No 548/2014 on Ecodesign requirements for small, medium and large power transformers.

[81] *Category 1: Module-level power electronics (MLPE) – specified to operate at a PV module base level interfacing up to four modules.*

1.4.3.2 Measurement and test standards

Dedicated standards have been developed for PV inverter performance, such as EN 50530. This however is officially marked as withdrawn, although the procedure for determining the "European Efficiency" could still be considered technically valid. This would allow a transitional method for calculating a functional parameter in terms of AC power output for a nominal PV array. Regarding the definition of technical lifetime and operational service life the situation is similar to that for PV modules and again a transitional method may be required, also taking into account field data.

1.4.3.3 Product functional unit

In addition, a proposal has been formulated for definition of the primary product performance parameter (functional unit) for inverters. This definition would limit the scope to standalone inverters, so as to ensure comparability at product level.

The definition has been aligned with the IEC 61683 method for calculating the efficiency of a utility interactive inverter. This method is considered the most suitable for making estimates of the efficiency of an inverter in converting DC power to AC power according to a pre-determined annual load profile.

To ensure that performance along the life cycle of an inverter and in a system context is taken into account, the proposal supposes that the performance is modelled for a reference service life and as a component of a system. To be representative the anticipated reliability and associated fault mechanisms for inverters, as well as the ability to carry out repairs in response to failures, would therefore also need to be taken into account.

Proposed inverter functional unit
The functional unit shall be 1 kWh of AC power output from a reference photovoltaic system (incorporating the efficiency of a specific inverter) under predefined climatic and installation conditions as defined for a typical year and for a service life of 10 years.

1.4.4 Photovoltaic systems: recommendations and proposals

1.4.4.1 System definition and scope

As for modules and inverter products, system definitions developed by IEC and IEA, were consulted with the aim to develop a suitable system definition. They all establish several concepts used to make the categorisation. Systems can be categorised according to the following distinguishing features/properties:

- Spatial arrangement: Based on the spatial relationship between the different component arrays (e.g. centralised, distributed).
- Electricity end-use: Based on the primary end use that the electricity generated is earmarked for (e.g. domestic, non-domestic).
- Grid configuration: Based on the type of physical interface with the electricity distribution grid (e.g. grid connected, off-grid, hybrid).
- Electrical configuration: Based on the systems modes of operation (e.g. isolated, utility interactive).

In the same way as for modules and inverter products, stakeholders were consulted in the same questionnaire on an example and possible scope delimitations for photovoltaic systems. The feedback received can be summarized as it follows:

- Market segmentation, i.e. residential, commercial, utility, and system size, should be included in the definition and scope
- The main scope exclusion selected by respondents is 'specific end-uses' of the electricity such as street lighting and urban furniture or consumer electronic products and other gadgets.
- Grid configuration, module array, power conditioning, tracking systems, spatial configuration, roof or ground mounted, and were considered to be of relevance for the definition and scope of PV systems.

In addition, the majority of respondents considered that all systems should be included within the scope. However, to reflect the main scope exclusion proposed by some respondents, and given that most systems are connected to the grid, the scope of the Preparatory study does not include street lighting, urban furniture, consumer electronic products nor standalone systems. These systems are too complex and often tailor made. The savings of introducing a regulation are minimal in comparison with the grid connected systems (including solar home

systems). Moreover, public authorities or consumers are buying these products with solar PV integrated or not, whereas our focus is on the purchase of a solar PV system.

Substations and transformers for power conditioning directly connected to the distribution network, that may be present in utility scale PV plants are neither considered within the scope. Transformers are already in the scope of the Commission Regulation (EU) No 548/2014 on Ecodesign requirements for small, medium and large power transformers.

The first proposal for the product definition and scope of photovoltaic systems is presented below.

Proposed solar photovoltaic system definition and scope

A photovoltaic system is an assembly of components that produce and supply electricity based on photovoltaic conversion of solar energy. It comprises the following sub-systems: module array, switches, controls, meters, power conditioning equipment, PV array support structure, and electricity storage components. It also comprises cabling connecting these components.

Included in the scope of systems are therefore DC optimisers and module integrated inverters falling within category 1 as defined in IEC 62093 ('Module-level power electronics') and specified to operate at a PV module base level interfacing up to four modules.

The provision of energy generated by solar PV systems as a service shall be included within the scope for the purpose of public procurement.

Excluded from the scope are products which are only designed for the following specific applications:

- For use only in street lighting, urban furniture, electric vehicles
- PV integrated consumer and electronic products, i.e. power banks, watches, calculators, etc.
- Systems in which there are modules with DC output power of less than 50 Watts under Standard Tests Conditions (STC)
- Substations and transformers for power conditioning

1.4.4.2 Measurement and test standards

The situation for PV systems reflects a combination of the situation for PV modules and inverters, as well as the system location and design. Aspects of PV system design are the subject of new draft norms, including the full construction cycle and the local environmental conditions, that can have a significant effect on the final energy yield (and therefore also on the material balance).

On-site power measurement and verification standards exist. However, there is no single standard for the calculation of expected energy yield of a PV system. A transitional method would be required here, based either on existing monitoring standards or on the module energy rating standards and integrating a model to include the effects of local environment relative to the specific geophysical position and other derate factors.

1.4.4.3 Proposed functional unit

In addition, a proposal has been formulated for definition of the primary product performance parameter (functional unit) for systems. This definition would limit the scope to grid connected systems.

The 'PV system' encompasses all components required to deliver the functional unit. If it has some storage options (e.g. battery) that if included would extend the boundaries of the system used to supply AC electricity. If a transformer is required, for example on larger utility scale installations, this would be included within this boundary, but may require allocation if only part of its capacity is used.

Proposed system functional unit

The functional unit shall be 1 kWh of AC power output supplied under fixed climatic and installation conditions as defined for a typical year (with reference to IEC 61853 part 4) and for a service life of 30 years.

2 Task 2: Markets for Ecodesign, Energy Labelling and EU Ecolabel

2.1 Generic economic data

As was identified in section 2.1.2.1 of the Task 1, with the exception of gross electricity generation from solar photovoltaics there is no official disaggregated production or trade data in the PRODCOM or EUROPROM databases for solar photovoltaic modules or system components produced for solar photovoltaic end-use applications.

Following a detailed check of the NACE economic activities and Classifications of Products by Activity (CPA) codes of potential relevance, it was identified that the only specific references to solar photovoltaics are made under:

- Section C ('photovoltaic cells'), which refers to the cell component of a module, and
- Section F ('electric solar energy collectors'), which relates to electrical installations.

The related activities for these production codes, together with others that are relevant but do not specifically identify solar photovoltaic products, are presented in Table 31. This can be used to map other sources of data onto existing EU and international classifications. The most directly relevant CPA code is 26.11.40, which includes solar photovoltaic cells and assembled modules within its definition. However, a cross check of this data revealed that it aggregates the import and export value of a range of other semiconductor devices, including Light Emitting Diodes (LEDs).

The same happens for the CPA code related to inverters, 27.11. which comprises the manufacture of electric motors, generators and transformers, being not possible to isolate inverters from the other equipment. The conclusion is that annual shipment data cannot be isolated from the data under this code. In section 3.2 data has therefore been collated from a range of non-official sources and these will later be mapped onto the CPA codes already identified.

Data is not currently collected for the installed capacity of solar photovoltaic systems. Instead the gross supply and consumption of solar photovoltaic electricity is reported in terajoules for each Member State as a dataset provided by Eurostat's SHARES tool[82].

[82] *Eurostat, Energy from renewable sources, http://ec.europa.eu/eurostat/web/energy/data/shares*

Table 31. NACE economic activities and Classifications of Products by Activity (CPA) codes of potential relevance to the product group

Section	Division	Class	Sub-class	Activities (CPA code)
C Manufacturing	26. Manufacture of computer, electronic and optical products	26.1 Manufacture of electronic components and boards	26.11 Manufacture of electronic components	26.11.10 – Manufacture of dice or wafers, semi-conductor, finished or semi-finished
				26.11.22 – Photosensitive semiconductor devices; solar cells, photo-diodes, photo-transistors, etc.
				26.11.40 – Parts of diodes, transistors and similar semiconductor devices, photosensitive semiconductor devices and photovoltaic cells, light-emitting diodes and mounted piezo-electric crystals
	27. Manufacture of electrical equipment	27.1 Manufacture of electric motors, generators, transformers and electricity distribution and control apparatus	27.11 Manufacture of electric motors, generators and transformers	27.11.01/02 – Electrical apparatus for switching or protecting electrical circuits 27.11.04 – Electrical transformers
			27.12 Manufacture of electricity distribution and control apparatus	27.12.04 – Parts of electricity distribution and control apparatus
		27.2 Manufacture of batteries and accumulators	27.20 Manufacture of batteries and accumulators	27.20.10 – the manufacture of non-rechargeable and rechargeable batteries
		27.3 Manufacture of wiring and wiring devices	27.33 Wiring devices	27.33.10 – manufacture of boxes for electrical wiring (e.g. junction, outlet, switch boxes) – manufacture of bus bars, electrical conductors (except switchgear-type)
		27.9 Manufacture of other electrical equipment	27.90 Manufacture of other electrical equipment	27.90.10 – miscellaneous electrical equipment other than motors, generators and transformers, batteries and accumulators, wires and wiring devices, lighting equipment or domestic appliances.

D Electricity, gas, steam and air conditioning	35. Electricity, gas, steam and air conditioning supply	35.1 Electric power generation, transmission and distribution	35.11 Production of electricity	35.11.10 – Electricity (solar photovoltaic)
			35.14 Trade of electricity	35.14.10 – Sale of electricity to the user – Activities of electric power brokers that arrange the sale of electricity via power distribution systems operated by others – Operation of electricity and transmission capacity exchanges for electric power
F Construction	43. Specialist construction activities	43.2 Electrical, plumbing and other construction installation works	43.21 Electrical installation	43.21.10 – Electrical installation works of other electrical equipment, including electric solar energy collectors and baseboard heaters of buildings

2.2 Market and stock data

As reported in Task 1, section 2.1.2, official statistics provided by Eurostat for this product category are too broad since they present aggregated data for semiconductor devices, LEDs apart from PV modules. Therefore, in this section market and stock data have been compiled from market research conducted amosng other sources by GTM Research (inverters) and the Becquerel Institute (modules and systems). The module and system data is in part based on research carried in support of the IEA PVPS programme 83 and the PV Market Alliance[84]. A first section compiles general information of the sector from a report prepared by Ernst and Young for Solar Power Europe[85].

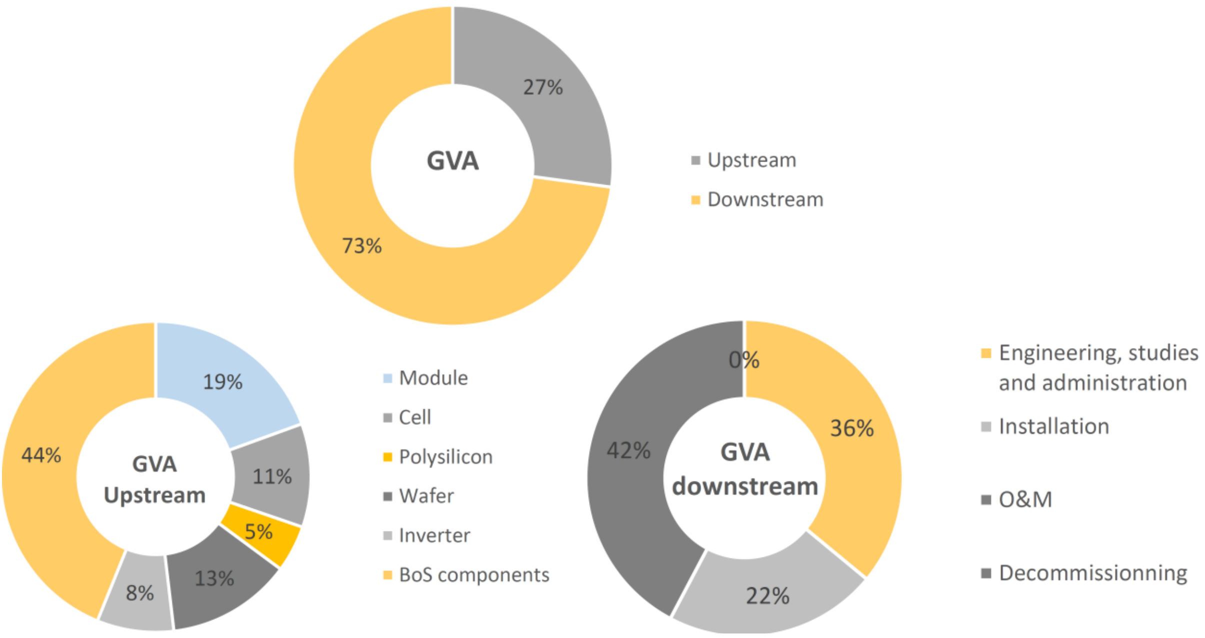
2.2.1 Sectorial figures – gross value added

The value chain for PV systems can be split between upstream and downstream activities.

- Upstream activities are the processing of raw materials: manufacturing of polysilicon, wafers, cells, modules, inverters, mounting and tracking systems and electrical components (Balance of System).
- Downstream activities are services provided within the PV industry such as engineering/studies/administration, installation, operations & maintenance and decommissioning.

The gross value added by the PV industry, considering this split can be seen in Figure 18. The manufacturing of electrical components (Balance of Systems components) created 43% of total upstream jobs and GVA in 2016.

Figure 18. Gross Added Value (GVA) created by the PV industry in 2016, by value chain structure (upstream and downstream)



Source: Solar Power Europe, 2017

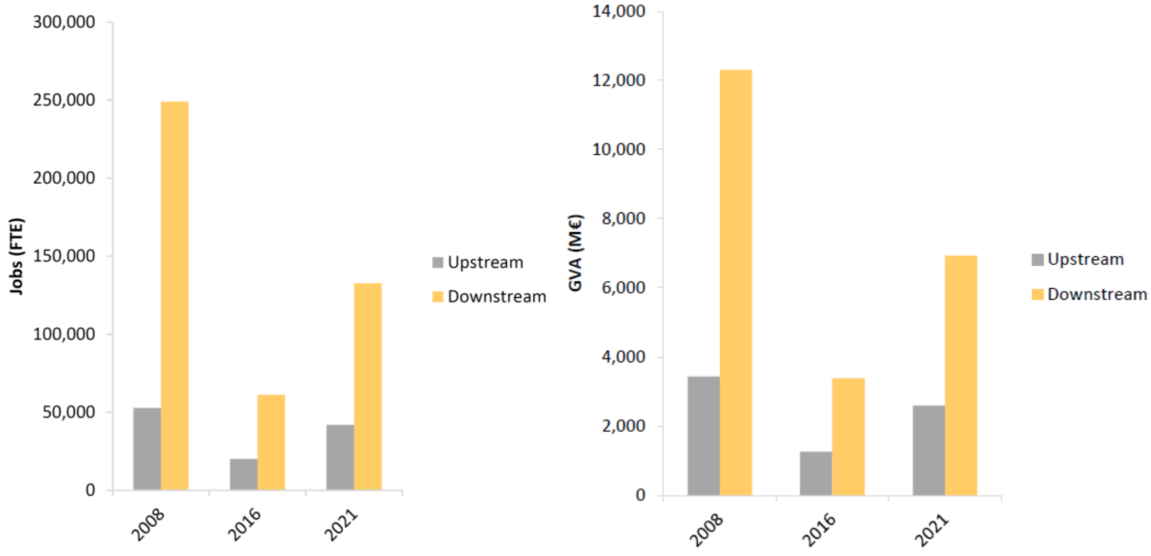
There is a strong correlation between jobs created and GVA in the activities of the value chain. Job support and GVA have decreased since 2008 for both upstream and downstream activities, as demonstrated in Figure 19.

[83] *IEA Photovoltaic Power Systems Programme (PVPS) http://www.iea-pvps.org/*

[84] *The PV Market Alliance, http://www.pvmarketalliance.com/about-us/the-pv-market-alliance/*

[85] *Solar PV Jobs & Value Added in Europe, EY Solar Power Europe, 2017*

Figure 19. Direct and indirect jobs supported (left) and gross value added (right) by the PV industry in 2008-2016-2021, by value chain structure (upstream and downstream)



Source: Solar Power Europe, 2017

When comparing the unit cost (€/W) for PV modules (upstream) and installation (downstream) in 2008 and 2016 for example, the relative reduction for PV modules is almost 3 times more important than that of installation. According to Solar Power Europe report, the increase of job support and GVA between 2016 and 2021 will be mainly driven by the acceleration of new installed capacities in most European countries.

Table 32. Share of jobs support and gross value added per step of the value chain per year for EU28.

		Jobs supported (% total FTE)			GVA (% total M€)		
		2008	2016	2021	2008	2016	2021
Upstream	Polysilicon	3%	1%	1%	4%	1%	1%
	Wafer	1%	3%	2%	2%	4%	2%
	Cells	1%	3%	2%	1%	3%	2%
	Modules	1%	5%	3%	2%	5%	4%
	Inverters	4%	2%	2%	6%	2%	2%
	BoS components	6%	11%	15%	8%	12%	16%
Downstream	Engineering, studies, admin.	53%	23%	31%	54%	26%	32%
	Installation	28%	16%	22%	22%	15%	21%
	O&M	1%	36%	22%	1%	31%	20%

Source: Solar Power Europe, 2017

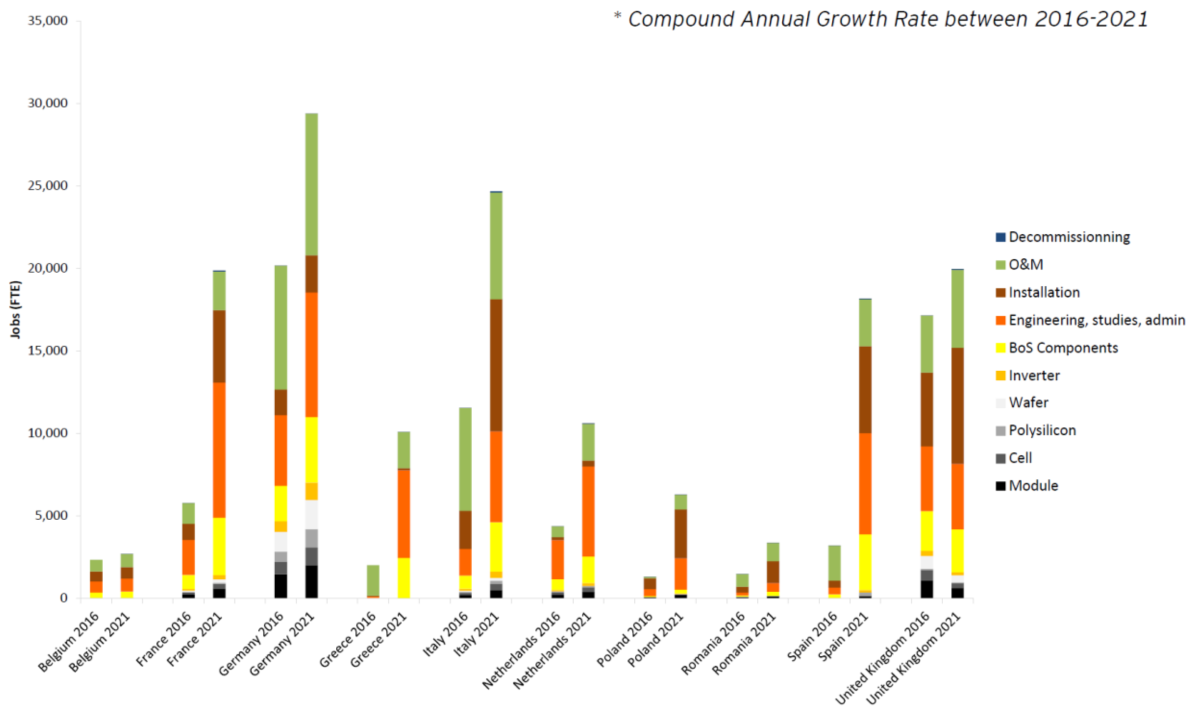
In the upstream segment, the majority of jobs and GVA creation will shift from PV modules and inverters to Balance of Systems (BoS) components over the 2016-2021 period (Table 32).

Job support and GVA per step of the value chain and per country is very heterogeneous, as installed capacity and production intensity differs from one country to the other. Job support and GVA in downstream activities is systematically higher than that of upstream activities.

As Figure 20 reveals, Germany has the highest number of upstream jobs, which is linked to relatively high national shares of production in Europe for upstream activities compared to other countries. This is one of the reasons why Germany has the highest jobs in 2016, although new installed capacity is more important in the UK (second highest level of jobs). Other

countries, such as Belgium, Spain, Greece, Italy, Poland and Romania have low yearly new installed capacities and a low national share of production for upstream activities. This explains the limited number of jobs and GVA in these countries in 2016. Regarding downstream activities and as a consequence of their highest cumulative capacities, a large number of operation and maintenance jobs are supported in Germany and Italy.

Figure 20. Number of direct and indirect job supports in 2016 and 2021, for both market segments (for ground-mounted and rooftop), by step of the value chain.



Source: Solar Power Europe, 2017

As installation and maintenance & operations are easier and less time-consuming for ground-mounted systems, these activities have a lower cost per MW. This means that fewer jobs are supported per MW compared to rooftop PV systems.

2.2.2 Photovoltaic modules

2.2.2.1 Technology segmentation and base assumptions

The shipment and stock data presented is segmented by technology. The main module technologies have been split in six categories, reflecting those with a market share greater than 1%: multi-crystalline, mono-crystalline, amorphous silicon thin films, cadmium telluride films, CIGS films and high efficiency technologies. The technologies have been compared according to their production (shipped capacity). However, reference to the shipment numbers as the basis for stock modelling should be treated with caution for three possible reasons:

1. Double counting of some of the production of OEM companies made without official reporting. This has been discussed many times within the industry but not quantified.
2. Replacements that are made due to failure or performance losses may not be apparent in recycling statistics, either because of recycling by the company itself or because of re-sales to other second hand markets.
3. Inventories awaiting for sales, or installations: the counting of installations based on commission date triggers a data glitch between shipments and installations in case of a growing market from one year to another.

It is therefore generally considered more accurate to base shipment estimates on reported installations. Here it can be assumed that the ratio of technology is similar within shipments as for final installations.

Modules capacity is generally expressed in watts of DC rated output (Wp). Because inverter market data is generally expressed in watts of AC rated output (W_{AC}), this issue will be dealt in the inverters section 3.2.3. to understand how the two may interrelate depending on the marker segment

In terms of the possible lag time between the arrival of modules in shipments and their use in an installation, this is considered to be no more than 3-6 months, depending on the number of intermediaries. For larger systems the modules may be supplied with a month of arrival directly to a site. A potentially more significant factor to take into account is the additional lag time before a system is connected to a network and formally reported on in statistics.

Each technology has a distinct manufactured price, which has often made them usable in some market segments rather than others. In relation to underlying pricing, the following generalized trends can be identified:

- Multi-crystalline is less expensive than mono-crystalline. Until 2015 mono crystalline was dominant at utility-scale but since then prices for mono-crystalline have declined as production has expanded.
- High-efficiency mono-crystalline has been used in all segments even if the residential segment has probably seen a higher penetration of that technology. But their share is difficult to measure over time.
- Cadmium Telluride has been used almost exclusively for utility-scale applications. Their use in other segments was extremely small.
- Copper Indium Gallium Selenide CI(G)S has been used in all segments, even if there is limited data to translate their application into a segmentation. This report considers to use an indicative share between segments.
- The share of amorphous silicon technology for residential applications has been very low due to space constraints.
- High efficiency technologies are defined as those achieving efficiencies indicatively greater than 22% with present technology, which may include modules based on heterojunction, back contact and bifacial cell structures.

Hence, it is not possible to estimate the monetary value of shipments, due to the lack of the official shipments data that is differentiated by module technology and pricing.

In terms of projected capacity this will be dealt with in the systems section 3.2.4. The base assumption is that modules will have a technical lifetime of 25 years, in line with the typical product performance warranty period provided by manufacturers (see section 3.3.2.3). However, further assumptions must also be made about the financial time horizon of a project and the buildings and land onto which a system has been installed in order to model lifetime. These assumptions are further discussed in section 3.2.3.

2.2.2.2 Stock data and forecasts

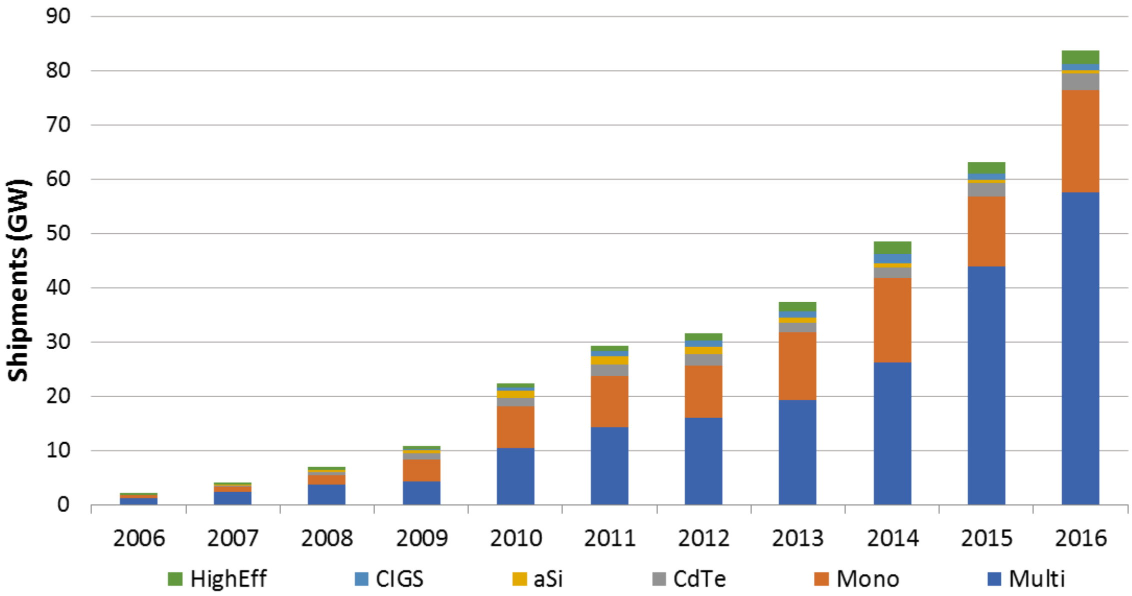
The global shipment figures for PV modules are shown in Figure 21 with a division per technology, i.e. multicrystalline Si (Multi), monocrystalline Si (Mono), cadmium telluride (CdTe), amorphous Si (aSi), CIGS and high efficiency modules[86] (HighEff). Concentration and Ribbon PV modules figures were found to be negligible. Cadmium telluride is the technology which has experienced the largest growth in the decade 2007-2016, followed by Multicrystalline and Mono silicon, and CIGS (around 500% each).

The total cumulative power of PV modules imported into Europe was approximately 87 GW up until the reference year, 2016. Adding the local production (23.92 GW) and subtracting the exports (9.43 GW)[87], we can have the installed base 101.86 GW for year 2016 that constitutes the stock. This figure represents one third of the cumulative global shipments up until the reference year (340 GW).

[86] *Monosilicon with the addition of PERC technologies*

[87] *According to Becquerel Institute, 2018*

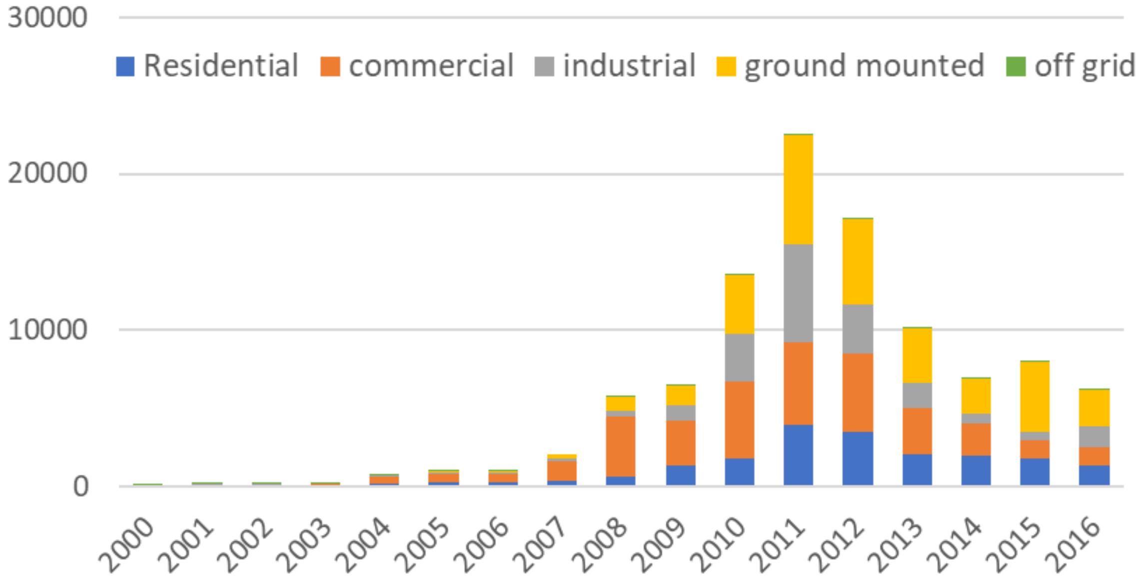
Figure 21. Cumulative global shipments of PV modules to the EU per technology. CPV and Ribbon PV data are negligible.



Source: Becquerel Institute, 2018

The evolution of the stock in Europe has seen years where the capacity installed was doubled (Figure 22), having received the momentum of feed in tariffs in the pioneer countries (e.g. Germany, Netherlands, see Task 1). From 2012 a decline was seen as a combination of factors: a retreat from the feed in tariffs that had driven the market and the impact of the economic crisis on properties and investments.

Figure 22. Evolution of the European PV stock showing the market segments, residential, commercial, industrial, ground-mounted and off-grid.



Source: Becquerel Institute, 2018

The PV technologies used in 2016 per market segment, i.e. residential, commercial, industrial, utility-scale and off-grid, are shown in Table 33. It is worth noting that there are technologies such as CdTe, aSI and CIGS that are less frequently used in sectors such as residential, commercial or even off-grid. These sectors are predominantly using multi or monocrystalline

silicon technologies. The figure reported below for CdTe technology may be an underestimate based on the installed inventory of the leading manufacturer, suggesting that the cumulative power of installations may be in the range of 4.5-6 GWp.

Table 33. Cumulative power of installations per market segment and technology at the end of 2016 (GWp).

	Multi	**Mono**	**CdTe**	**aSi**	**CIGS**	**HighEff**	**Total**
Residential	11.38	6.55	0.00	0.00	0.54	1.01	19.48
Commercial	17.73	10.53	0.00	1.58	0.76	1.88	32.48
Industrial	9.95	6.18	0.00	0.92	0.50	0.83	18.38
Utility-scale	16.88	9.36	1.84	1.20	0.79	1.32	31.39
Off-grid	0.08	0.05	0.00	0.00	0.00	0.01	0.14
Total	56.02	32.67	1.84	3.69	2.59	5.04	101.86

Source: Becquerel Institute, 2018

The annual sales growth for the different market segments is reflected in systems section, 3.2.3.

The module prices are further analysed in Consumer expenditure section 3.4.

2.2.3 Inverters for photovoltaic applications

2.2.3.1 Technology segmentation and base assumptions

The main inverter technologies reported on in market data can be related to the categories for Power Conversion Equipment (PCE) identified from IEC standard 62093 in the Task 1 report, but with some modifications noted as follows:

- Category 1: Module-level power electronics (MLPE) – specified to operate at a PV module base level.
  - In general reference is made to inverters that interface with one module rather than up to four as described in the standard.
- Category 2: String-level power electronics – designed to interface multiple series or parallel connected modules and specified for wall, ceiling or rack mounting.
- Distinction is made between single and three phase AC power delivered by a string inverter.
- Category 3: Large-scale power electronics – also designed to interface multiple series or parallel connected modules, but due to their complexity, size and weight are housed in a free standing electrical enclosure.
  - Distinction is made between those delivered as a standalone unit or packaged as a complete 'solution' with other power conditioning equipment such as transformers.

In addition to the definition of the technologies, a number of additional factors are important to take into account when interpreting inverter market data:

- Inverter capacity is generally expressed in watts of AC rated output (W_{AC}). Because inverter market data is generally estimated from module DC capacity it is important to understand how the two may interrelate depending on the marker segment:
  - in the residential segment for any given system the two tend to be closely related, although a ratio of up to 1.15 could be used.
  - In the industrial segment the inverter AC capacity may be less than the module DC power, with an indicative ratio of up to 1.22.
  - In the utility scale segment the inverter AC capacity will tend to be significantly less than the module DC power, with an indicative range for the ratio being 1.2 – 1.4.
- The presence of inverter distributors in the EU means that the final destination for a proportion of shipments will be off-grid markets in Africa.

In terms of relating the stock data to photovoltaic system market segments the following broad assumptions can be made:

- Micro-inverters attached to the module itself are less common but have experienced some market development in the last years. These are almost exclusively used in the residential market.
- Smaller installations of less than 1 MW have been using string inverters which collect electricity from a set of strings.
- In the last years, the cost decrease and capacity increase of string inverters (now up to 125 kW) has allowed to them to now be used in utility-scale plants instead of central inverters.
- Most utility-scale PV plants are using central inverters which collect the electricity from several PV module arrays through combiner boxes.

In order to ascertain the installed stock for any given year the data for installed systems must be used as the shipment data is an overestimate and does not account for the lag time to market and the redistribution of products to other markets (as noted in section 2.2.2.1).

In terms of projections for the evolution of the stock the following base assumptions and sources are proposed to be used:

- New capacity: newly installed module array capacity should be used as the reference point for estimation, as data is not collected for inverter installation. Forecasts for module array installed capacity are presented in section 2.2.3.
- Technical and economic product life: The very limited number of independent reviews of inverter failure rates suggest a 1%-15% annual failure rate. Peak failure rates have been estimated to occur in the first three years of product life, with average rates of between 3% and 4% quoted per annum. According to an IEA Task 13 report on the financing of PV systems the technical life of an inverter is considered to be between 10-15 years. For the purpose of this study a minimum technical lifetime of 10 years is assumed for an inverter. There is some emerging evidence from the Solar Bankability project that longer technical lifetimes of up to 13 years are now being used by investors in their financial planning for commercial PV systems. This is based on assumptions for PV systems up to 100 kW of a 15.5% replacement rate on average by year 10 and a 17% replacement rate on average by year 13.
- Replacement rates and time cycles: The typical failure modes for an inverter are assumed to trigger replacement. A minimum technical lifetime of 10 years is therefore assumed to also correspond to the minimum service lifetime, although it is to be discussed if this should be extended to reflect assumptions currently used by investors in larger scale systems.

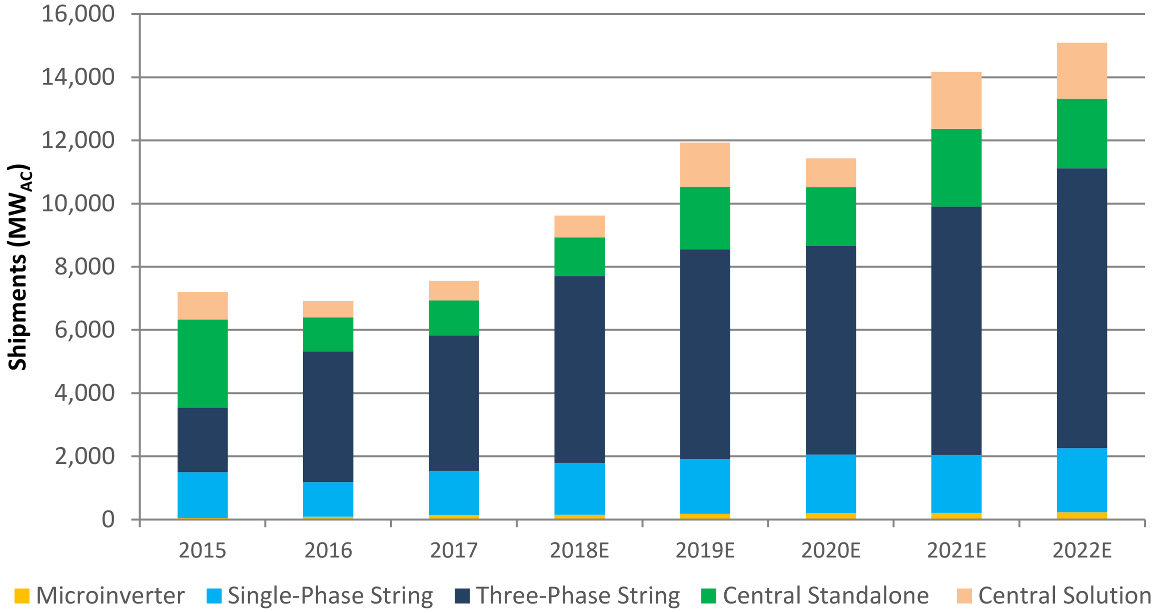
2.2.3.2 Stock data and forecasts

Figure 23 presents the shipment data for inverters for the reference year 2016 and 2015. The shipment data is compiled from periodic surveys of manufacturers. In total 6,854 MW_{AC} of inverter capacity was shipped to the EU market in 2016. It can be seen that overall the EU market is dominated by three phase string inverter technology.

Estimates are then presented for 2017 through to 2022. These estimates are based on assumptions made about market trends and are cross-checked by manufacturers for their credibility before publication as a market intelligence source. Annual growth rates have been derived from this data and are presented in *Table 34*.

The total for new installed module array capacity was in the range of 6,216 to 6,734 MW_{DC} in the reference year 2016. With an adjustment for the undersizing of inverter AC capacity in proportion to module DC capacity on larger systems, the installed new stock in 2016 is estimated to be in the range of 5,678 and 6,151 MW_{AC}. Using similar assumptions the total installed stock until the end of 2016 is estimated to be in the range of 94,400 and 96,913 MW_{AC}.

Figure 23 EU inverter shipments by technology (MWac) E=Estimate



Source: GTM Research (2017)

Table 34 Projected annual sales growth rates for inverters

Inverter type	**2016**	**2017E**	**2018E**	**2019E**	**2020E**	**2021E**	**2022E**
Microinverter	81%	58%	11%	17%	13%	6%	10%
Single-Phase String	-24%	28%	17%	6%	7%	-1%	10%
Three-Phase String	103%	4%	38%	12%	-1%	19%	13%
Central Standalone	-62%	4%	10%	61%	-6%	32%	-10%
Central Solution	-41%	21%	11%	103%	-35%	97%	-2%
Total	*-4%*	*9%*	*27%*	*24%*	*-4%*	*24%*	*7%*

Source: calculated from data provided by GTM Research (2017)

2.2.4 Photovoltaic systems

2.2.4.1 Technology segmentation and base assumptions

Segmentation of systems depends on several parameters and, as was discussed in the Task 1 report, the definition can vary between Member States based on system size, the end-user and/or the type of site. In a post-feed-in tariff market there are some examples of segmentation based on the type of grid connection and interaction with the electricity market. Nevertheless, installed capacity thresholds have in the last ten years of PV market development segments been used as the basis for reporting by the IEA PVPS programme. In relation to this, the following segmentation has been followed, and is reflected in IEA PVPS national survey reports:

- Residential: systems up to 10 kW
- Commercial: from 10 to 250 KW
- Industrial: Systems above 250 kW, either on a building or used for self-consumption
- Utility-scale: systems above 1 MW, ground-mounted

In referring to these segments, it should be recognized that there can be overlaps between them. For example, the notion of a commercial building differs from country to country. Large industrial buildings can host larger PV plants than the smallest ground-mounted PV installations.

In order to estimate the segmentation in as accurately as possible, 90% of the installed capacity in Europe during one year is considered. The segmentation is then analysed at Member State level based on national reporting, and then from this an estimate for the EU is derived. In addition the overall dataset has also been cross-referenced with a dataset published by Solar Power Europe.

In terms of projections for the evolution of the installed system stock the following base assumptions are proposed to be used:

- Residential PV systems won't be decommissioned unless the roof requires replacing. While loss of performance will happen through for example degradation mechanisms, it is not a reason to consider decommissioning. It is assumed that the system lifetime will correspond to that of the modules, which could be higher than 20, 25, perhaps 30 years. Most probably some house owners will decide to replace their system with new panels but the probability of this occurring cannot easily be estimated. It is therefore assumed here that the systems as a whole will be decommissioned on average after 25 years.
- Commercial and industrial systems may be constrained by other factors such as the lifespan of the building itself on the site. However, assumptions that can be made from a PV system perspective are not readily available. A 25 year lifetime shall be taken as an initial assumption, but this will reviewed against EU data for typical building lifespans. For example, industrial buildings may have a shorter service life than that of the PV system.
- Utility-scale systems have mostly been developed based on 13 to 25 years incentives. It can reasonably be considered that they will be either decommissioned or repowered after 20 years on average. It could be possible to refine this assumption by looking at the amount of PV systems financed in each country under specific incentive schemes.
- Off-grid systems follow the same pattern as residential systems in terms of lifetime and decommissioning. They are out of the proposed scope, although data are presented in the tables below for completeness

2.2.4.2 Stock data and forecasts

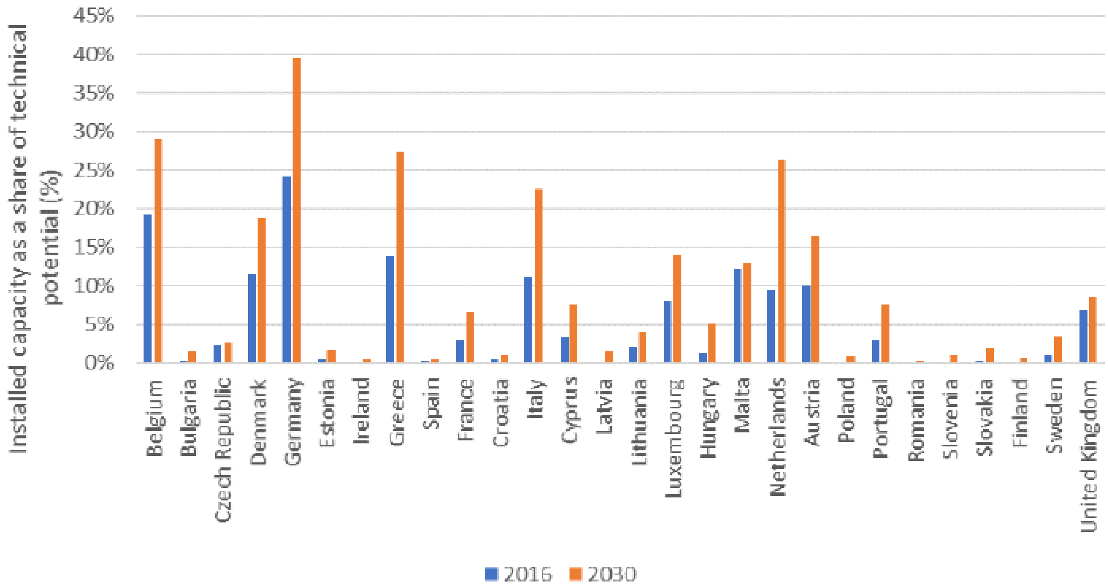
Table 35 presents the evolution until the reference year 2016 of annual system installations in the EU. The data is segmented according to the five main system types and has been extrapolated from a detailed composition of 90% of the market to 100% of the market. The total installed system stock in 2016 is estimated to be 101,788 MW_{DC}. The majority of this stock was accounted for by commercial (32%) and ground mounted (31%) systems. Residential and industrial systems accounted for 19% and 18% respectively.

The annual sales growth of the PV systems per segment is shown in Table 36. The ground mounted (which can be mainly considered as utility scale) which has experienced the largest growth in the years 2001-2016, followed by the industrial and commercial sectors where there were years especially between 2008 and 2011 that the growth doubled (over 100% each year). The total compound growth rate for the period 2001-2016 is close to 1000%.

Table 35 Year on year EU installed system capacity by PV system market segment (MW_{DC})

	Residential	**Commercial**	**Industrial**	**Ground mounted**	**Off grid**
2000	43.17	18.23	3.73	0.00	15.40
2001	86.80	37.98	6.94	0.00	2.25
2002	80.72	43.30	8.42	0.00	4.53
2003	104.07	85.44	5.75	0.00	3.92
2004	152.61	470.02	58.34	44.99	3.27
2005	234.32	591.54	90.18	65.04	3.16
2006	261.95	579.01	86.37	66.44	3.11
2007	319.72	1316.30	151.03	243.47	0.00
2008	588.01	3884.60	332.97	931.81	5.52
2009	1352.28	2811.19	1036.91	1232.19	5.40
2010	1746.36	4929.61	3102.10	3766.29	6.84
2011	3954.43	5246.40	6269.12	6966.72	2.82
2012	3474.66	5051.45	3135.12	5410.80	1.45
2013	2099.02	2872.98	1610.58	3490.25	98.58
2014	1934.51	2090.14	607.60	2242.69	1.18
2015	1779.15	1203.04	468.85	4535.95	0.46
2016	1339.44	1190.44	1350.36	2333.55	2.61
Total installed stock	*19551,21*	*32421,66*	*18324,36*	*31330,20*	*160,49*

Figure 24. Installed capacity as a share of technical potential in 2016 and 2030



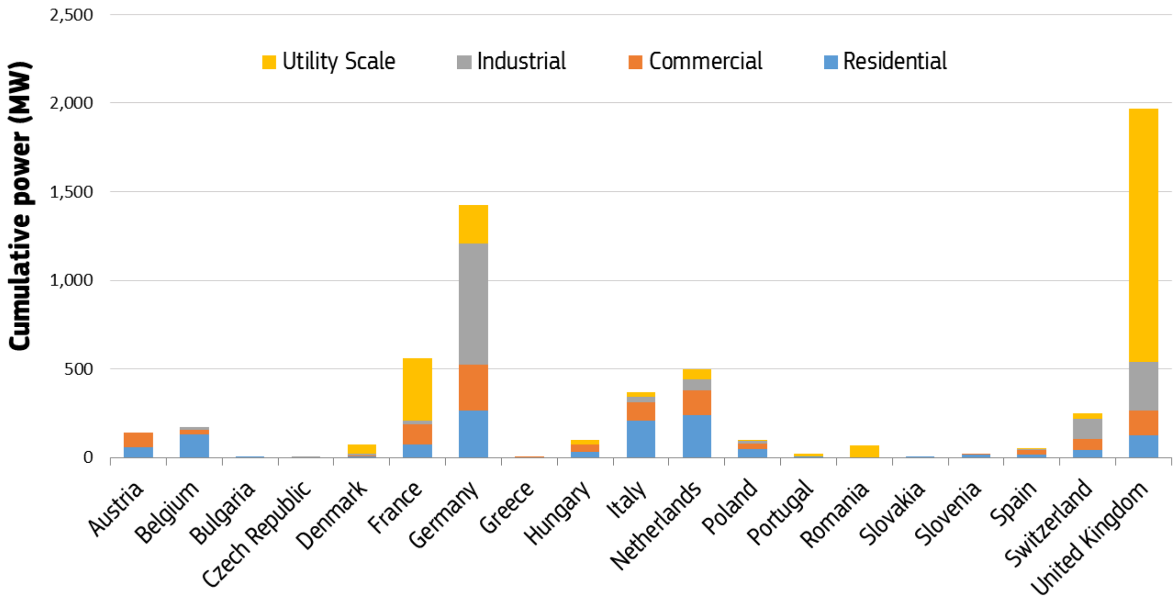
Source: GfK (2017)

Table 36. Annual sales growth of PV modules per segment in percentage. Derived from the data in Figure 22.

Year	Residential	Commercial	Industrial	Ground mounted	Off-grid	Total
2001	201%	208%	186%	-	15%	166%
2002	62%	77%	79%	-	26%	64%
2003	49%	86%	30%	-	18%	57%
2004	48%	254%	235%	-	13%	132%
2005	50%	90%	108%	145%	11%	77%
2006	37%	46%	50%	60%	10%	44%
2007	33%	72%	58%	138%	0%	62%
2008	46%	124%	81%	222%	15%	109%
2009	72%	40%	139%	91%	13%	58%
2010	54%	50%	174%	146%	15%	78%
2011	80%	36%	128%	110%	5%	72%
2012	39%	25%	28%	41%	3%	32%
2013	17%	11%	11%	19%	171%	14%
2014	13%	7%	4%	10%	1%	9%
2015	11%	4%	3%	19%	0%	9%
2016	7%	4%	8%	8%	2%	7%

Figure 25 takes the reference year of 2016 and presents the installed capacity per Member State and by market segment. The country with the largest capacity installed was United Kingdom, accounting for almost 2 GW_{DC} of capacity. Germany follows UK with 1,42 GW and in a third but further place lies France, with 559 MW. With the decline of feed-in subsidy for residential systems the installation figures are dominated by larger industrial and utility scale systems.

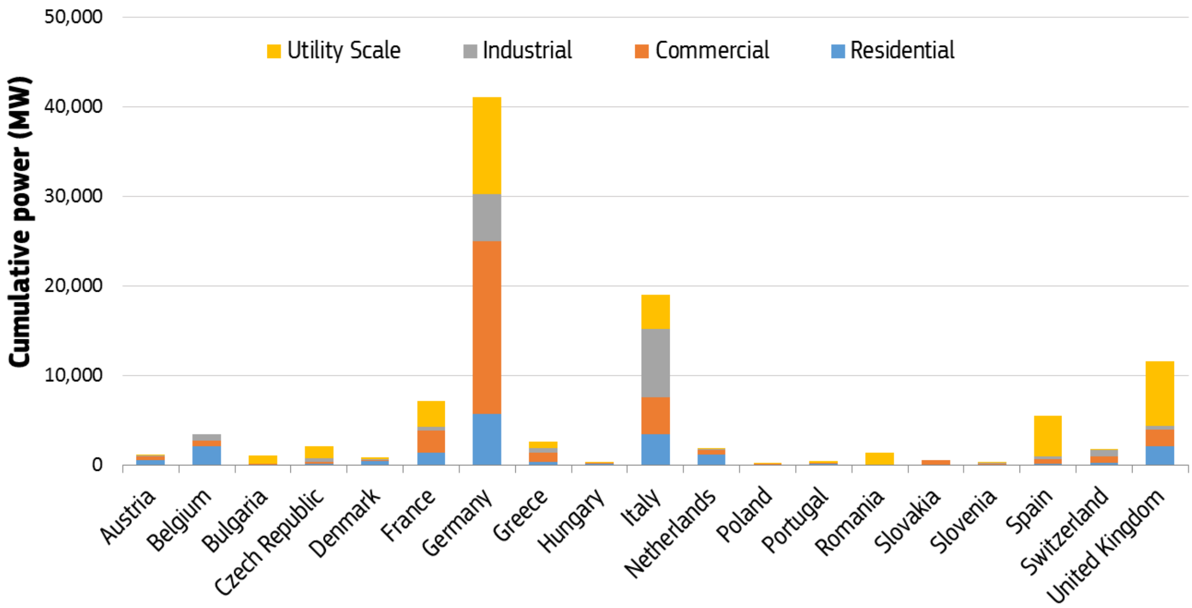
Figure 25. Capacity installed in most European countries in 2016 in MW_{DC}.



Source: Solar Power Europe, 2017.

Looking in turn at the cumulative power in Figure 26, it can be seen that Germany stands out among the other EU countries with 41.1 GW installed up to 2016. The second country is Italy with 18.98 GW historical data.

Figure 26. Cumulative Capacity installed in most European countries up to 2016 in MW_{DC}.



Source: Solar Power Europe, 2017.

Forecasts for the future PV system installations are fundamental in order to also develop stock models for modules and inverters, but a broad range of assumptions must be made and adjusted depending on the time horizon. The following assumptions for short, medium and long-term forecasts are presented as the starting point for discussion:

- *Short term (until 2020).* Short term forecasts are based on bottom-up market analysis, including Member State policies supporting PV and the general trends in PV development. Such forecasts are in general valid for 2 or 3

years. Here the data published by the PV Market Alliance has been used. The relative stability of European policies for PV in the last two years indicate that until 2020, little changes can be expected. Starting from 107 GW in 2017, the installed capacity in 2020 could reach up to 137,5 GW according to the reference scenario and up to 146 GW according to the PV Market Alliance high scenario.

- *Medium term (2020-2030),* the situation is more complex since many countries have only defined policies to reach 2020 decarbonisation and RES targets. For the period until 2025, a mix has been used of the PV Market Alliance scenarios until 2022 and the European Reference scenario afterwards. It is notable that the numbers are quite low and show a significant market decline. The forecast is heavily dependent on EU policy. Development of the policy assumptions is explained further in the box below.

PV system forecasts to 2030

Modelling the influence of EU renewable energy targets

Major factors influencing that post 2020 situation relate to the political willingness in Europe to fulfill climate change commitments and the expected PV market developments due to price competitiveness (parity) in most European countries.

The decision to opt for a 35% RES target (or 63% RES-E target) could change the investment climate and lead to additional PV installations. In general it is estimated that the development of the PV market will continue, driven by the declining prices of PV systems, and its emerging competitiveness with wholesale market prices in several key countries.

This derives into two scenarios until 2025 and 2030. To assess the possible contribution of PV to these of a 35% RES, the number of RES-E TWh in 2030 is considered under such scenario (3528 TWh of electricity x 63% = 2223 TWh. Since 1210 TWh of RES-E could have been installed by 2020, the difference to be covered is 1013 TWh. Two main assumptions are then made:

- PV could provide one third of this difference, because according to scenarios published by EPIA (now SPE) in 2012-2013 the ratio between wind and PV could be 2:1.
- Most other renewables won't grow fast until 2030 given the competitiveness of wind and solar in the electricity sector.

This would translate into 334 additional TWh of PV electricity by 2030. These 334 TWh could translate into 281 GW (assuming 1200 kWh/kWp per year in average in Europe at that time). Since the starting point could be 146 GW in 2020, PV could increase up to 427 GW in 2030.

- *Long-term (2030-2050)*, the main driver is likely to be decarbonisation of the energy mix in Europe under the reference scenario and a more ambitious one that is provided. The same methodology could be applied as for the RES as described for 2020-30. To reach 95% of decarbonisation in the electricity sector by 2050, based on the reference scenario, the additional amount of RES-E electricity compared to 2030 is calculated based on an assumed consumption of 4064 TWh in 2050. The reference scenario estimates nuclear production to 737 TWh in 2050, which leaves 3124 TWh to be produced with RES-E electricity. Or compared to 2030, an additional 900 TWh. This would translate into 300 TWh of additional PV, or using the same ratios, 250 Additional GW of PV or in total 678 GW by 2050.

The technical lifetime for the module component of a system is expected to differ more and more from the economic lifetime. PV modules conceived decades ago without cost limitations showed that, apart from the degradation of performance due to aging semiconductors, they could often last much more than 20 years. Since then the onset of mass production has raised concerns about manufactured quality and the lifespan of newer designs and bills of materials.

Once the current quality issues that are mentioned in several studies (IEA PVPS task 13 for instance) and which are currently the subject of intense interest within the industry are solved, PV modules should be capable of providing electricity more than 20 years. However, the economic lifetime depends on business choices and it is considered that 20-25 years will become a corresponding intended service lifetime for most PV plants (see the discussion in section 2.2.3.1 above).

2.3 Market trends

In this section the market channels and production structure are described in order to prepare the ground for the improvement potential to be analysed in Task 6. Firstly, meta trends for the development of solar photovoltaic sector are identified. Secondly, product level trends related to modules, inverters and systems are identified and then analysed. The following aspects are addressed in turn as part of the market analysis:

- Channels to market: direct to end-users, wholesalers & distributors, OEMs, own use, system integrator, etc., and its relation to placing on the Community market. B2B (business to business) versus B2C (business to consumer), distribution channels (retail versus wholesale), role of installation services;
- General trends in product design and product features; feedback from consumer associations
- Competitive analysis of the market: major players, main models, new players and new models, maturity of the market;
- Usual market segmentations: market shares of the major players and main models,
- Public procurement: tenders and auctions at member state level

The share of SMEs in the production and the segments of the markets in which SMEs are present are also addressed under these headings.

2.3.1 Meta trends – EU and Global solar photovoltaic market

In order to develop a global view of the major market trends that may affect the evolution of the market in the short to medium term (to 2020 or 2030), sets of major global trends identified by market analysts have been analysed. The trends identified have each been evaluated qualitatively in order to identify:

- the possible technological and market implications,
- the likely time horizon for their mainstream adoption, and
- the related degree of certainty.

The main sources of the trends synthesised are the IEA PVPS programme, Solar Power Europe, the PV Market Alliance and GTM Research. The results are presented in tabular form in Table 37. In summary the main trends identified can be categorised as relating to:

- the structure of global module production and supply,
- the type of the financial incentives and market arrangements that will be used by Member States to support further market growth,
- the relationship of utilities with their consumers and their extent of their role in providing solar PV systems,
- the extent to which self-consumption models will shape system designs in the future,
- a diversification in the range of digital and operational support services available to system owners, and the benefits these can bring.

Table 37. Identification and evaluation of global market trends

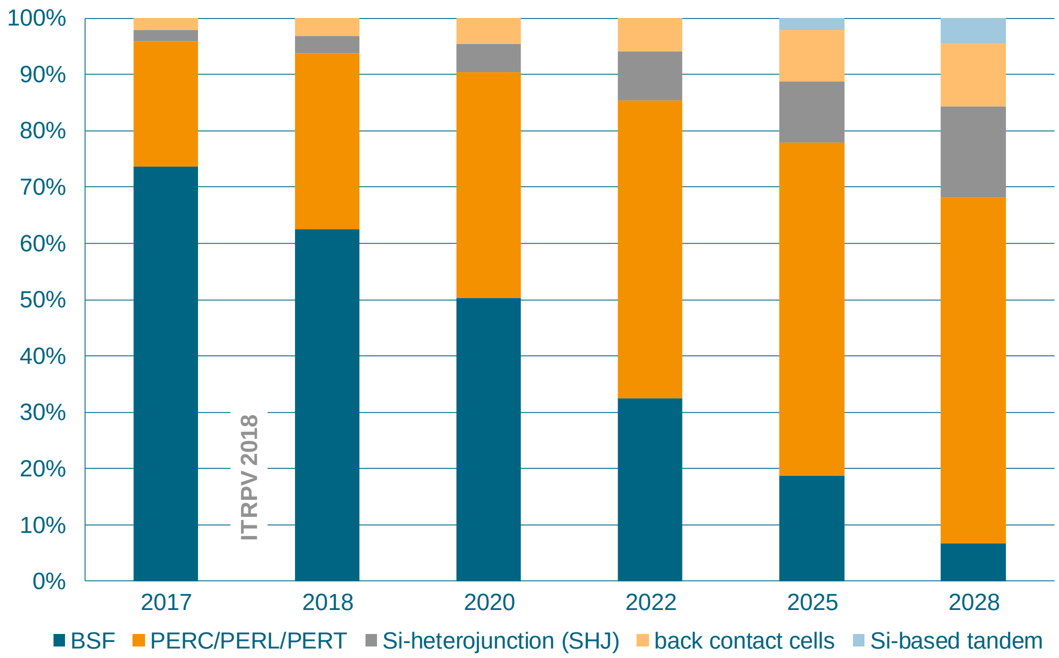
Trend	**Description**	**Potential technology and market implications**	**Time horizon**	**Degree of uncertainty**	**Source(s)**
Continued overcapacity in global module production	The ratio between supply and demand for modules will continue to pass through periods during which there is excess capacity and oversupply, forcing module prices to be driven down further.	○ Further rationalisation of the leading manufacturers who will in turn lead on the mainstreaming of new module technologies.	Short term	Medium	IEA PVPS (2017) GTM (2018)
Phasing out of financial support schemes	A reduction or complete phase-out of financial support schemes and their replacement by self-consumption policies or competitive tendering or auction processes. Self-consumption is still incentivized through net-metering within existing financial incentive schemes.	○ Larger projects with greater cost reduction potential will be incentivised. ○ More efficient module technologies will receive greater attention.	Medium term	Low	PV Market Alliance (2018)
Increased use of solar auctions to drive down prices	EU state aid rules have driven an increase in the use of competitive auctions and tenders for electricity price subsidy contracts in order to support deployment.	○ Ensures that solar PV is supported on a continuous basis rather than leaving the market open to bid with the cheapest technologies. ○ Contracts will be indexed to changes in market electricity prices. ○ Auctions have been introduced at the larger end of the market. ○ Reverse auctions by municipalities on behalf of citizens may become more common.	Medium term	Low	Solar Power Europe (2017) PV Market Alliance (2018) GTM (2018)
An increase in Corporate Power Purchase Agreements for solar energy	Public and private entities wishing to purchase renewable electricity are increasing seeking the 'additionality' of on or near site installations.	○ Installations may be driven by municipalities and a range of manufacturing and service companies. ○ A diversity of sites and project sizes may be brought forward.	Medium term	Low	Solar Power Europe (2017)
An increased focus on operation & maintenance services	A shift from feed-in tariffs to grid parity is driving a focus on maximising the output from systems over the long-term in order to repay higher financing costs and maintain asset value.	○ Service companies will offer a range of on-site services, which could include repair and replacement. ○ Data analytics will be a key component required to support real-time monitoring.	Medium term	Medium	Solar Power Europe (2017)
An increase in the number of utilities that provide solar PV services	An increase in the number of utilities that, in response to competition for residential energy services, seek to provide solar PV services to households and businesses.	○ A range of business models could emerge ranging from third party ownership to off site PV generation projects.	Medium term	High	PV Market Alliance (2018)
An increase in self-consumption by system owners	An increase in the number of consumers that seek to maximise self-consumption of the electricity generated by their photovoltaic systems, stimulated by reduced availability of subsidy.	○ The complexity of schemes together with distribution company charges may limit their take-up. ○ Self-consumption will drive further market penetration of battery storage as an integrated component of solar PV systems. ○ Integrated BoS packages incorporating batteries will become more commonly offered to customers at a range of scales. ○ Batteries are not yet considered to have the same level of reliability as modules and inverters, which may lead to market differentiation. ○ 'Virtual net-metering' at grid level will increasingly be offered by utilities in competition with battery consumption. ○ Collective self-consumption from PV systems installed across several buildings or a community will attract more interest/support. ○ PV plug in modules coupled with microinverters as a root to cheaper and easier installation in apartment blocks.	Medium term	Medium to high	Solar Power Europe (2017) PV Market Alliance (2018) IEA PVPS (2018)
Digitalisation of PV systems and components	An increase in the devices integrated into a system design that support capture and analysis of data for a range of purposes, including fault diagnosis and demand side management.	○ Increased digital and smart integration in the offer for home systems. ○ Increased pooling of data from systems in order to identify common faults and to provide economies of scale for O&M services.	Medium term	Low	Solar Power Europe (2017)

2.3.2 Product trends – PV modules

2.3.2.1 Market segmentation

Figure 27 illustrates the global market share for the predominant crystalline silicon cell types for the reference year 2016 and as projected to 2027. It can be seen that the PERC family of cell types has quickly entered the market, achieving already a significant market share, and is projected to account for the largest market share by 2021.

Figure 27. Worldwide market share for different silicon based cell technologies



Source: ITRPV (2018)

At a global level the market is increasingly being driven not only by the shipped price but also the module efficiency, which in turn influences the Levelised Cost of Electricity (LCOE) that can be achieved. In this respect the most significant innovations that have been introduced into the global market in the period 2014-2016 are modules based on:

- Back Surface Field (BSF) cells,
- Passivated Emitter and Rear Cell (PERC),
- Back contact cell types,
- Heterojunction cell types,

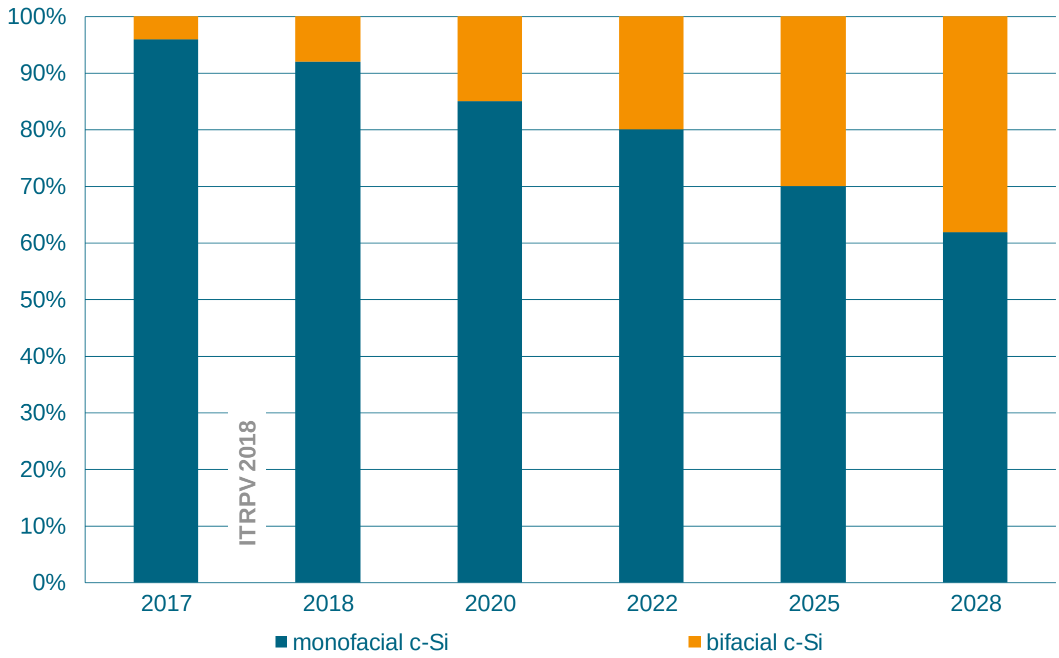
These innovations at cell level have also been accompanied by a shift from cast p-type polycrystalline silicon to grown n-type monocrystalline silicon wafer substrates.

Bifacial cell types are projected in Figure 28 to grow steadily, and to reach approximately 20% market share by 2021, driven largely by large rooftop and utility scale system installations. The ITRPV projection reflects the views of commentators that once PERC cell structures have become the mainstream industry standard then bifacial modules will quickly follow within as short as a 12-18 month period [88].

The market for Building Integrated PV is expected to continue to retain a niche in the market, accounting for an estimated 2% of the PV market as a whole. In 2015 Europe was estimated to account for approximately 42% of the installed global capacity, which translates into 967 MW or approximately 11.4% of EU installed capacity. France and Italy can be seen to have led the development of this market segment. Cumulative installations to 2016 and projections to 2020 are presented in *Figure 29*.

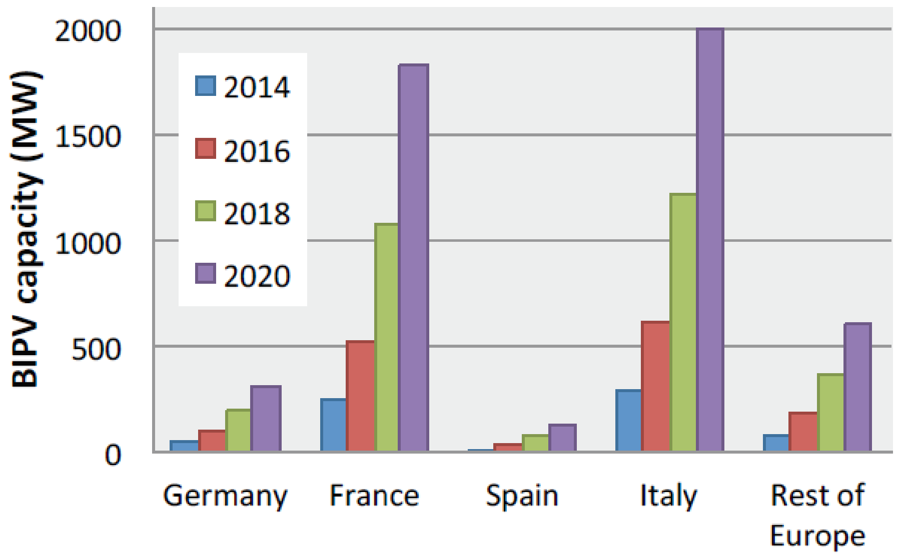
[88] *PV Tech, Mono based PERC modules to drive bifacial market entry in 2018,*

Figure 28. Worldwide market share for 'true' bifacial modules



Source: ITRPV (2018)

Figure 29. European recent past, current and future (2014-2020) analyses of BIPV market for Germany, France, Spain, Italy and the rest of Europe. Source: Global Industry Analysts (2015)

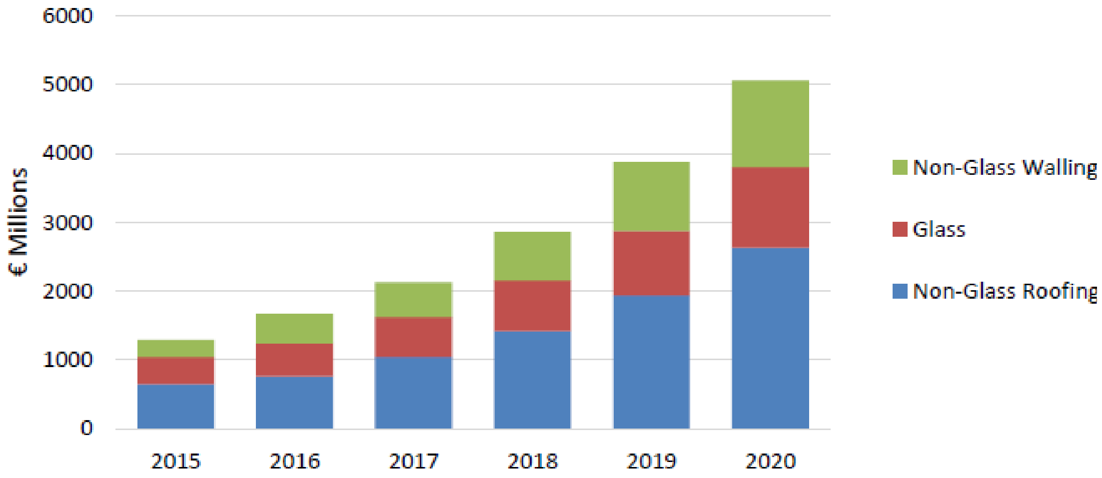


It has been claimed based on market analysis that two thirds of BIPV applications are to be found on new buildings. Moreover, In terms of the types of buildings the market split is been estimated to be as follows - residential buildings (19%), public infrastructure (14 %), showroom offices (13%), universities and schools (9%) and historical buildings (7%).

Studies have differed in which product applications are most significant in the market. The PV Sites project identified three main product applications have been identified – roofing, walling and glazing products (PV Sites 2016). Non-glass based roofing products can be seen in their market analysis in Figure 30 to account for the majority of the market value. Meanwhile

a separate study of the EU BIPV market carried out in 2015 identified that the majority of BIPV applications were façades (over half), followed by roofs (one third), and combined roof/façade products.

Figure 30 European BIPV market forecast 2015-2020 in € millions



Source: PV Sites project (2016)

2.3.2.2 Trends in product design and features

2.3.2.2.1 Crystalline silicon cell-based modules

The principal trends apparent to purchasers of crystalline silicon cell-based modules relate to the cell structure, with a number of new cell types, dimensions and bus bar arrangements having rapidly gained global market share. These improvements have in turn been reflected in higher stabilised efficiency values for the cells used to manufacture module and, for modules products as a whole, improved Cell to Module (CTM) power ratios.

It can be seen in Figure 31 that p-type polycrystalline cell types achieved an upper limit to efficiency levels of approximately 21% in 2016, projected to rise to 23% by 2027 (represented by PERC/PERT cell types) whereas n-type monocrystalline cell types supported efficiency levels in the range of 21% to 23% in 2016, projected to rise to 24 -26% by 2027 (represented by heterojunction and back contact cell types).

In terms of cell technology trends, other than those that related to the PERC family, the following can be identified:

- *Back contact cell types* without visible front busbars have also been available for some time in the market as a niche product that provides both improved efficiency and distinct aesthetics. The market share cell type is projected to continue to grow steadily after 2017.

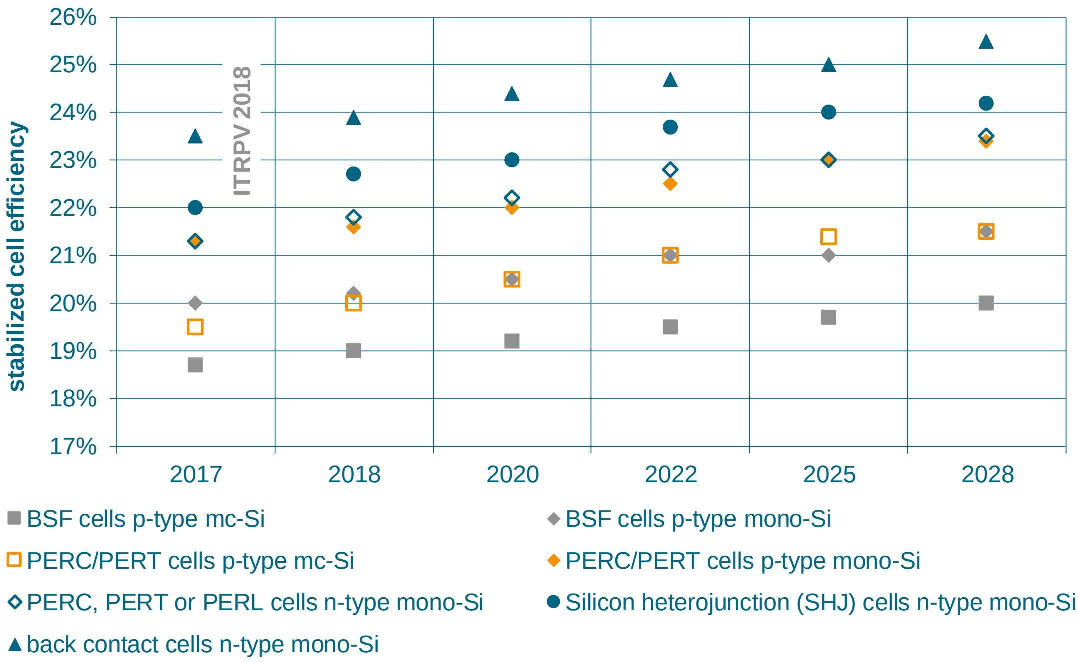
- *Silicon heterojunction cell types* have been available for some time in the market, as pioneered by Sanyo, but they are not projected to achieve a market share greater than 10% until 2021 - 2024.

- *Silicon-based tandem cells* can theoretically achieve higher efficiencies by layering an additional cell with a different spectral band gap on top of a silicon cell, but for the purposes of this study are still considered to be classified as a Best Not (yet) Available Technology (BNAT) They are currently projected to enter the market in some form from 2019 onwards, although the status of research into perovskite type cells, which are commonly identified as a potential tandem cell component, suggests that this is an optimistic.

- *Bifacial cell types* allow for both faces of a cell to generate electricity. Field tests suggest increases in yield of upwards of 20%. This cell type is considered to be particularly relevant to modules that will be installed on raised or ground mountings, usually in systems on commercial roofs or at a utility scale. It is anticipated that the predominant bifacial cell structure will be PERT with n-type silicon [89]. This module type will come at a higher cost due to the 5-10% premium for the n-type wafer, so commentators have also suggested that new cell structures that allow for use of cheaper p-type wafer substrates will gain market share – for example, mcPERT and pPERT.

[89] *Kopecek,R, Who's who at the leading edge of bifacial PV technology, PV-Tech special report, September 2017.*

Figure 31. Average stabilised efficiency level for C-Si solar cells (156 x 156mm^2)



Source: ITRPV (2018)

Whilst the *number of cells* in a module is anticipated to increase, with the market standard number increasing from 60 to 72 by 2021, *the size of cells* is anticipated to now decrease in order to minimise *cell interconnection losses*. Half cells are projected to grow steadily, achieving a market share of 20% by 2024.

A number of *module level design innovations* are available in the market and are claimed to offer a range of life cycle and operational benefits. They include:

- Alternative framing materials: Steel instead of aluminium is claimed to give a reduction in life cycle embodied CO_2 emissions, as well as simplified manufacturing processes [90]. However, frame material changes are not projected to gain market significance in the medium term.
- Frameless modules: With associated reductions in framing materials and the advantage of greater protection of the cells from damage [91] whilst allowing for bifacial performance gains. Their market share is projected to rise to over 20% by 2028.
- Simplified fixing systems: With associated reductions in the bill of materials, the time of site required for installation and the spacing between modules.
- Anti-soiling coatings: The application of repellent coatings to the module glass which can reduce the accumulation of dust and dirt on the surface of each module [92].

Encapsulation and back sheet materials are both major cost contributors in module manufacturing. The intense efforts made in the recent years have lowered the cost of encapsulants. New materials such as polyolefins are expected to increase in the coming years, as seen in Figure 32. However, it is predicted that EVA will remain dominant encapsulant (above 60% share) over a ten year period according to ITRPV, 2018. According to the same roadmap, back glass is expected to gain a significant share over foils as backsheet material, reaching 40% share by the next decade.

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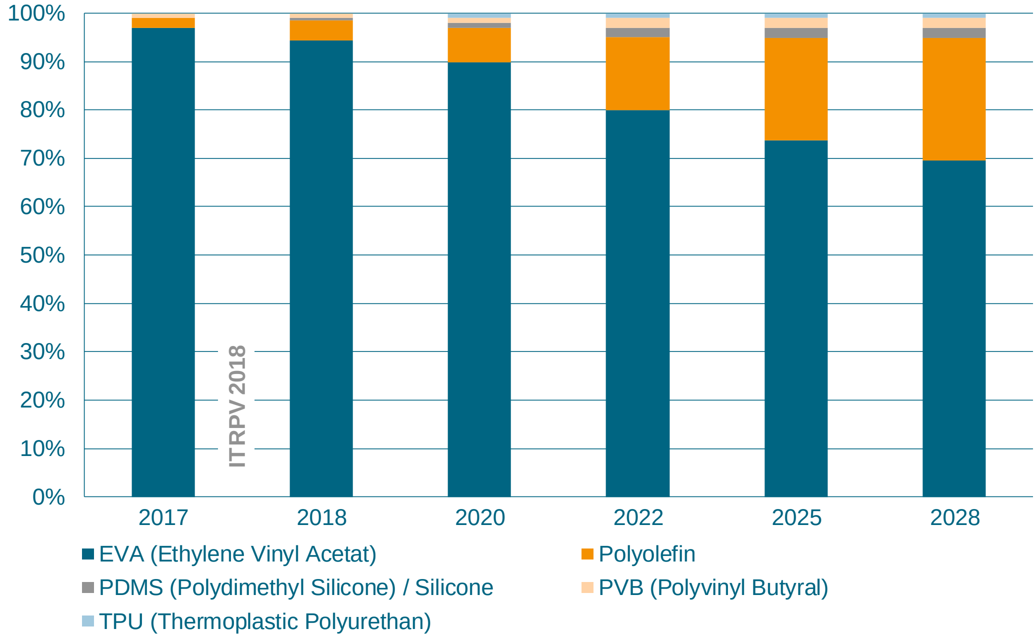
[90] *Bessing, N, Q Cells – Steel frame and other module level innovations, Presentation made by Q Cells at PV Module Technology & Applications Forum 2018, 29th January 2018.*

[91] *Verlinden,P. Advance module concepts, Chapter 10.4, p-502 in Reinders et al (2017) Photovoltaic solar energy – from fundamentals to applications, Wiley.*

[92] *Voicu et al, Anti-soiling coatings for PV applications, Presentation made by DSM at PV Module Technology & Applications Forum 2018, 29th January 2018.*

In terms of the module junction box, the bypass diodes will increasingly be connected using solder and potting instead of clamps. Improvements in junction box sealing can provide improved moisture ingress protection. However, both of these specifications create a dilema as both are understood to have implications for the ease of access to and replacement of bypass diodes, as will be discussed further in section 4.3 of Task 3.

Figure 32. Expected trends in module encapsulation materials



Source: ITRPV (2018)

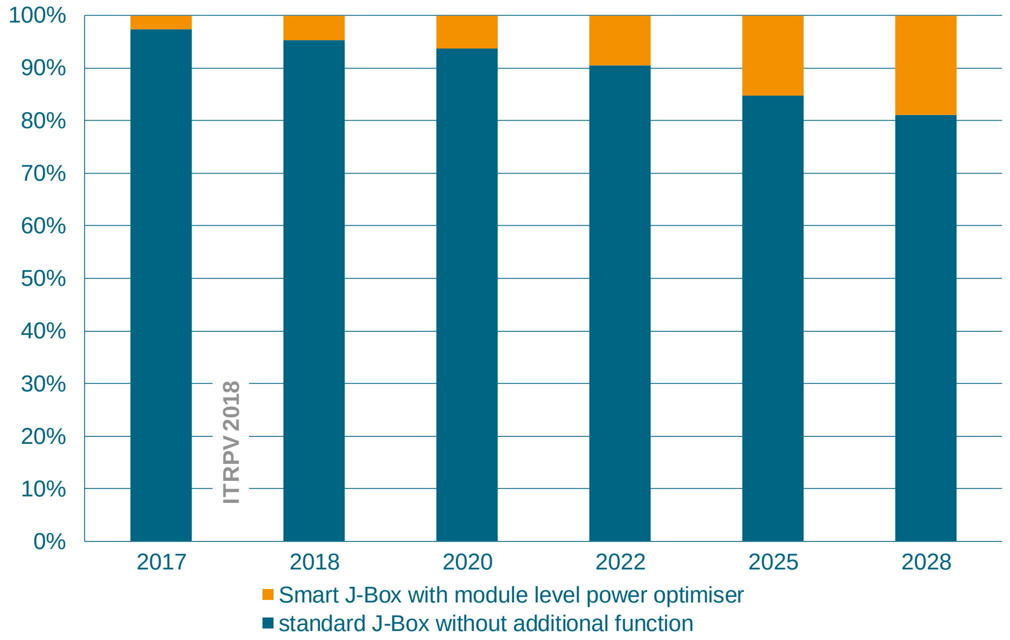
Decentralised junction boxes are a module design improvement that has the potential to both reduce cabling length per module and contribute to a marginal reduction in cable resistance losses across a module array.

A broader trend towards 'smart' junction boxes integrating a number of additional functions can be identified in Figure 33. Additional functions will largely include the integration of a micro-inverter and/or a DC/DC converter or optimiser that provides Module Level Power Management (MLPM). Both are projected to enter the market, but are not anticipated to make major inroads in the next 5-10 years. 'Cool' bypass switches designed to prevent overheating are understood to be becoming adopted in high output modules but have a cost implication.

The *quality and durability* of modules has become an increasing focus of attention for both manufacturers and buyers. This had led to action to improve design and manufacturing processes.

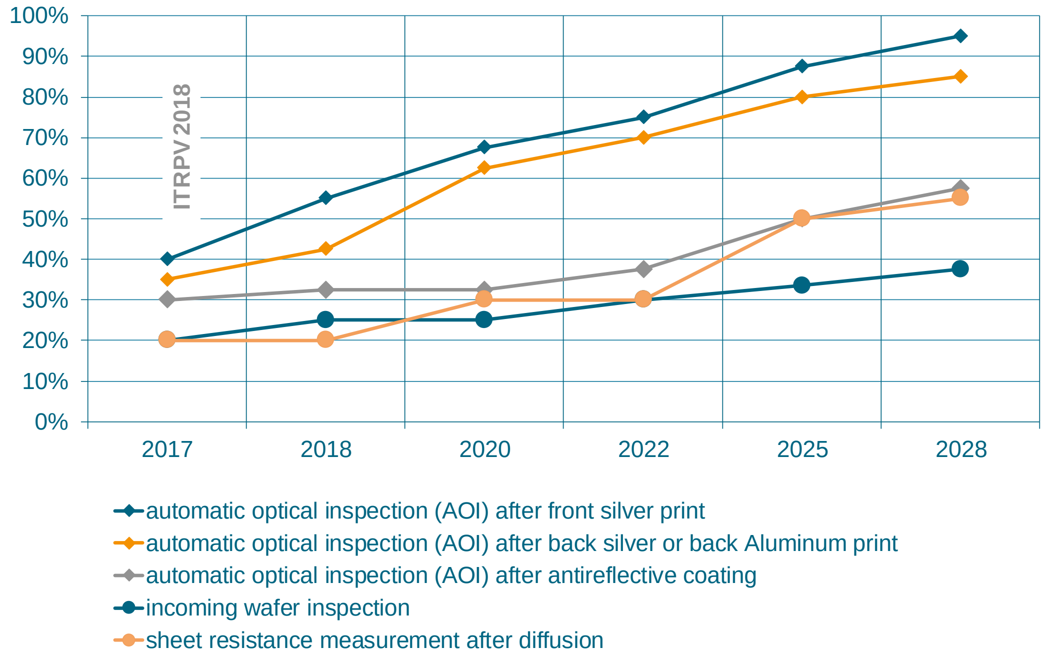
In line process control is a focus of attention to improve the reliability of modules in their first few years of operation. Reference to process control was made in Task 1 because some feed-in tariff schemes have established factory quality certifications for cells and/or modules as a pre-qualification requirement. Eleven control methods for cells and five for modules have been identified by the roadmap ITRPV, and are identified in Figure 34, Figure 35 and Figure 36. Over time these methods as applied to cell preparation are projected to become more common. Their contribution to reliability will be explored further in the Task 4 report.

Figure 33. Expected trends in junction box technology



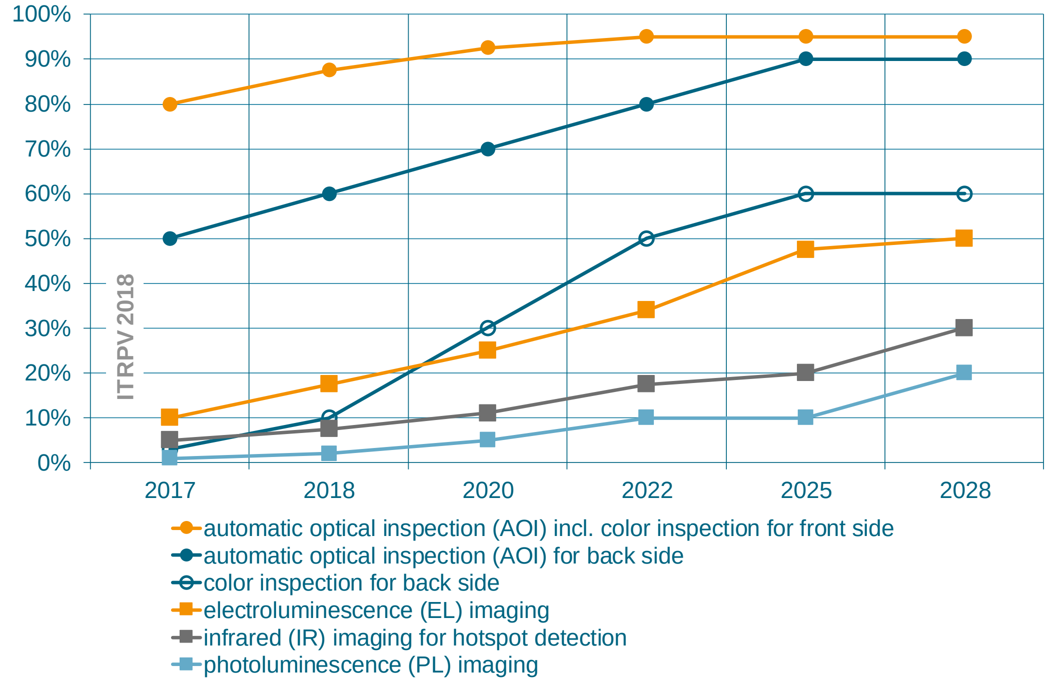
Source: ITRPV (2018)

Figure 34. Expected trends for in line process control of wafers and cells (coating stage)



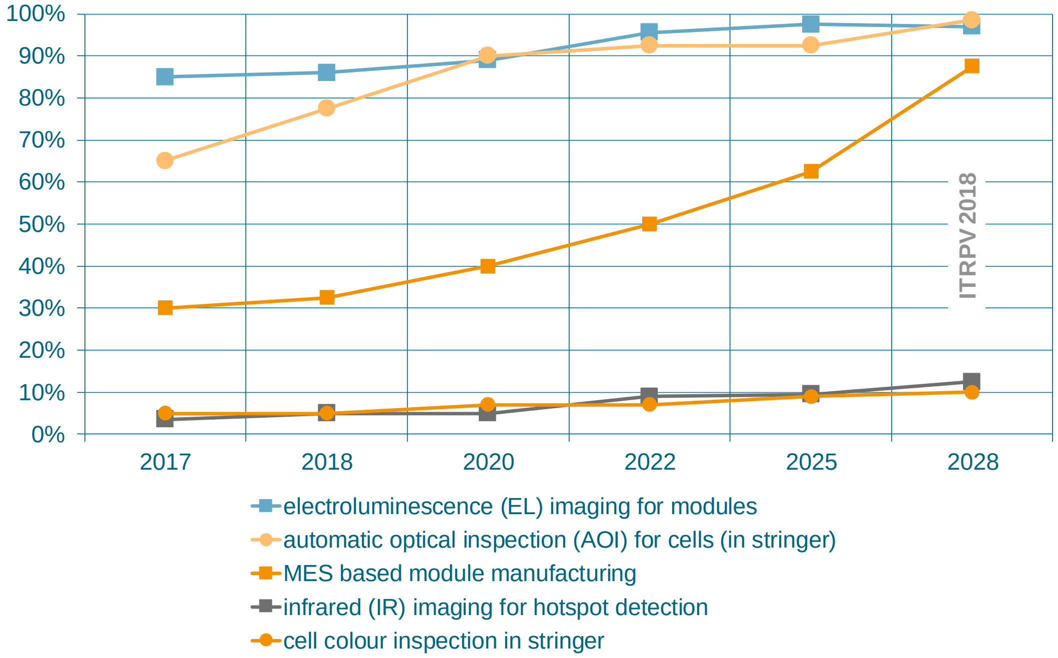
Source: ITRPV (2018)

Figure 35. Expected trends for in line process control of cell testing and sorting



Source: ITRPV (2018)

Figure 36 Expected trends for in line and manufacturing execution systems for modules

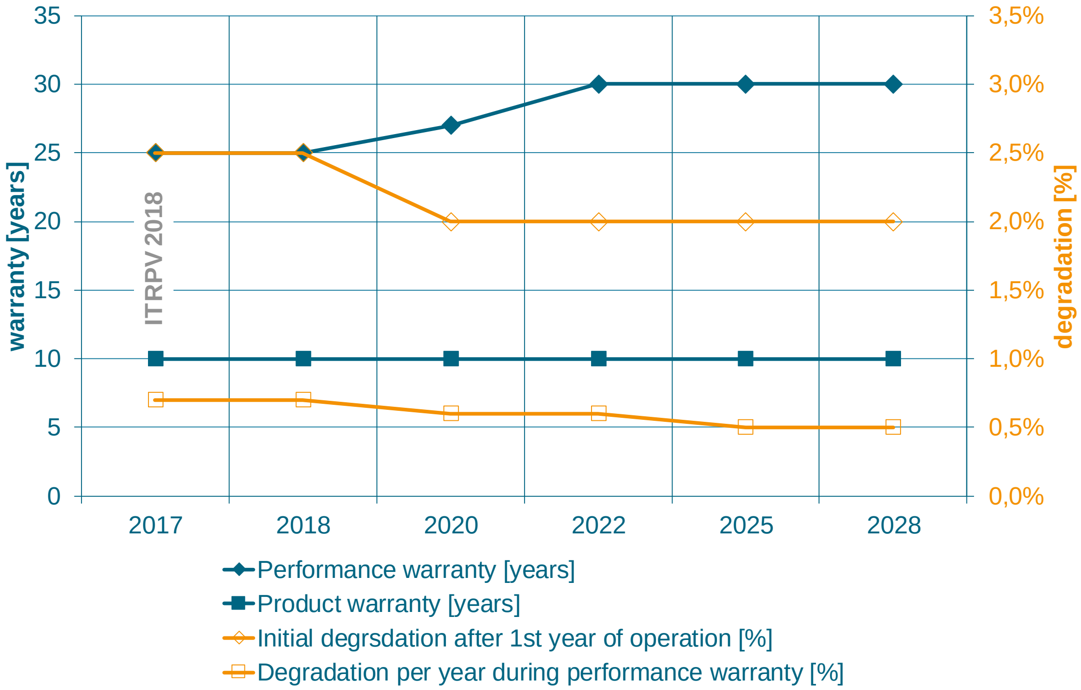


Source: ITRPV (2018)

Another important aspect of performance is degradation over time. This performance aspect, alongside other aspects that influence the overall functional life span (durability) of a module, are an increasing focus of attention for manufacturers and buyers. The initial degradation during the first year of operation, otherwise referred to as the burn in period, is projected to improve from 3% to 2% by 2019. Although the length of product (defect) warranties are not anticipated to increase in length above 10 years. The annual level of degradation during a performance warranty is projected to improve marginally from 0.7% to 0.5% over the next decade, allowing for performance warranties to be extended to up to 30 years. Although it is notable

that some manufacturers already offer a product warranty that is the same length as the performance warranty (25 years, see Figure 37).

Figure 37. Expected trends for crystalline silicon module warranties and degradation



Source: ITRPV (2018)

2.3.2.2.2 Non-crystalline film-based modules

Compared with silicon based technologies the availability of information about the trends for thin film technologies is rather limited. Trends and improvements for the mainstream products mainly refer to cost reduction and improving material efficiency, i.e. solar cells with less material but with higher efficiency. Moreover, because of the encapsulation techniques used thin-film technologies fulfil most of the architects' and constructors' requirements for the building skin, hence the BIPV market is expected to gain importance for these technologies.

Thin Si solar technology, which includes amorphous thin film technology as well as nano and micro crystalline technology, has seen major progress made in terms of efficiency gains made using the multi-junction strategy (up to quadruple junction). This includes the use of:

- advanced light trapping schemes,
- deposition regimes and processing allowing high quality material or highly textured substrates,
- the use of proper supporting and buffer layers, and
- an optimized photocurrent matching[93].

Notwithstanding the objective of targeting record efficiencies, the low cost manufacturing and aesthetics of the thin films should still make this technology attractive for the BIPV market.

Cadmium Telluride (CdTe) technology seeks to reduce the demand for raw materials (e.g. tellurium) on a per watt basis, through bandgap engineering. In the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 12% to 17% (Super-mono 21%). At the same time, CdTe module efficiency increased from 9% to 16%.[94]

[93] *Photovoltaic solar technology: from fundamentals to applications. 2017 John Wiley & Sons. Several authors*

[94] *ISE PV report june 2018 Fraunhofer. https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html*

Failure Mode and Effects Analysis (FMEA) has been incorporated by the main CdTe thin film producer, as well as a continuous Product Reliability Monitoring ("PRM") program to ensure product reliability is maintained globally during high-volume manufacturing. The reuse of glass from disposed PV modules for the production of new modules as well as semiconductor material (in 2016 new CdTe modules contained 8% recycled content) forms part of a global recycling program.

Copper Indium Gallium Selenide (CIGS) PV technology is starting to be produced in large volumes, and companies are pursuing different manufacturing pathways. One of these is the production of flexible modules that could be easily integrated in BIPV applications. As for reducing the cost and increasing production capacity, the main strategies are identified are[93]:

- cell thickness reduction,
- absorber materials with an increased band gap to enhance the open circuit voltage,
- lowering the series resistance and losses reduction in the transparent conduction oxide layers (TCO) and interconnects, and
- improved TCO materials and cells interconnect.

Interconnecting thin film modules with different strategies may lead up to 50% material saving with a potential to become commercial, as it has proven to give results in R&D (Cheetah project 2017)[95].

Beyond the evolution of the technologies this sector is more focused on module design, increasing the module area, junction boxes (e.g. two rear boxes), quick installation features, etc. The search for low cost encapsulants and packaging has also gained importance for flexible modules.

2.3.2.2.3 Building Integrated PV products

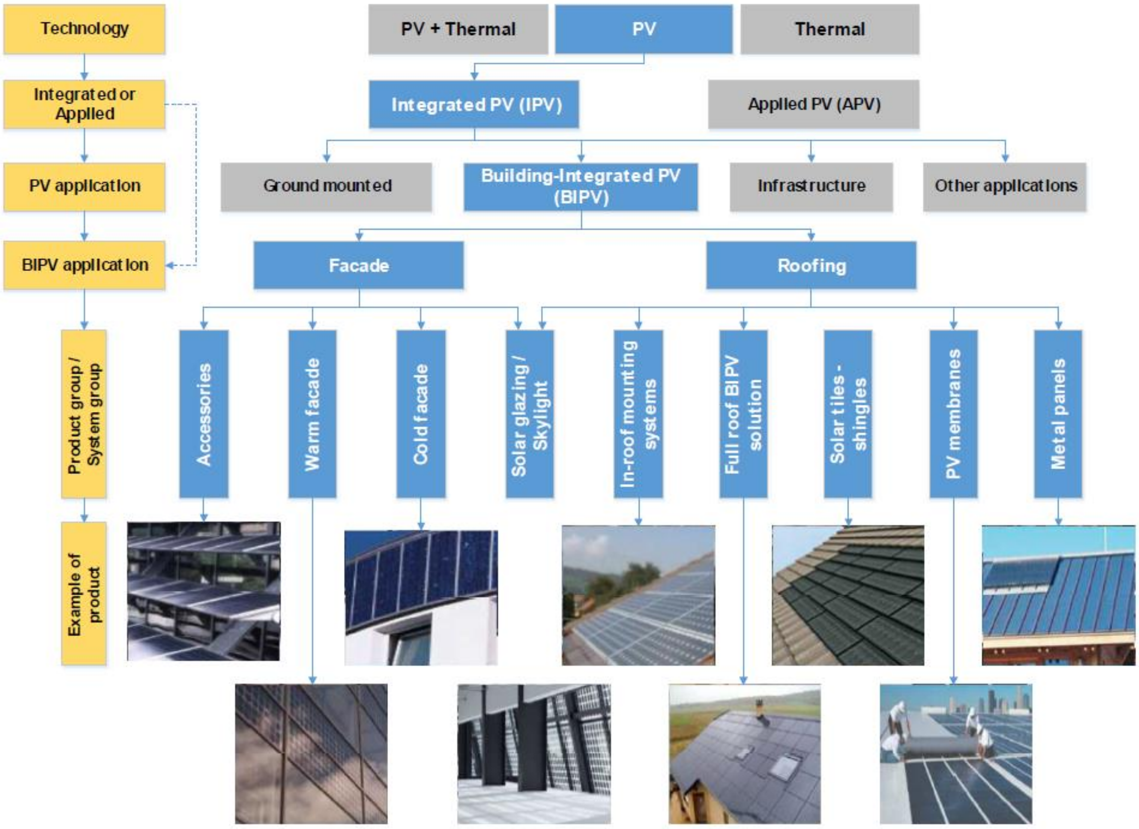
A market analysis carried out in 2014 defined eight main categories of roof and façade BIPV products in the EU market (see Figure 38)[96]. A 2015 BIPV status report identified 200 distinct BIPV products as being available on the market [97]. These products in general respond to existing architectural needs by substituting like for like an existing functional building fabric element. A BIPV producer survey carried out by Verberne et al (2014) found that crystalline silicon cells are preferred for roof applications and thin film large area cells for façade applications, as a result of price and aesthetics being more critical in commercial applications.

[95] *Cheetah project deliverable: D8.19, Interconnected thin film modules with up to 50% material saving. December 2017: http://www.cheetah-project.eu/fileadmin/user/Deliverables/CHEETAH_D8.19_VF.pdf*

[96] *Verberne.G, Bonomo.P, Frontini.F, van den Donker.M.N, Chatzipanagi.A, Sinapis.K and W.Folkerts, BIPV products for facades and roofs: a market analysis, Presented at the 29th EU-PVSEC in Amsterdam, The Netherlands, session 6DO.7, Thursday 25th, 2014*

[97] *F. Frontini, P. Bonomo, A. Chatzipanagi, G. Verberne, M. Van den Donker, K. Sinapis, W. Folkerts, BIPV Product Overview for Solar Façades and Roofs - BIPV Status Report 2015, Eindhoven (NL) & Lugano (CH), 2015*

Figure 38 BIPV product categorisation according to a market study



Source: Verberne et al (2014)

2.3.2.2.4 Feedback from the stakeholder questionnaire

The first stakeholder questionnaire included a question on what stakeholders considered as the commercial state of the art for module technology. The answers given by respondents are briefly summarised in this section.

Q1.5 Please indicate what you consider as the commercial state of the art for each of these technical aspects

- *Power conversion efficiency:* Six out of the 22 respondents suggested looking at the International Technology Roadmap for Photovoltaic (ITRPV) 2017, while a good fraction of them, 7, highlighted PERC technologies as the state of the art, with efficiencies ranging from 16% to 20%. Heterojunction technology with efficiencies from 19% up to 22.7% in 2018 were reported by 5 respondents. Monolithic integrated CIGS cells with an efficiency of 14% were cited by 2 respondents.
- *Quality, durability and lifespan:* Extending the module life to over 25 years, or that the warranty is both on product and power output was noted by 8 out of the 23 respondents. New standards were considered to be required to estimate the design service lifetime, IEC 61215 and 61730 test standard exist but there is no true durability or lifespan standard and the tests should be extended compared to the IEC standards. Tests should incorporate combined loads and stresses. Other technical improvements identified included glass glass modules, new encapsulants and edge sealing.
- *Material intensity and raw material use:* 5 out of 20 respondents focussed attention on the forecast reduction in silicon, the reduction in silver needs for contact fingers and busbars (below 50mg/Wp) was also mentioned by 4 respondents. Some respondents also stated that there are on-going initiatives for replacing silver with copper or other substitute materials.
- *Hazardous substance presence:* Three main issues were pointed out by the majority of 14 respondents: lead free soldering (10), REACH or RoHS conformity (4) halogen free backsheets (3).
- *End of life management:* the majority of respondents (14 out of 18) noted that compliance with WEEE through recycling is needed. Some suggested the possibility to have recycling facilities or that modules are designed for recycling, as well as the need for collecting systems or a payback system for the producer/importer. Reference was made to the PV Cycle scheme.
- *Other aspects:* A range of other technical aspects were identified:
  - use of copper plating to reduce silver consumption (TetraSun was cited),
  - several wafer production methods were cited that avoid cutting losses (e.g. Kerf less: http://1366tech.com/technology-2/),
  - methods to lower the energy demand of silicon (e.g. FBR solar grade silicon production https://www.elkem.com/no/elkem-solar/),
  - low temperature, solution based absorber deposition for perovskite solar cells to lower the energy demand of PV module manufacturing, though this is not commercialised yet.
  - sourcing PV manufacturing electricity from low carbon electricity sources such as PV itself (PV breeder concept)

2.3.2.3 Competitive analysis

The world PV modules market is dominated by the production of silicon technologies. China in particular can be seen to dominate the whole value chain, including polysilicon production, ingot production, wafer production and cell/module production. The country accounts for almost half of global module supply and deployment today. FIGURE 39 and Figure 40 show the Chinese shares in 2015 of the production volumes of cells and modules, being 65% and 69% respectively.

Silicon based PV technologies account for approximately 90 percent of the market share, and the major producers can be identified as forming part of what has been referred to by commentators as the Silicon Module Super League (or SMSL)[98]. The SMSL is comprised of the seven companies that are expected to each ship in excess of 4GW of modules in 2018, well above the expected output of all other module suppliers to the industry and it is estimated that they will account for over 50% of global shipments (see in Figure 41 the leading companies). Initially formed by Canadian Solar, Hanwha Q CELLS, JA Solar, Jinko Solar, and Trina Solar, it was expanded in 2016 to include LONGi and GCL.

[98] PV-Tech, Silicon Module Super League defines key metrics for PV ModuleTech 2017, 21st August 2017, https://www.pv-tech.org/editors-blog/silicon-module-super-league-define-key-metrics-for-pv-moduletech-2017-part

Figure 39. Share of production volumes of PV cells in 2015. Source: IEA Trends in 2016 PV applications

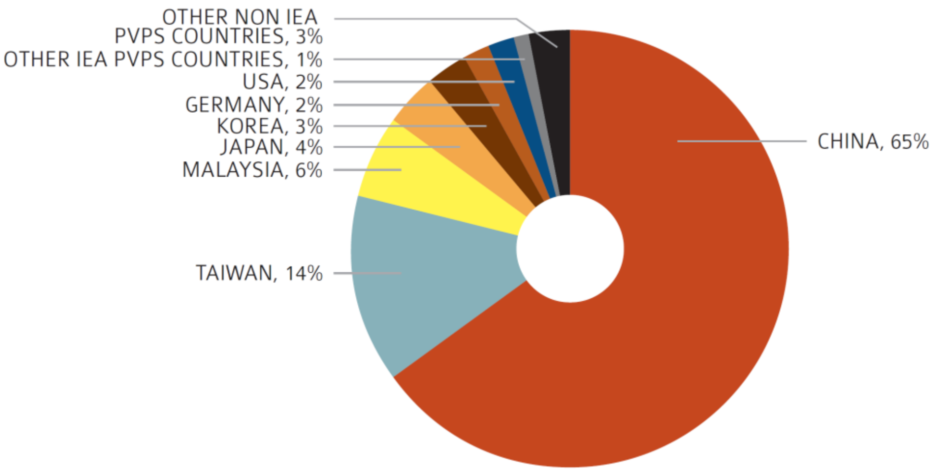
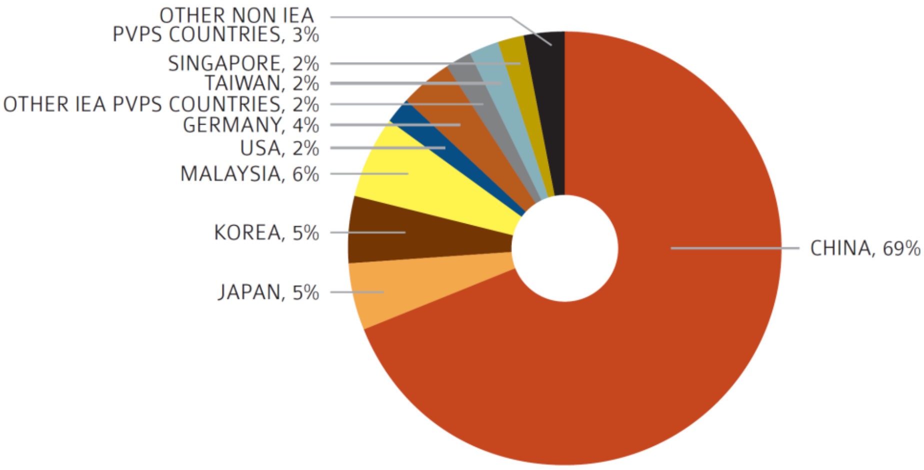


Figure 40. Share of production volumes of PV module in 2015. Source: IEA Trends in 2016 PV applications



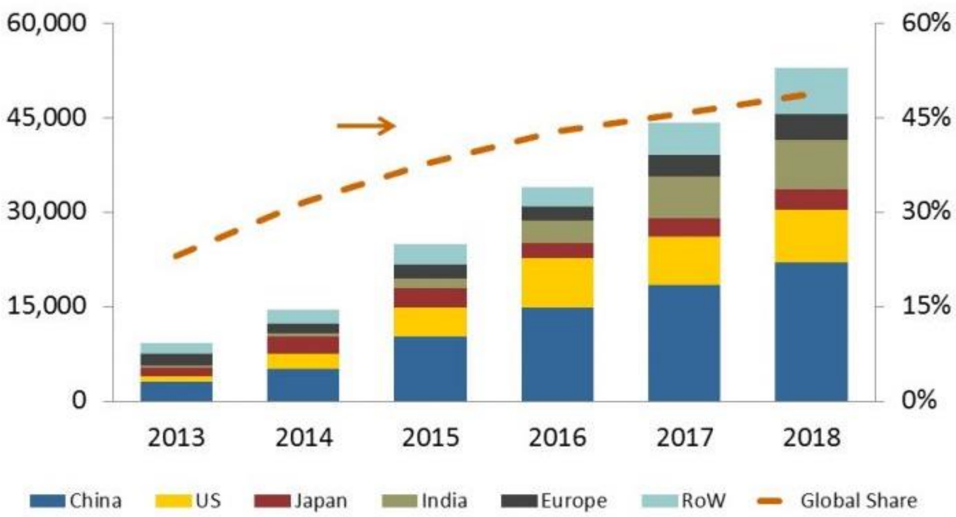
Six of the SMSL members are headquartered in China, with the seventh, Hanwha Q-CELLS (Korean), having about one-third of its cell/module capacity based at the former Solarfun facilities in China. Critically, all of the SMSL have the potential to supply multi-GW levels of modules to the largest market in the world today, China. Shipment levels of solar modules in 2017 appears to be well above 90GW, significantly higher than any of the market forecasts that other third-party market research firms have been giving for the past 12 months, at least. The two most recent members of the SMSL (GCL-SI and LONGi Solar) are relative newcomers to cell and module manufacturing having made their mark in the industry as poly/wafer dominant suppliers.

In terms of destination for shipments **Figure 42** illustrates the importance of China in sustaining the SMSL members. It has been the leading driver of shipment growth coupled with domestic initiatives such as Top Runner programme, which was described in the Task 1 report, have clearly helped the SMSL to prioritise investment in new production and cell technology. In comparison Europe and recently the USA, both with protective trade stances, have become relatively less important in sustaining large volume manufacturers such as the SMSL.

Figure 41. Leading module suppliers to the China/non China industry in 2016 (left) and 2017 (right). Source: PV-Tech Solar Media (August 2017)[99]

	2016 Global	Producer
1	JinkoSolar	JinkoSolar SMSL
2	Trina Solar	Trina Solar SMSL
3	Canadian Solar	Canadian Solar SMSL
4	JA Solar	JA Solar SMSL
5	Hanwha Q-CELLS	Hanwha Q-CELLS SMSL
6	GCL-SI	GCL-SI SMSL
7	First Solar	LONGi Solar SMSL
8	LONGi Solar	Risen Energy
9	Yingli Green	Shunfeng (incl. Suntech)
10	Shunfeng (incl. Wuxi Suntech)	Yingli Green

Figure 42. Silicon Module Super league (SMSL) shipments by geography (in MW). 2018 data is a forecast. Source: PV-Tech Solar Media (August 2017)[100]



Module supply from the SMSL is understood to be setting the benchmarks for all PV module suppliers to the industry today, in part driven by their response to the Chinese market and its Top Runner programme. This group of companies have been investing heavily in new production technology and cell structures. Until the end of 2015, in-house cell production by the SMSL mainly consisted of standard (full-Al BSF) p-type multi cells, with upgrades confined to moving from 3 to 5 busbars. They have subsequently quickly moved from p-type polycrystalline cell-based modules to p-type monocrystalline cells with PERC-type structures and p-type polycrystalline cells based on black silicon that can be cut with diamond wire saw technology.

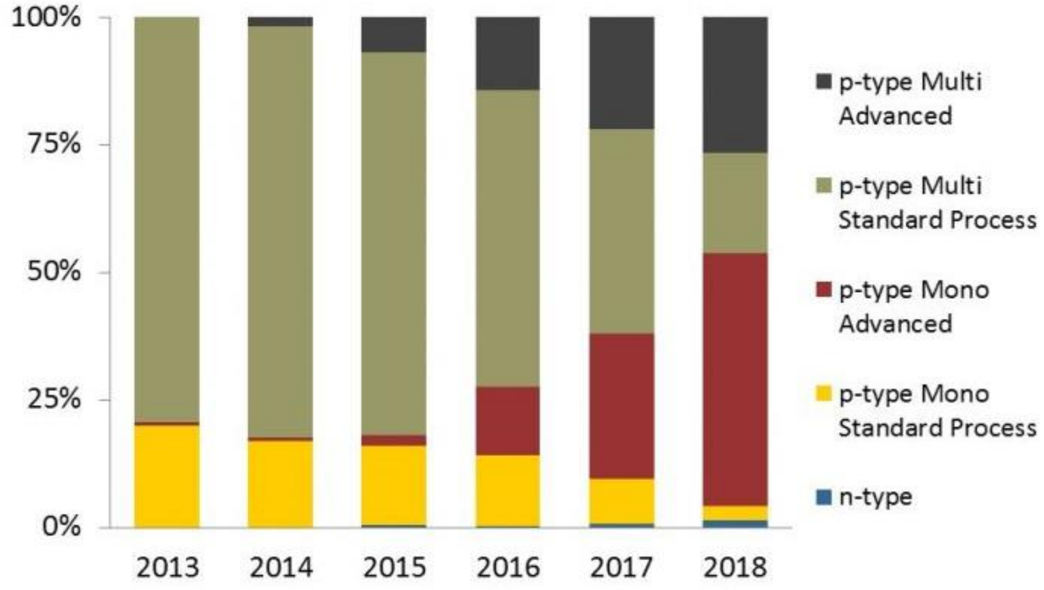
[99] *PV-Tech, Silicon Module Super League defines key metrics for PV ModuleTech 2017, 21st August 2017, https://www.pv-tech.org/editors-blog/silicon-module-super-league-define-key-metrics-for-pv-moduletech-2017-part*

[100] *PV-Tech, Silicon Module Super League defines key metrics for PV ModuleTech 2017, 21st August 2017, https://www.pv-tech.org/editors-blog/silicon-module-super-league-define-key-metrics-for-pv-moduletech-2017-part*

The result is that, as can be seen in Figure 43, by the end of 2018, almost all in-house cell capacity will be through advanced cell processing (PERC and 'black-silicon' based cell variants on p-type mono and multi).

Following large scale adoption of new cell structures and module technologies it is now predicted that during 2019-2020 SMSL members will turn to bifacial cells and glass-glass module structures. Out of the top ten global manufacturers three of them are now (in 2018) producing bifacial technologies (Yingli, Trina and LONGi Solar). Although bifacial PV systems are currently based on PERT and Heterojunction (HJ) technologies, recently more PERC producers have decided to enter the bifacial market segment. They include PVGS, Yingli, LG, HT-SAAE, QXPV and Adani. [101]

Figure 43 . In –house cell capacity by technology. Source: PV-Tech Solar Media (August 2017)



Source: Trinomics report, 2016. [100]

While the manufacturing of modules now largely takes place outside of Europe, the manufacturing of turnkey production line solutions for silicon wafer-based and thin-film module production, as well as other manufacturing components such as grinding machines, screen printing, wafer saws or analysis tools, continues to be an European important competence with Germany companies in particular playing a key role by continuing to capitalise on their early establishment in the EU market [102]. It is claimed that **PV machine tools made in Germany still account for 50% of the global** market's production capacity.

While not all cell manufacturing production lines are the same, the following processes are among those used to fabricate silicon-based PV cells:

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[101] *Kopecek,R, Who's who at the leading edge of bifacial PV technology, PV-Tech special report, September 2017.*

[102] *Trinomics, Assessment of photovoltaics, Task D - Opportunities for European Reindustrialisation, Final report presented to the European Commission, 23rd November 2016*

- wafer inspection,
- anti-reflective coatings,
- frontside and backside printing,
- (acid) texturing,
- doping,
- diffusion,
- testing and
- final classification.

All of these steps require specialised equipment. the situation for module manufacturing is relatively similar, with steps such as testing/sorting, string assembling, busing, lamination, framing and trimming also requiring specialist equipment. So whilst Chinese module manufacturers will be responsible for introducing new PERC, heterojunction and bifacial cell structures into the global and EU market, they will be to a great extent relying on European production line technology.

With regard to CdTe technologies, key players in the sector are First Solar, Antec Solar, Calyxo, CNBM Roth&Rau/CTF Solar. The main manufacturer, member of the Solar Module Super League, First Solar has aproduction of around 4 GW/year.

In terms of product (defect) warranties it is notable that some manufacturers have extended their warranties to cover the same term as performance warranties for which, as identified in section 3.3.2.2.1, the industry standard is 25 years. For example, Sun Power's X series of modules is covered by an extended 25 year warranty coverage for both product defects and power yield [103]. A summary of some of the extended product and performance warranties available in the market is provided in Table 38. There is also emerging evidence from the market that the anticipated greater durability and reduced degradation associated with bifacial module structures is already being reflected in longer warranty periods.

2.3.2.4 Channels to market

In general it can be seen that the photovoltaic modules market is highly competitive, which means that there are limited margins which in turn restricts the number of intermediaries. Manufacturers' channels to market for conventional modules are generally limited to:

- Direct sales to developers or large installers,
- Sales via local subsidiaries,
- Sales via distributors then to installers
- Products then sold under the brand name of another company.

Each of these will be discussed in turn in the following section. Retail may be an additional sales route, especially for very small systems, for modules and for inverters. The market for Building Integrated Photovoltaics (BIPV) is rather more diverse, although also with a limited number of intermediaries, and is briefly also reviewed in the following sections.

[103] Sun Power, Accessed April 2018, https://global.sunpower.com/high-efficiency-solar-technology/

Table 38 Indicative examples of extended product and performance warranties

Module manufacturer	***Product warranty term***	***Performance stability and warranty term***
Sunpower • Standard terms	25 years	90% after 25 years
LG • Mono type • Bifacial glass-glass	25 years 15 years	80% after 25 years 86% after 25 years
Winaico • PERC mono type	15 years	80% after 25 years
Trina Solar • Bifacial glass-glass	10 years	80% after 30 years
Hanwha Q Cells • Back contact type	12 years	80% after 25 years
First solar • - CdTe Series 6	10 years	86% after 25 years

Source: compiled from manufacturers' publicy available literature

2.3.2.4.1 Conventional modules

In general for systems of a size greater than 100 kW, the system developer will tend to go directly to the manufacturer. This is a question of price since distributers take a 15-20% margin on modules. The regional or country representatives of manufacturers are in general subsidiaries of the manufacturer. In some cases, they are established companies, which could be considered as distributers. In some cases competition can exist between local subsidiaries and international distributors.

Distributors have served as important intermediaries since the beginning of the mass deployment of PV in Europe by providing products (modules, inverters) to installers of small, mainly residential systems. They tend as a result to be well established companies (e.g. Krannich solar in Germany). Table 39 provides an approximation based on an industry directory of the number of wholesalers and distributors in each Member State.

Table 39. Number of wholesalers, wholesalers-distributors and distributors of PV modules in EU per country

	Wholesalers	Wholesalers/ Distributors	Distributors
Austria	22	2	2
Belgium	11	6	12
Bulgaria	9	2	3
Croatia	5	-	1
Cyprus	2	1	2
Czech Republic	11	7	12
Denmark	15	-	7
Estonia	2	1	1
Finland	4	1	2
France	31	9	14
Germany	148	29	39
Greece	15	5	7
Hungary	12	7	9
Italy	34	21	34
Ireland	3	-	5
Latvia	-	1	-
Lithuania	2	1	-
Malta	1	1	2
Netherlands	93	12	14
Poland	16	5	8
Portugal	5	2	5
Romania	19	2	4
Slovakia	3	-	1
Slovenia	5	1	1
Spain	25	17	18
Sweden	14	3	1
United Kingdom	33	17	13
Total	496	138	166

Source: ENF Solar (2018)

Due to cost pressure, the market share of distributors in the large-commercial and industrial segment is rather small, since the margins they take don't allow them to be competitive in these markets. Larger installations do not normally use distributers for the cost reasons already cited unless a manufacturer is unable to deliver on time and the project must be finished at all costs (often due to financial penalties).

Instead of a spot market, a market exists based on future prices. A customer can book for a designated price some quantities of PV panels for a delivery in the future. This is usually done in order to guarantee a fixed price for a project to be realised in the future. Both developers and distributors are working with such future contracts.

The question of how distribution will look in the future is a complex one. The distributors found their place on the market since small installers started to develop. As already seen in some countries (such as Germany for instance, or the USA), large companies, including traditional utilities are starting to offer PV products for residential and commercial applications. These companies compete directly with small installers, with a competitive advantage for well organised large players: the ability to buy directly from the manufacturer and propose reduced prices. Companies such as EON in Germany, Engie in Belgium, Iberdrola in Spain or Enel in Italy as proposing such PV products. Not all of them are targeting the residential segment but all are looking at rooftop installations. This could lead to a decrease in the price at which modules are invoiced for small applications, putting a high pressure on traditional distributors.

Re-branding exists for modules. Some modules could be sold under a different brand than the manufacturers' one. This is especially valid with packaged products, and for small installations. With the issue of quality having assumed a greater priority in recent years, the rebranding of modules and the use of OEM production is potentially problematic for verification and traceability, which will be required for a module product to be considered as 'bankable' [104]. This tends therefore to favour companies that have vertical integration of production and raw material supply.

The importance of Original Equipment Manufacturers (OEMs) for module manufacturing has been reduced significantly in the last few years due to the consolidation in the sector and the lack of competitiveness of European manufacturers. In a very fragmented value chain, the module manufacturers were buying cells from the cheapest providers in order to be competitive. Even companies integrated vertically (i.e. producing wafers, cells and modules) started to buy some wafers or cells on the market when it was more profitable for them to do so than to use their own products.

On the module side, many small actors with some dozens of MW of production capacity were either producing niche products or were used as OEM for larger manufacturers. JABIL in Poland, which close a few months ago in 2018, used to do OEM for large Chinese companies in Europe, in order to circumvent the anti-dumping taxes, but also to increase their production when the demand was higher. In China, former tier 3 companies are not selling directly anymore but are producing modules for Tier 1 companies. The lack of competitiveness of these small actors in Europe has led to a quasi-complete abandonment of OEM contracts.

System integrators have in general contracts with several module manufacturers but for large quantities will put out calls to any of them. As has already been mentioned, there is no real "spot" market for modules as such since the price of PV modules depends on the technology, amount and the delivery date. The cheapest (bankable) manufacturer is in general therefore able to sell. Large tenders favor the cheapest manufacturers, since quantities are important and the visibility is high. To reach a deal for these tenders, most manufacturers are proposing their lowest prices, often very reduced or no margin, in order to get the contract.

2.3.2.4.2 Building Integrated PV products

Building Integrated PV products represent a small segment of the market. This segment is significant for having distinctly different channels to market, originating from specialist suppliers and being largely distributed via the building trade rather than the wholesale distribution route identified for modules.

With roofing having been identified as the most significant BIPV market segment, a wide range of possible channels to market can be identified based on the diversity of roofing materials used across the EU (see Figure 44). Facades represent a more challenging market in terms of pricing and quality. Figure 45 identifies the predominant materials used for facades.

The building sector is recognised as being relatively conservative. Barriers identified to increased market penetration include:

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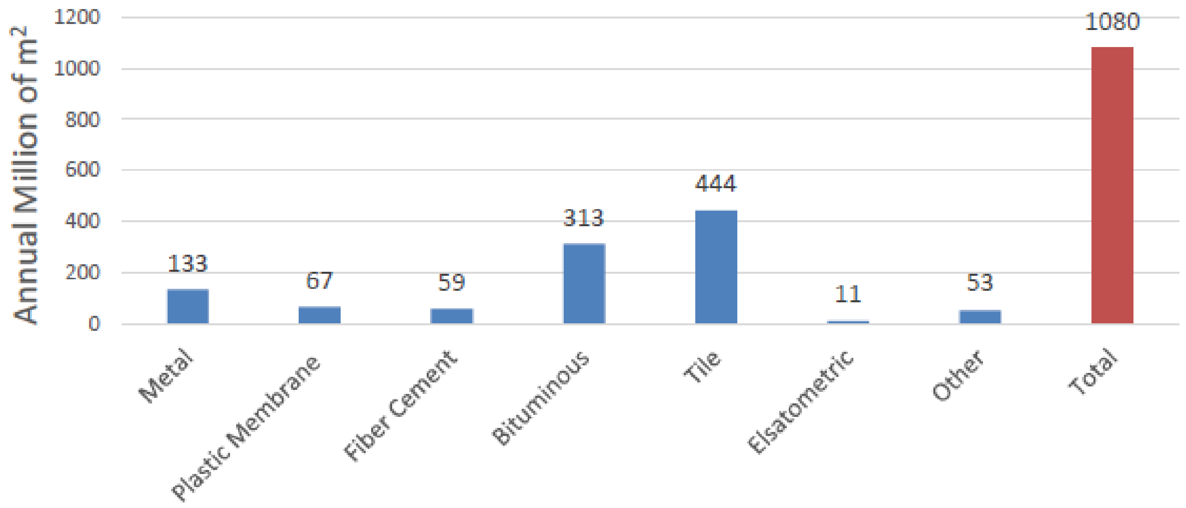
[104] *Colville.F, Module quality emerges as new marketing tool for the solar industry, PV Tech Magazine, 3rd October 2017, https://www.pv-tech.org/editors-blog/module-quality-emerges-as-new-marketing-tool-for-the-solar-industry*

- flexibility in design and aesthetics considerations,
- lack of tools integrating PV and building performance,
- demonstration of the long-term reliability of the technology,
- compliance with legal regulations,

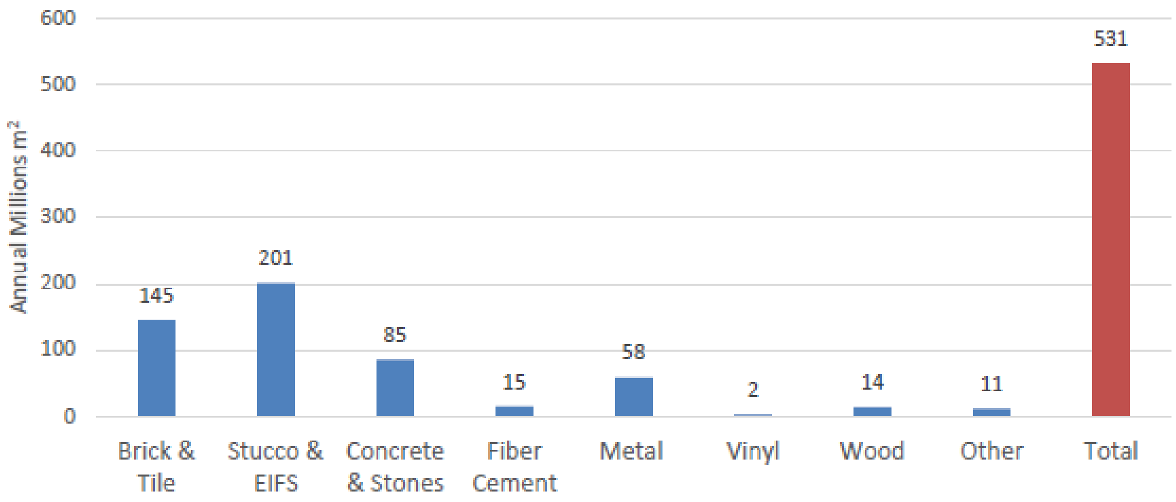
As was identified in Task 1, targets at Member State level for all new buildings to achieve NZEB performance and a further recasting of the Energy Performance of Buildings Directive are likely to drive the uptake of BIPV products in the new-build and major renovation market segments.

Figure 44 Overview of roofing material segmentation in Europe in 2014



Source: PV Sites project (2016)

Figure 45 Overview of façade material segmentation in Europe in 2014



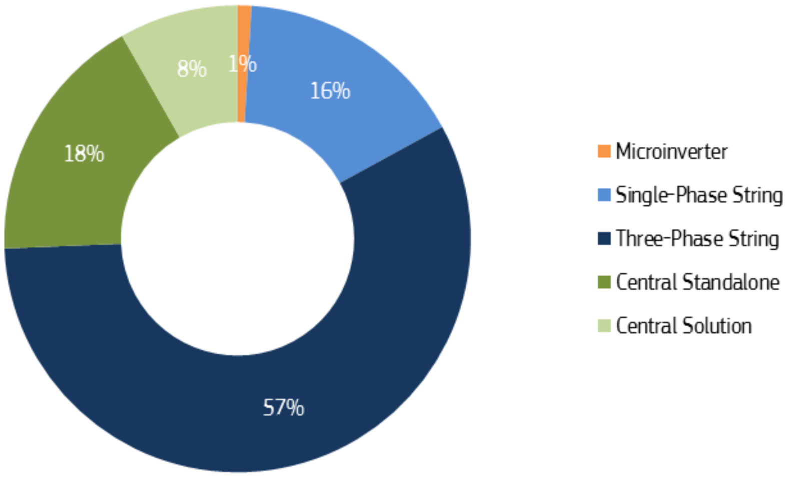
Source: PV Sites project (2016)

2.3.3 Product trends - Inverters

2.3.3.1 Market segmentation

The European inverter market is dominated by single and three phase string inverter technology (73%), as can be seen in Figure 46. The remaining portion of the market is accounted for by centralised inverters (26%), delivered either as a standalone unit or packaged with other power conditioning equipment such as transformers, and micro-inverters (1%).

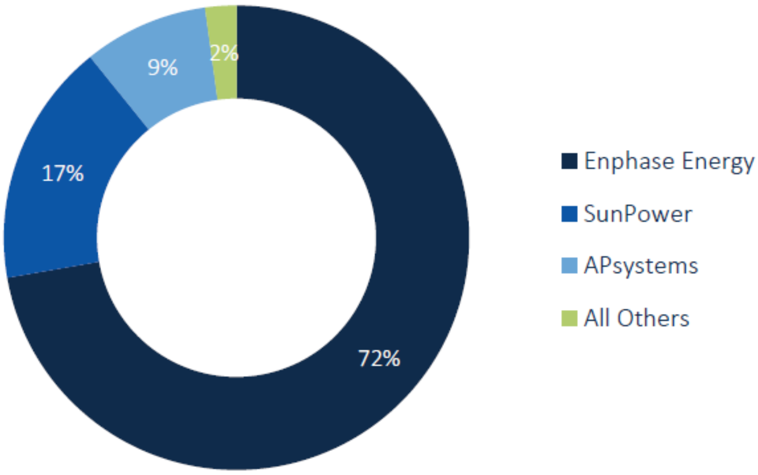
Figure 46. European inverter shipments by technology (2016)



Source: GTM Research (2017)

The main market for microinverters is currently the USA where they accounted for just over 5% of shipments in 2016 (Figure 47). The EU and Australia are identified as growth markets after the US, with a focus on the sub 5kW market, where the financial case is strongest.

Figure 47. Global micro-inverters market share



Source: GTM Research (2017)

In terms of module level power electronics, the European shipments of DC optimisers in 2016 were of greater market significance than micro-inverters, being equivalent in capacity to approximately 7.7% of the total EU shipped inverter capacity and accounting for just under a third of the global shipments of DC optimisers.

2.3.3.2 Trends in product design and features

As the cost of modules has fallen the proportion of a system's costs accounted for by Balance of System (BoS) components has risen. At the same time inverter efficiency has increased to the point where the majority of system-level inverters have a declared efficiency in the region of 98%. With the exception of micro-inverters, which still appear to have potential for efficiency improvements, attention has therefore also turned to the role of inverter configurations and power electronics as means of improving system performance.

Inverters have therefore been the major focus of attention for BoS performance optimisation and cost reduction. Functional requirements that have influenced designs include:

- an increase in power density (or power to weight ratio),
- the need for higher reliability and the management of fault modes, and
- the use of smart grid control under different conditions.

In the field of string inverters with a power rating of up to 100 kW, transformerless circuit topologies with high switching frequencies and Maximum Power Point Tracking devices represent the state of the art. A so-called three level topology is widely used – conversion to high frequency AC, then to DC, then to distribution network voltage.

The application of three phase string inverters to larger utility scale systems is an important application trend. However, this has largely only been seen for systems requiring inverters of less than 1500 volts (<50 kW). The first 125 kW string inverter was launched in 2017, and represented at the time the largest available on the market. They are cited as having the advantage of being easier to handle, install and maintain than central inverters [105]. To achieve the necessary power density a five level topology must be used.

In terms of performance improvement, the most significant trend projected as taking place in 2018 is the potential introduction into the market of inverter designs with silicon carbide (SiC) and gallium nitride (GaN) switching components (transistors). It is claimed their introduction support increased power densities whilst reducing cooling requirements, thereby reducing the bill of materials, a large part (70%) of which is accounted for by mechanical and electromechanical components such as metal heat sinks [106]. This can be achieved by so-called 'hot core' architectures that require heat sinks to be made of composite materials with greater thermal conductivity [107].

As was identified in the analysis of module trends, there are indications that the integration of power electronics at module level will continue to increase. This will see the further development of modules with integrated micro-inverters and DC power optimisers. Interest in micro-inverters has been driven by the need to reduce installation costs, but also by the claimed improvements in system performance in the range of 5-25% that can obtained[108].

Module level power electronics are claimed to have become more popular due to a combination of system offers that aim to improve system efficiency and increased safety requirements. MLPE can include features that support a number of other functions that related to operational control of a photovoltaic system. Inverter and panel level monitoring of power output and fault detection are now available. Smart inverters can be configured to notify installers of fault occurrences.

There are also indications that in the future inverter electronics will be integrated with battery storage systems – so-called hybrid inverters. There are already examples in the market where the DC charge controller electronics are integrated with the power electronics of an inverter and DC optimiser. The inverter architecture must be configured differently in this case because of the need to support two operating modes – grid parallel (or grid 'feeding') and islanding (or grid 'forming') – and to control the voltage and frequency. The inverter products expected design life must also reflect the associated extension in operating hours. The inverter will need to operate in the day-time operation during periods of sunlight and also at night time to supply power demands.

2.3.3.2.1 Feedback from the stakeholder questionnaire

The first stakeholder questionnaire included a question on what stakeholders considered as the commercial state of the art for inverter technology. The answers given by respondents are briefly summarised in this section.

Q2.5 Please indicate what you consider as the commercial state of the art for each of these technical aspects

- *Power management*: Two out of the eight respondents who addressed this aspects identified Module Level Power Management (MLPM) in conjunction with DC optimisers. Two further respondents identified Maximum Power Point Tracking (MPPT) including the potential for 2-3 devices on one inverter. Two further respondents identified new

[105] *PV Tech, 1,500V and beyond – where next for inverter technology, Special report – Next generation inverters, December 2017*

[106] *PV Tech, Technical trends in next generation solar inverters, Special report – Next generation inverters, December 2017*

[107] *Fraunhofer ISE, PV-Pack – Innovative Solutions for New, Highly Integrated PV Inverters in the Power Range from 30 to 70 kW,Accessed April 2018, https://www.ise.fraunhofer.de/en/research-projects/pv-pack.html*

[108] *US EPA, Energy Star Market and Industry Scoping Report - Solar Inverters, December 2013.*

power semi-conductor technology such as silicon carbide. Benefits identified include faster switching speeds, an improved power density, reduced losses and reduced heat rejection requirements. In addition connectivity, intelligent home energy systems, integrated storage, reactive power management, and active power management were also mentioned.

- *Lifespan:* There were six respondents to this aspect. A design life of between 10 and 20 years was identified. IP (Ingress Protection) standards, as well salt and ammonia resistance tests, were identified. Case design to facilitate heat rejection but also provide ingress protection was highlighted. One respondent identified the need for the *'identification of critical components and enhancements to inverter reliability'*. Standards of potential relevance under development were listed:
  - ANSI/TUV-Rheinland 71830, "Microinverters and Microconverters – Design Qualification and Type Approval,"
  - IEC 62093 ed. 2, "Photovoltaic System Power Conversion Equipment Design Qualification Testing,"
  - IEC 63157 ed 1 - inverter quality assurance technical specification with guidelines for increased confidence in design qualification and type approval.
  - Material intensity and raw material use: One respondent identified the exclusion of *'tantalum, tin, tungsten and gold from suppliers that are considered "conflict minerals"'* and an additional respondent identified *'responsibility in the supply chain'*. Another respondent identified weight to power ratio as a metric.
- *Hazardous substance present*: Two respondents identified lead-free solder. One respondent identified that some larger inverter products (> 1MW) on the market are liquid cooled and the need for practical alternatives to the coolant HFC-134a, such as propylene glycol and ethylene glycol. New semi-conductors will support air cooling. RoHS and REACH compliance were identified by two respondents.
- End of life management: Five out of the eight respondents to this aspect identified recycling and refurbishment, with one noting that *'typically, defective inverters get refurbished and defective components get recycled or disposed off'* and that *'disposal without recycling would only happen in case of severe damages, i.e. after a fire incident'*. The recyclability of materials and components were identified by two respondents. WEEE compliance was identified by two respondents.

2.3.3.3 Competitive analysis

The European inverter market is led by three companies (SMA, Fronius and ABB) that are also in a favourable position in the world market. SMA Solar (Germany) is the world's highest ranked company with regard to R&D investment in the PV sector.

Global solar PV inverter shipments grew 23% on 2016 (34% in EU), reports GTM Research in its latest Global Solar PV Inverter Market Shares and Shipment Trends 2018 report. Revenues, meanwhile, increased by 11%.

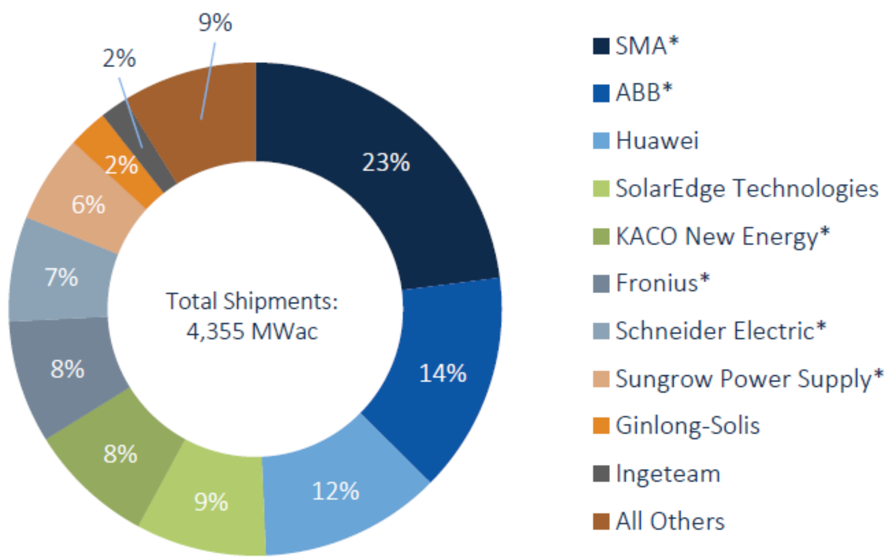
Manufacturers supplying three phase string inverters for sub 1MW systems – namely SMA, ABB, Huawei, SolarEdge Technologies, Fronius and Ginlong Solis, who together are estimated to account for 67% of the shipped capacity for these types of products in 2017 (Figure 48).

The leading manufacturers supplying centralised inverters were KACO New Energy, Schneider Electric, Sungrow Power Supply and Ingeteam, who together are estimated to account for 23% of the shipped capacity in 2017.

European manufacturers play an important role in the market, being estimated to account for just over 50% of shipments in 2016. These manufacturers are considered as mature suppliers, having inverter products with a relatively long track record, and whose competitiveness is proved by their survival of the downturn in the market during 2010-15. Their products are valued as being cost effective given the advanced features they incorporate, including advanced grid integration and control systems.

GTM Research identify that there are 13 EU manufacturers of significance at a global scale, with SMA (Germany), Fimer (Italy), Fronius (Austria), KACO New Energy (Germany), Power Electronics (Spain) and Schneider Electric (France) each achieving a global market share of greater than 1% in 2016. Swiss company ABB also has an important market share, and has some production facilities in the EU (e.g. Poland and Czech Republic).

Figure 48. European inverter shipments (2017)



Source: GTM Research (2017) **estimates*

Approximately 1.5 GWac of SMA's 8.2 GWac shipments made in 2016 were into Europe. Fronius were the next most significant EU supplier, shipping 754 MWac out of 1.4 GWac, followed by Schneider Electric with 649 MWac out of 2.0 GWac..

It is notable overall that Chinese manufacturers accounted for 25% of shipments into Europe in 2016, up from 17% in 2015 and 11% in 2014. The three leading Chinese manufacturers were Sungrow Power Supply, Huawei and and Ginlong Solis.

Sungrow Power Supply and KACO New Energy are notable for having introduced in 2017 high voltage 125kW string inverters aimed at the >1MW market. General Electric is cited as being likely to be the first inverter manufacturer to introduce higher switching frequency inverters in 2018. Other manufacturers likely to follow suit are, for silicon carbide transistors and high voltage inverters - Delta, SMA, ABB, Fuji Electric, Omron, Sungrow and Schneider Electric – and for gallium nitride transistors and low voltage inverters - Yaskawa, Enphase, Tata, SMA and SolPad. Of these manufacturers, only SMA, ABB, Sungrow, Schneider Electric and Enphase currently have a significant presence in the European market.

Enphase Energy are the most significant manufacturer globally of micro-inverters for integration into AC modules. Jinko Solar, LG and Solar Power are notable suppliers of AC modules. Most micro-inverters products in the EU are understood to form part of the shipped AC module products of Jinko Solar and LG. SunPower are understood to only presently supply AC module products to the US market.

In terms of module level power electronics, SolarEdge, Tigo Energy and Maxim Integrated can be identified as the leading manufactures of DC power optimisers for use in combination with transformer-less string inverters. Manufacturers currently offering inverter level power electronics that support battery integration include SolarEdge , Huawei and SMA [109].

Labour costs seem to be an important factor for international competitiveness, which is indicated by ABB's choice for locating inverter production in the Czech Republic and Poland, where SMA also maintains a production facility. The relationship between regional R&D capacities, specialisation and chosen production sites is not as clear as in other parts of the PV value chain.

2.3.3.4 Channels to market

In general it can be seen that the photovoltaic market is highly competitive, which means that there are limited margins which in turn restrict the number of intermediaries. Manufacturers' channels to market are generally limited to:

[109] *SMA, Sunny Boy Smart Energy, https://www.sma.de/en/products/solarinverters/sunny-boy-3600-5000-smart-energy.html*

- Direct sales to developers or large installers,
- Sales via local subsidiaries,
- Sales via distributors then to installers
- Products then sold under the brand name of another company.

Each of these will be discussed in turn in the following section.

In general for systems of a size greater than 100 kW, the system developer will tend to go directly to the manufacturer. This is a question of price since distributers take a 15-20% margin on inverters. The regional or country representatives of manufacturers are in general subsidiaries of the manufacturer. In some cases, they are established companies, which could be considered as distributers. In some cases competition can exist between local subsidiaries and international distributors. For example, in the case of Spanish distributors delivering in Belgium at a cheaper price than the Belgian subsidiary for SMA inverters.

Distributers tend to be well established companies (e.g. Krannich solar in Germany) that sell mostly to the residential and commercial segments. Larger installations do not normally use distributers for the cost reasons already cited unless a manufacturer is unable to deliver on time and the project must be finished at all costs (often due to financial penalties). Table 40 provides an approximation based on an industry directory of the number of wholesalers and distributors in each Member State.

Instead of a spot market, a market exists based on future prices. A customer can book for a designated price some quantities of inverters for a delivery in the future. This is usually done in order to guarantee a fixed price for a project to be realised in the future. Both developers and distributors are working with such future contracts.

The question of how distribution will look in the future is a complex one. The distributors found their place on the market since small installers started to develop. As already seen in some countries (such as Germany for instance, or the USA), large companies, including traditional utilities are starting to offer photovoltaic products for residential and commercial applications. These companies compete directly with small installers, with a competitive advantage for well organised large players: the ability to buy directly from the manufacturer and propose reduced prices. Companies such as EON in Germany, Engie in Belgium, Iberdrola in Spain or Enel in Italy as proposing such PV products. Not all of them are targeting the residential segment but all are looking at rooftop installations. This could lead to a decrease in the price at which inverters are invoiced for small applications, putting a high pressure on traditional distributors.

Re-branding exists, for inverters. Some inverters could be sold under a different brand than the manufacturers' one. This is especially valid with packaged products, and for small installations. For instance SolarWorld used to sell inverters under its own brand, while they were produced by a specialised manufacturer. This can also be seen for central inverters which could be partially installed by third parties, which are selling them under their brand, while a large part of the components and the technology would come from a specialist in the inverter sector.

Table 40. Number of wholesalers, wholesalers distributors and distributors of inverter for photovoltaics in EU per country

	Wholesalers	**Wholesalers/ Distributors**	**Distributors**
Austria	25	3	3
Belgium	10	1	5
Bulgaria	11	2	2
Croatia	5	-	-
Cyprus	4	1	1
Czech Republic	10	5	14
Denmark	18	1	9
Estonia	2	1	-
Finland	3	1	3
France	32	11	12
Germany	177	36	30
Greece	17	6	8
Hungary	16	8	8
Italy	47	23	25
Ireland	2	-	3
Latvia	1	1	-
Lithuania	6	-	-
Malta	1	1	2
Netherlands	99	12	13
Poland	14	4	8
Portugal	4	1	6
Romania	21	-	4
Slovakia	3	-	1
Slovenia	5	1	1
Spain	37	16	10
Sweden	17	4	1
United Kingdom	33	15	9
Total	*620*	*154*	*178*

Source: ENF Solar (2018)

2.3.4 Product trends – Systems

The PV industry is moving away from the early approach in which the customer not only owned and financed the PV system, but also managed most aspects of installation. A classification of the PV system business models has been made to reflect the evolution of them[110]. The first or zero generation model is referred to a relatively small group of so-called pioneers who were committed to PV's environmental, energy security, and self-generation benefits. The PV industry has evolved to 1st Generation PV business models where the product is more attractive to a broader market, moving into the so-called early adopter customer category (see Table 41). 2nd Generation business models have yet to emerge, but will emphasize greater

[110] Frantzis, L., Graham, S., Katofsky, R., & Sawyer, H. (2008). Photovoltaics Business Models.

integration of the PV systems into the grid because emerging technologies and regulatory initiatives are likely to make such integration more viable and valuable.

Table 41. Evolution of PV systems business models.

0 Generation	1st Generation	2nd Generation
PV System Supply	**Third-party Ownership and Operation**	**Full integration**
• Business models focused on manufacturing, supply and installation of PV systems • End-user is the owner • Utility is largely passive, providing net metering and standard/simplified interconnection, but otherwise, unaffected.	• Business models driven by third parties which develop projects and own PV systems, resulting in: –Reduction of hassle & complexity for end-user –Better access to financing –Leveraging of current incentives structure (especially for commercial building applications) • Utility gradually takes on a facilitation role as PV market share grows	• Business models allow PV to become an integral part of the electricity supply and distribution infrastructure • Business models emerge with variation of system: –Ownership –Operation –Control • Utility becomes more deeply involved, as PV becomes major consideration • PV product supply chain becomes "commoditized"

Source: Frantzis, L., Graham, S., Katofsky, R., & Sawyer, H. (2008). Photovoltaics Business Models.

2.3.4.1 Market segmentation

This section reviews the market segmentation with a focus on the ownership of the PV systems. As seen above, the requirements of the owners of the systems (being end users, third parties or utility) are creating new market demands for e.g. new technologies, contracting services, and maintenance services. In the EU, there are two major applications for grid-tied PV: residential and utilities. Of the nearly 6216 MW of PV deployed in EU in 2016, grid-tied residential and utility comprised 22% and 38%, respectively[111]

2.3.4.1.1 Residential scale

Up to the year 2016, almost 20GW residential solar PV had been installed in the EU (Becquerel Institute, 2018). The further expansion of residential self-generation requires the dedicated analysis of the interests of a variety of market players such as energy suppliers, grid operators, technology suppliers etc.

Residential prosumers have installations to produce electricity for their own use while they also have the possibility to feed the surplus that they do not consume into the grid. According to DG JUST study[112], in all EU Member States we assumed that 47% of electricity generated is self-consumed and the remaining 53% of electricity is exported to the grid. See Table 42 for the distribution of prosumers across the EU countries plus Norway and Iceland.

[111] Bequerel Institute, 2018

[112] Study on "Residential Prosumers in the European Energy Union" JUST/2015/CONS/FW/C006/0127

Table 42. Take up of residential solar PV – baseline results with a share of prosumers.

	Residential solar PV capacity in 2015 (MW)	Residential solar PV capacity in 2030 (MW)	Growth rate, 2017-2030 (% pa)	Share of total potential residential solar PV capacity (2030)	solar PV prosumers as a share of all households (2030)
Belgium	1,976.9	3,255	3.5%	29.0%	8.2%
Bulgaria	8.9	40.6	10.2%	1.4%	0.5%
Czech Rep.	95.0	106.3	0.8%	2.6%	0.7%
Denmark	454.1	838.1	4.2%	18.7%	6.8%
Germany	5,240.5	9,137.8	3.8%	39.5%	5.8%
Estonia	1.1	5.6	8.2%	1.7%	0.2%
Ireland	1.1	12.4	15.3%	0.4%	0.2%
Greece	350.0	950.2	4.4%	27.4%	6.7%
Spain	48.6	57.9	1.2%	0.4%	0.1%
France	1,049.0	2,622.7	6.3%	6.6%	2.6%
Croatia	12.1	30.3	6.3%	1.2%	0.5%
Italy	2,640.0	5,614.1	5.1%	22.6%	5.9%
Cyprus	20.6	55.7	6.7%	7.6%	3.1%
Latvia	0.4	5.6	14.9%	1.5%	0.3%
Lithuania	19.7	31.2	3.1%	3.9%	1.1%
Luxembourg	33.6	80.6	6.0%	14.1%	5.0%
Hungary	60.5	282.8	10.0%	5.0%	2.3%
Malta	19.7	23.6	1.3%	13.0%	3.6%
Netherlands	1,086.0	3,684.0	8.1%	26.4%	9.5%
Austria	377.5	684.2	4.3%	16.4%	5.1%
Poland	10.2	151.2	16.5%	1.0%	0.4%
Portugal	147.1	382.9	6.5%	7.5%	4.1%
Romania	13.3	18.7	2.3%	0.3%	0.2%
Slovenia	1.8	13	12.9%	1.1%	0.5%
Slovakia	5.9	40.4	12.5%	1.9%	0.6%
Finland	4.0	24.5	12%	0.7%	0.2%
Sweden	52.0	257.6	9.4%	3.4%	1.1%
UK	2,499.0	3,539.9	2.1%	13.1%	3.5%
Iceland	-	-	-	0.0%	0.0%
Norway	11.3	25.6	5.5%	0.4%	0.3%

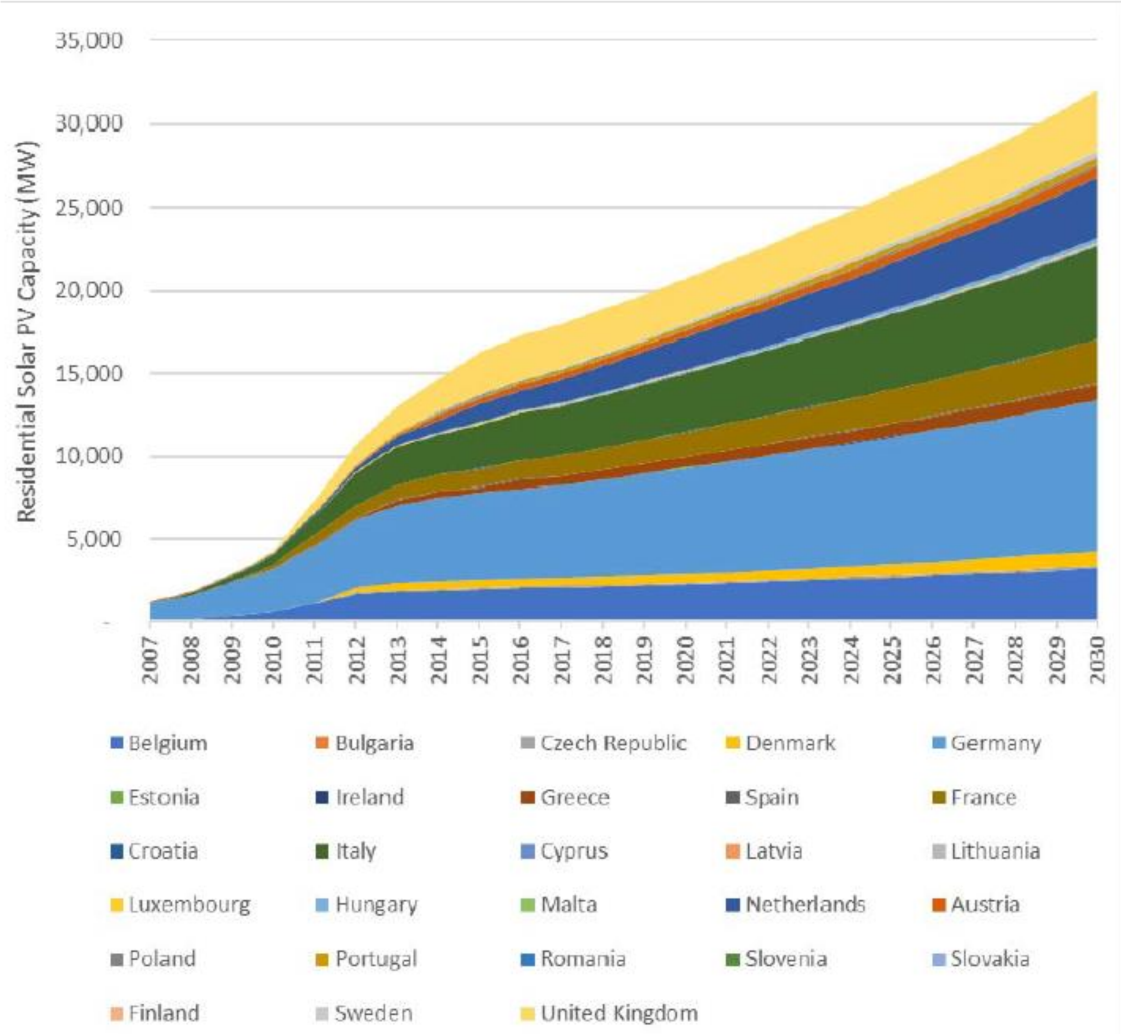
Source: DG JUST study "Residential Prosumers in the European Energy Union"[112]

Across Europe, the situation with regard to remuneration for feeding electricity into the grid is not uniform and different rules apply: in many countries Feed-in Tariffs are (still) available, alongside net-metering, or the electricity fed into the grid can benefit from premiums. Besides, other forms of support are available depending on the country, including green certificates, tax reductions, loans and investment support. Falling solar PV prices coupled with high retail electricity prices have made it possible for residential prosumers in some EU Member States to achieve grid parity[113]. Figure 49 shows the capacity take up of the EU residential sector.

[113] *Deutsche Bank Market Research, Solar Industry, 2015.*

https://www.db.com/cr/en/docs/solar_report_full_length.pdf

Figure 49. Take up of residential solar PV: base line results.



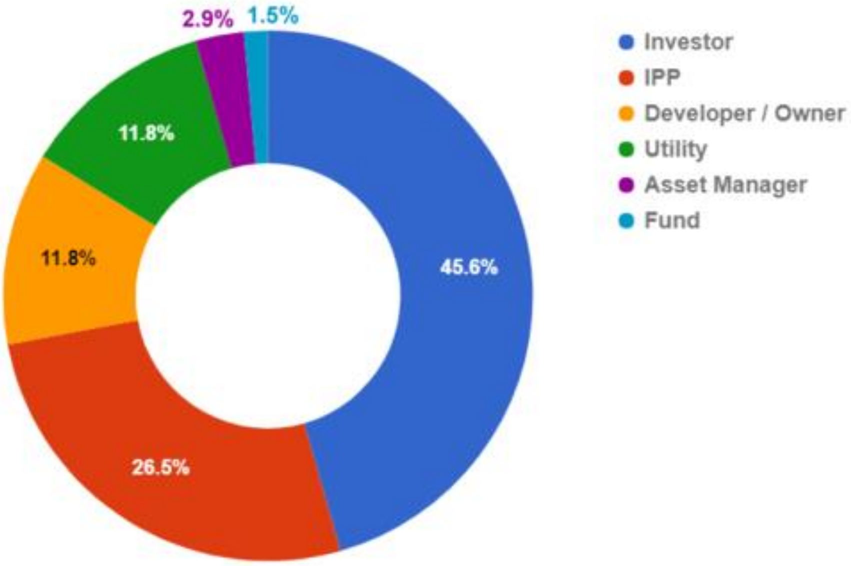
Source: *GfK (2017)*

2.3.4.1.2 Large, utility scale systems

Solar investment portfolios

The investment community considers Europe to be a mature market for solar photovoltaic investments. Notwithstanding the uncertainty created by changing Member State subsidy regimes, as was discussed in section 1.3.2 of the Task 1 report, solar systems continue to be a bankable investment as a fixed asset. The split of ownership for the top 70 EU portfolio owners of large solar photovoltaic plants is illustrated in Figure 50. The majority are reported as being investors, followed by Independent Power Producers (IPPs), developer/owners and utilities.

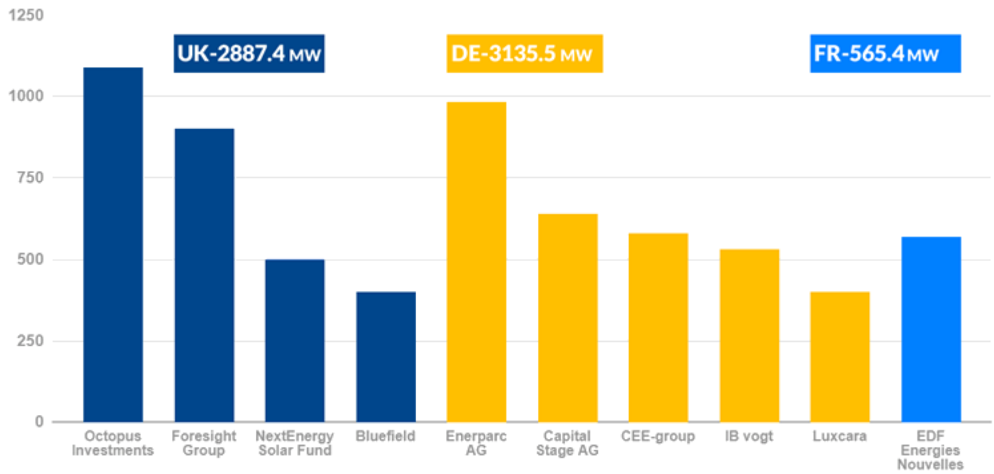
Figure 50. Breakdown of ownership types for the top 70 EU solar investment portfolios



Source: Solar Asset Management Europe (2017)

The ten largest investment portfolios, measured in terms of installed capacity and as illustrated in Figure 51 accounted for approximately 6.6 GW of installed capacity in 2017[114]. The capacity identified in the figure is largely understood to be located in the three countries of registration of the investors. The leading funds were Octopus Investments (UK), Enerparc AG (Germany) and the Foresight Group (UK). The average capacity at each site in the portfolio of the largest investor, Octopus Investments, is estimate to be 5.4 MW.

Figure 51. The top 10 EU solar investment portfolios in 2017



Source: Solar Asset Management Europe (2017)

2.3.4.2 Trends in photovoltaic systems and features

In order to identify and understand how trends may affect different parts of a system a number of different elements have been identified, some of which relate to component choices at the design stage, others of which relate to services provided during the operational phase of a system.

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[114] *Solar Asset Management Europe, Top 70 European solar portfolios, Accessed February 2018, https://www.solarassetmanagementeu.com/new-updates-source/2017/7/31/top-70-european-solar-portfolios-2017*

- Design stage: new components for the module array and balance of system that have overall implications at a system design level.
- Operational stage: new IT systems and operational services that facilitate better monitoring and maintenance of performance.

For each component, system or service their relevance to the four PV system types is also identified – namely residential, commercial, industrial and utility scale.

2.3.4.2.1 Design stage

Dynamic energy yield simulation

The use of dynamic simulations (those with an hourly and shorter time series without averaging) of a PV system's performance improves its precision. Relative errors of up to 5% in precision are found for annual energy yield simulations have been found between those using either hourly or averaged weather input [115]. This precision is particularly important for PV system designs that are integrated with batteries or connected to a congested electrical grid.

The use of dynamic simulation software is already prevalent in the design of larger, commercial systems. For example, the tool PV Sys is understood to be widely used for commercial and utility scale projects. It is also used for commercial buildings that may incorporate BAPV or BIPV systems such as offices, but rarely in the residential sector. Software tools of this kind allow for more complex modelling, taking into account for example geographic location, orientation, shading, module efficiency, module technology, inverter efficiency, etc.

Tracking systems

Tracking systems have traditionally been of most significance to larger systems. These systems allow the module array to track the path of the sun, thereby maximising the energy yield. Two axis tracking is generally more expensive and its complexity can create maintenance issues. However, one axis trackers are receiving greater attention as a cheaper, lower maintenance alternative to increase yield.

The projected market share of tracking systems in large scale PV plants is shown in Figure 52. According to the ITRPV roadmap, 1-axis systems will increase the market up to almost 50% by 2020 onwards. While bifacial modules may capture up to 10% more light than monofacial modules, single-axis trackers typically add 25% to that bifacial gain, resulting in a roughly estimated 12.5% gain from the two technologies combined. [116] Bifacial panel use in combination with single-axis trackers is expected to grow to a double digit share within a year, and eventually become the dominant design.

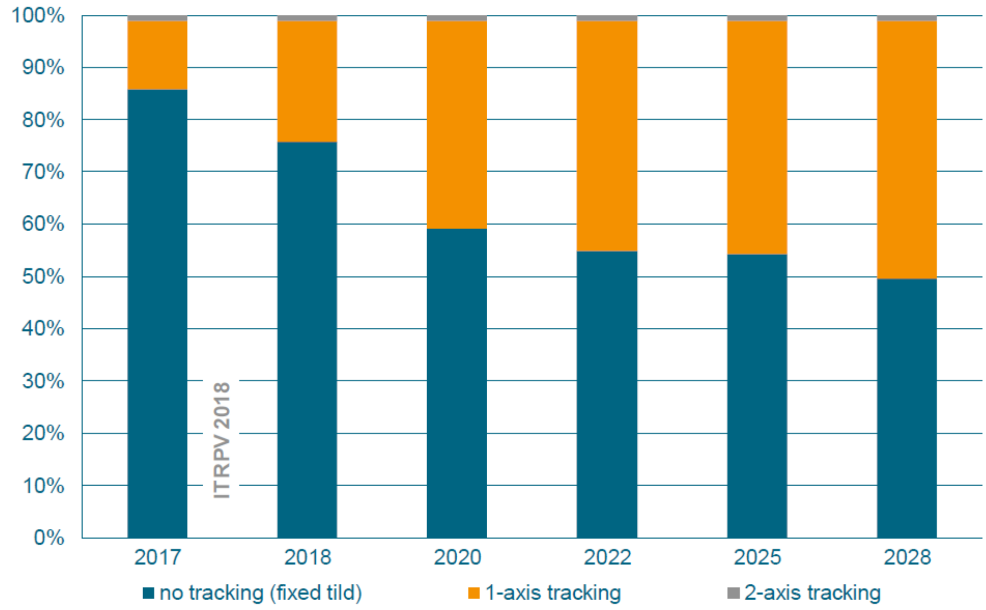
Another substantial step forward in tracker design is adding storage, this has been seen in a 100 MW of double-axis trackers along with a 50 MW vanadium redox flow battery to provide a greater energy supply in the late afternoon and evening hours when demand is highest. The stored energy provides voltage variability services [117].

[115] *Thomas Huld, Gottschalg, Beyer, & Topič, 2010*

[116] *PV magazine, Solar trackers: Record 2017 shipments; up to 20 GW expected in 2018. https://www.pv-magazine.com/2018/02/22/solar-trackers-record-2017-shipments-up-to-20-gw-expected-in-2018/*

[117] *PV Magazine, Trackers spread globally as designs improve, July 2016, p-40*

Figure 52 Projections for tracking systems used for crystalline PV based systems



Source: ITRPV (2018)

Design to maximise array bifaciality

The projected mainstream entry in the market of modules with bifaciality – meaning that the cells and glass encapsulation allows for energy from sunlight to be harvested from the front and rear – will have an implication for array designs. This is particularly the case where the structure and roofing substrate is relatively unconstrained *e.g. on buildings with flat roofs*.

From the point of view of investors the claims made for additional energy yield are still unsubstantiated. Commentators have therefore emphasised the importance of array designs that are optimised to support bifaciality. This optimisation can include consideration of the type of mounting structure, the use of tracking systems and can even extend to include the treatment of flat roof or other underlying surfaces in order to reflect light onto the rear side of modules.

Storage components of Balance of System

Li-ion batteries are the most common storage technology, regardless of application. Lithium-ion batteries can typically deliver more cycles in their lifetimes than lead-acid. This makes them a good choice for applications where batteries are cycled to provide ancillary services to the grid. The most important benefit lithium-ion provides for solar is its high charge and discharge efficiencies, which help to harvest more energy. Lithium-ion batteries also lose less capacity when idle, which is useful in solar installations where energy is only used occasionally.

An increase in the demand for self-consumption is driving greater market penetration of battery storage as an integrated component of solar PV systems. Trends in storage are as mentioned in the market segmentation and also in the inverter section, the adaptation of inverter products to off-grid solutions combined with battery storage, and their integration at module level.

Module Level Power Electronics

As was mentioned already in the module section 2.3.2.2, there is a trend in residential systems to include a number of module level power electronic solutions. The integration of micro-inverters and DC optimisers at module level is claimed to facilitate improvements in overall efficiency at Balance of System level of anywhere between 5% and 25% are claimed, but this requires further substantiation. Moreover, a move to dual junction boxes is claimed to ease the installation time and reduce the cabling required for the interconnection of modules, offering potential reductions in the overall bill of materials.

Connectors

One of the trends for the connectors and cabling of the PV modules is the use of combiner boxes. A PV Combiner Box serves to bundle the output lines of individual strings and to connect them to the inverter. The design of the box has to be customized for each customer's application. Advanced surge protection devices, fuse links are usually included in combiner boxes. This trend is understood to largely relate to the recent entry into the market of string inverters that can be used instead of central inverters in larger systems.

2.3.4.2.2 Operational stage

Monitoring and data analytics

There is increasing interest at a commercial level in accurate monitoring in order to optimise operational activities. A key focus has been on the potential to accumulate performance data at array, BoS and system level which can then be analysed. Monitoring systems in this way can support the optimisation of maintenance tasks and the early detection of any need for intervention such as e.g. module washing frequency, ascertaining if string fuses have blown.

Tools for data analytics are now available based on artificial intelligence and machine learning. These can be used to verify the performance behavior of PV plants and at a later stage improve and automate the optimization of performance [118]. These types of tools can be used to detect early faults and performance degradation and to give actionable recommendations on the root causes.

Data analytics of this kind will increasingly form part of operation and maintenance contracts, as will be discussed in the following section.

Operation and maintenance services

Both preventive and corrective maintenance are generally considered as part of contracts for larger PV systems. For preventive maintenance detailed visual and physical inspections (e.g. aerial Infra-red imaging, on-site characterisation for selected modules) are standard practice. This type of maintenance can be supported by mobile testing labs, whereby modules can be deinstalled and tested on site. One of the latest trends involves the use of drones to remotely monitor module arrays.

Maintenance services can also a range of other factors relating to the external environment, and which can be detrimental to the Performance Ratio of systems. This can include cleaning, vegetation cutting and snow/sand removal. To minimise the downtime of the PV system the keeping of critical spare part stock also forms part of servicing. Examples of the full range of possible services are presented in Table 43.

[118] 3E, Retrieved March 2017, http://www.3e.eu/data-services/pv-health-scan/ and http://www.3e.eu/pv-performance-verification-meets-big-data/

Table 43. Example of some O&M services already available in the market

<table>
<tr><th rowspan="2"></th><th colspan="2">Operation & Maintenance services</th></tr>
<tr><th>Commercial</th><th>Domestic</th></tr>
<tr><td>System Health Check</td><td>– Visual check of all rails and mountings
– Visual check of module condition
– Full string test
– Visual & physical check of all module connectors
– Interrogation of inverter display error codes and logs
– Full inverter diagnostic testing and checking of monitoring connectivity
– Visual check of all system AC & DC electrics
– Inverter & fan dust and clean
– Irradiance test and other tests using Seaward diagnostic technology
– Full report of system condition & operation provided to system owner</td><td>– Visual check and test of key connections, switches and electrical components;
– Visual check of panels, mountings and other hardware components;
– Inverter diagnostics;
– Irradiance & DC circuit test;
– Clean inverter and fan;
– AC electrical safety certificate compliance
– Thermal transfer fluid check and top-up (recommended)
– System re-pressurisation (recommended)
– Report and recommendations</td></tr>
<tr><td>Solar Panel Cleaning</td><td colspan="2">– Use of specialist equipment and super-clean water to clean the panels (with low water usage)
– Extremely pure water produced on-site by mobile 3 stage filtration, reverse osmosis and de-ionisation equipment to ensure near zero deposits
– Specialist brushes clean and rinse panels thoroughly without damaging delicate mysophobic coatings
– Water-fed pole system offer up till a certain lateral reach
– Visual check of array condition</td></tr>
<tr><td>System Upgrades</td><td></td><td>– Battery Storage technology
– Air Source Heat Pumps
– Immersion Controllers (to convert the excess electricity produced by the PV system into piping hot water)</td></tr>
</table>

Source: Solarsense 2018

2.3.4.2.3 Feedback from the stakeholder questionnaire

The first stakeholder questionnaire included a question on what stakeholders considered as the commercial state of the art for system design and specification. The answers given by respondents are briefly summarised in this section.

Q3.4 Please indicate what you consider as the commercial state of the art for each of these technical aspects

- *Design and optimisation:* of the eight respondents to this aspect:
  - *Simulations:* five identified dynamic simulations of energy yield taking into account the 'real' ambient conditions.
  - *Real energy yield conditions*: One respondent highlighted the importance of using a spectral response based on real conditions within energy yield simulations. A reference was provided for a specific simulation software used for utility scale systems.
  - *Module Level Power Electronics:* One identified Module Level Power Electronics as being an important aspect.
- *Installation quality and performance:* of the ten respondents to this aspect:
  - *Monitoring:* three identified module level monitoring and two went further to identify module level optimisation as a further step. Linked to this, three respondents identified smart fault identification and reporting. One respondent identified systems >100 kW as being those that are normally monitored. The point of data collection could be a DC optimiser or a combiner box.
  - *Installation quality:* One identified the potential to focus on installation quality as a means of avoiding *'latent defects'*. One respondent highlighted the potential for installation criteria to ensure correct future functioning.
- *Active self-consumption:* of the nine respondents to this aspect:
  - *Demand-side management:* four identified smart metering and demand side management. One respondent additionally identified *'whole-home platforms via common standards'* such as EEBUS.
  - *Collective self-consumption*: two identified micro-grids and collective self-consumption based on the sharing of the output from systems between several end-users in the immediate vicinity (citing France law as an example).
- *Energy storage:* of the nine respondents to this aspect:
  - *Battery storage:* Four identified battery storage as state of the art.
  - *Grid interaction:* Three identified the need for grid interaction and support services. Systems should be able to contribute to the stabilisation and reliability of the grid.

2.3.4.3 Competitive analysis

Europe also has strong firms in more specific PV domains such as manufacturing of connectors, (sun) trackers, encapsulants and polymers in general, and solar glass. Most of these champions invest heavily in research and development (R&D). In order to identify and understand how trends may affect and relate to different segments of the market the competitive analysis has been divided into the design and the operational stage.

2.3.4.3.1 Design stage

Storage components of Balance of System

While there has been an overall downturn in residential installations, for example in the major EU markets of Germany, Italy and the UK, a diversified offer of components and services for 'prosumers' has emerged and there is evidence that it is growing. For example, in section 2.3.3 it was already mentioned that inverter manufacturers such as SolarEdge, Huawei, SMA are already offering inverter level power electronics that support battery integration.

The leading market for battery storage systems is Germany, where the introduction of financial incentives has led to the installation of more than 75.000 PV + storage systems by the end of 2017 (BSW - Bundesverband Solarwirtschaft e.V.) and where a total installed capacity of 500 MW is predicted by 2021[119]. The leading supplier is Sonnen (Germany), although Fenec, LG Chem and E3/DC are also identified by commentators.

SonnenBatterie from Germany, also called Sonnen, is located in the German region of Schwaben, but also has a strong presence in the US market. The company has received several awards recently, among them the EUPD recognition of best product in the class “Lithium-Ion-batteries under 5 kW”. Sonnenbatterie has managed to reduce the cost of its hybrid solar-battery by 20% thanks to the elimination of the external inverter. Sonnenbatterie has created its own community, which includes 12,000 families already using the battery and is expected to reach 20,000 by the end of 2016. This community also

[119] Colthorpe, A, Germany showing the way for storage, PV Tech magazine, May 2017

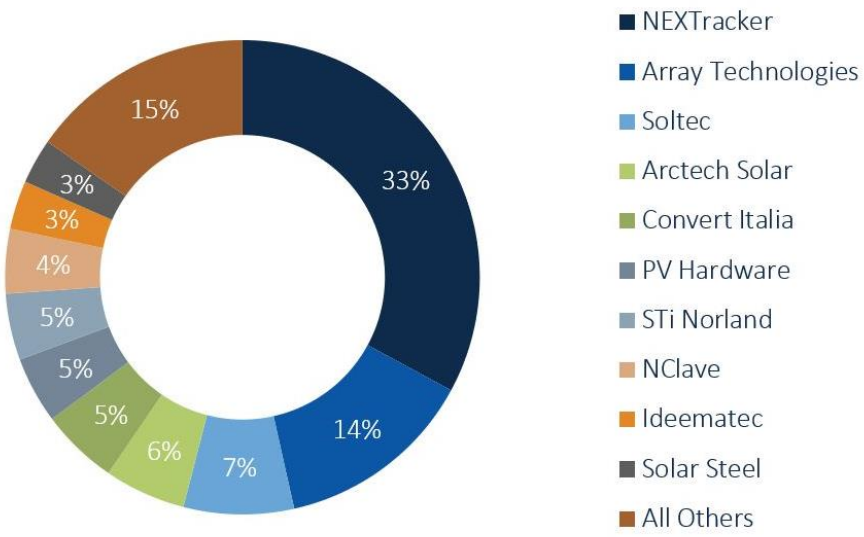
benefits from energy efficiency services provided by the company. The combined generation capacity of Sonnenbatterie's clients ascends to 2.5 GWh per week.

The data available for this emerging sector confirms the rather pessimistic viewpoint that the European position is rather weak, despite the promising results of some firms such as Sonnenbatterie. Soluxtec GmbH, also from Germany, is another company directly targeting the off-grid market, and the main inverter producers are also adapting to off-grid solutions combined with battery storage, as explained in more detail in 3.3.3. Spanish and Austrian companies are also understood to be launching products.

Tracking systems

A survey of the top international tracker companies shows that more than five dozen countries now have installed PV tracker arrays totalling more than 14.8 GW of cumulative capacity. The tier of countries with installed trackers totalling over 100 MW include: India with 466.4 MW; Spain with 296.2 MW; Italy with 238.5 MW; South Africa with 180 MW; Jordan with 161.7 MW; Greece with 153.2 MW; Honduras with 146 MW; China with 133.4 MW; France with 129.9 MW; Canada with 122.5 MW; and Germany with 115.9 MW.

Figure 53. Global solar PV tracker market shares by MW shipped, 2017.



Source: GTM Research (2017)

The commercial and industrial (C&I) market is set for exponential growth in tracking technology in 2018 at least in the US (PV magazine[120]). With diminishing utility-scale site availability and rapidly increasing tracker competition, the C&I segment seems poised for exponential growth in tracking technology, on advances in marketing with models like community solar, and advances in financing and technology.

Among the top five tracker manufacturers companies globally, two are European, Soltec (SP) and Convert Italia (IT), as seen in Figure 53. Trackers are an obvious choice in most developing solar markets; a 30 percent growth is expected globally in 2018, with shipments approaching 20 gigawatts.[121]

Connectors

Connectors must also be mentioned in this context, since their quality heavily influences the performance of the PV system as a whole. The main European company in this field is Multi-Contact AG, which manufactures connectors for diverse domains

[120] *PV Magazine article: Shifting demand and pricing pressure main solar tracker challenges – GTM Research. https://www.pv-magazine.com/2018/02/23/shifting-demand-and-pricing-pressure-main-solar-tracker-challenges-gtm-research/*

[121] *https://www.pv-tech.org/news/latin-america-was-largest-market-for-solar-trackers-in-2017-gtm-research*

such as electric utilities, robotics/manufacturing, medical equipment and renewable energy. Multi-Contact's competitive advantage is based on stringent quality control procedures, as it discovered that the interface between the module, connectors, wires and the combiner boxes caused up to 50% of the errors in PV-systems (one crystalline module has at least twelve interfaces between the junction box, the connector and its cable branch) and that such errors increase considerably between year four and eight of the useful life of the module. The company is struggling with unfair competition from counterfeit products from Asia, especially in the field of plug-in connections.

2.3.4.3.2 Operational stage

No data about Monitoring and data analytics and operation and maintenance services could be gathered.

2.3.4.4 Channels to market

As seen in previous sections, when dealing with systems, the channels to market can be quite diverse depending also on the scale of the system, whether it is large scale or small residential installer market. Project developers and engineering procurement and construction (EPC) companies are normally present in large installations, while system installers normally act at all scales.

Project developers initiate solar generation projects and are responsible for the initial design and early consent. With regard to capacity, the main project developers in Europe are found in Germany (with an accumulated value of 2,040 MWp), France (811), Austria (469), the UK (358) and the Netherlands (307) (Wiki-Solar, 2016b).

Analogously, EPC contractors are primarily responsible for the engineering, procurement and construction of the plant. This usually includes selecting the suppliers of solar modules, inverters and other key items of equipment; and finalising and underwriting the final design and output projections for the plant. In the case of EPC contractors, the Member States whose firms have the highest accumulated capacity are Germany (3,569 in MW_{AC}), Spain (631), the UK (585), Austria (466), France (369) and Portugal (318).[16]

Table 44. Numbers of solar photovoltaic system installers listed in a leading trade directory

Member State	**Number of installers**
Germany	2930
Italy	2511
United Kingdom	2460
Netherlands	1510
Spain	912
France	860
Belgium	596
Austria	429
Denmark	364
Poland	359
Czech Republic	249
Greece	231
Portugal	158
Others	1384
Total	*14953*

Source: ENF Solar (2018)

The sector of engineering, studies and administration has shown less sensitivity to the downsizing of the PV market (Ernst & Young 2015). Europe has a strong position in electrical installations and related service areas. However, smart grid solutions are not primarily aimed at promoting solar uptake, but a wider range of objectives (including service quality, energy

management, billing and electric vehicle connection) and crucial questions such as financing of smart grid investments and burden-sharing are not yet solved, so that immediate impacts on solar uptake are doubtful.

Unlike the USA, where better margins are understood to have driven growth of a number of large installation companies who now account for a significant share of the residential PV systems, the EU market is understood to be more fragmented . The ENF Solar database lists 14953 installers (see Table 44), although a size class distribution for these installers is not available.

There is emerging evidence that large retailers, utilities and conglomerates are now seeking to enter the market for solar photovoltaics, offering consumers a single point of contact to obtain information, provide advice, make arrangements for installations and provide aftercare services. A major example is the international home retailer IKEA which in Belgium, the Netherlands and the UK has worked in collaboration with the installation company Solar Century. Other examples include the utilities E.On [122], EDF and RWE, as well as car manufacturer Nissan [123].

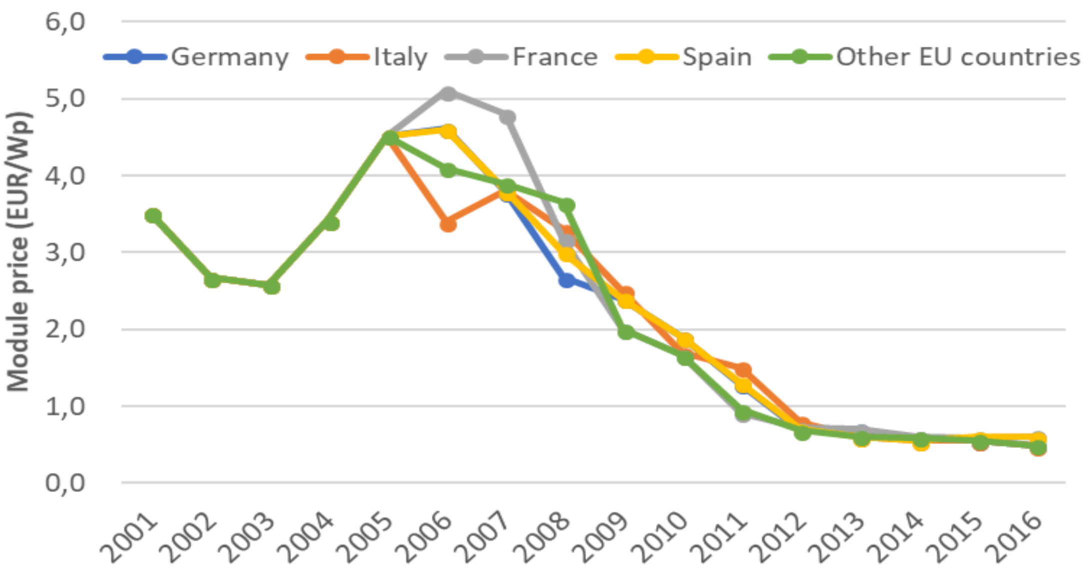
2.4 Consumer expenditure base data

2.4.1 PV Module prices

The module prices in the selected countries Germany, France, Spain, Italy and others, have followed the same trend along 2001 to 2016 (Figure 54). They all had a peak around 4.5 -5 EUR/Wp in 2005 (or 2006 in the case of France and Spain) and then a continuous reduction down to 0,5 EUR/Wp, which is an average of a -90% decrease.

According to Solar Power Europe report[124], unit costs for modules and cells are indeed expected to decrease, with unit costs for modules (-52%) falling more significantly than that of cells (-19%). These percentages are based on the average difference between the global market prices and the 2017 prices under the EU trade defence measures.

Figure 54. PV module prices in EUR/Wp for the years 2001-2016 for the selected countries



Source: created with data from Becquerel Institute, 2018

2.4.2 Inverter prices

Figure 55 and Table 45 present the historical factory gate prices for five different inverter types in 2015-2017, together with estimates made through to 2022. The prices have been converted from dollars using the European Central Bank's average

[122] E.On Solar, https://www.eonsolar.co.uk/

[123] Nissan Energy Solar, https://www.nissanenergysolar.com/

[124] Solar PV Jobs & Value Added in Europe, EY Solar Power Europe, 2017

published exchange rate for 2016 [125]. The historical prices are nominal values including inflation and the forecast prices are real terms. The unit of comparison is EUR per watt of rated AC power output.

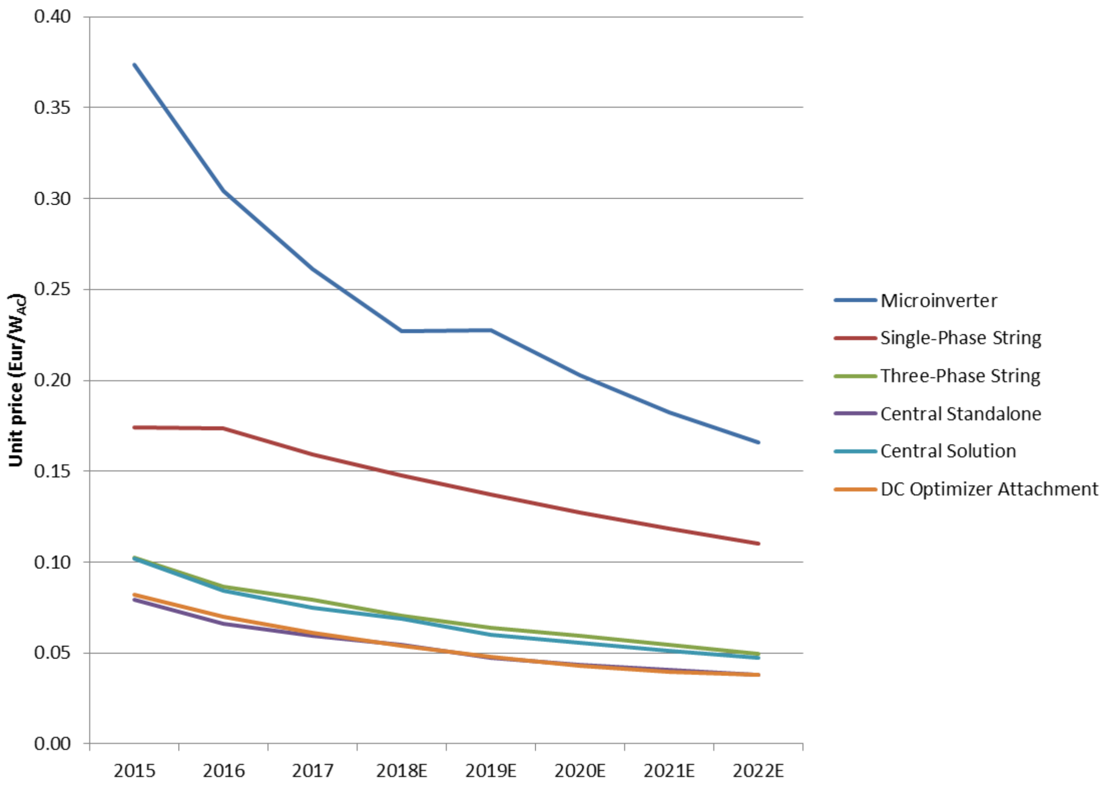
The most notable trend is the sharp decline in micro-inverter pricing, which reflects aggressive cost reductions by the market leader Enphase Energy, as well product innovation, such as dual module inverters. It is anticipated that further moves towards AC module integration will contribute to the downward price trend.

The relatively low unit prices of three phase string inverters reflects their historical path to large scale production of units for smaller systems as well as the global reach of manufacturers such as Huawei. String inverters have the broadest applications by system size, so the overall figures mask significant price variations. In particular the entry of string inverters into the utility scale PV system market segment (>40 kW) has contributed to continuing downward pressure on prices with, for example, utility scale models requiring less Maximum Power Point Trackers (MPPTs). The price difference between this segment and more expensive 10-40 kW models can typically be in the range of 36% and 66%.

Single phase string inverters are understood to be subject to the most price constraints, which may explain their continued relatively higher pricing. Their application in Europe has been mainly in smaller systems of <5 kW, in which this type of inverter tends to have a higher unit price.

In terms of future price forecasts, up until 2019 prices are estimated to decline on average between 10% and 20%, slowing to between 5% and 10% between 2019 and 2022. Future cost reduction potential exists in the shift from 1,000 volt to 1,500 volt utility scale applications, as well as the already identified entry into the market of inverters with new semi-conductor designs and greater power densities. Cost reductions resulting from manufacturer consolidation and learning are estimated to be in the range of 3-7% per annum.

Figure 55. Inverter factory gate prices 2015-2017 and forecast to 2022 E=Estimate



Source: GTM Research (2018)

[125] *European Central Bank, US Dollar (USD) https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html*

Table 45. Inverter factory gate prices 2015-2017 and forecast to 2022 (Eur/W_{AC})

Inverter type	2015	2016	2017	2018E	2019E	2020E	2021E	2022E
Microinverter	0.37	0.30	0.26	0.23	0.23	0.20	0.18	0.17
Single-Phase String	0.17	0.17	0.16	0.15	0.14	0.13	0.12	0.11
Three-Phase String	0.10	0.09	0.08	0.07	0.06	0.06	0.05	0.05
Central Standalone	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.04
Central Solution	0.10	0.08	0.07	0.07	0.06	0.06	0.05	0.05
DC Optimiser Attachment	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.04

E=Estimate

Source: GTM Research (2018)

2.4.3 PV System pricing and cost structure

2.4.3.1 Final system prices

The final system price has declined even faster than the module price in the recent years and for ground-mounted systems, prices below 0.70 EUR/Wp in Europe and below 0.65 USD/Wp have been registered in emerging markets such as India, thanks to very low cost for manpower. But the price decrease hasn't been that tremendous in all countries and market segments. In countries where the level of incentives remains sufficiently high, the decrease of prices was less significant. In Japan and in the USA, prices for rooftop system remain much higher than in the most competitive countries such as Germany for instance. The potential for price decline is still high in many segments and countries, while the current price of ground-mounted installations will continue to decline at a slower pace. Due to the increasing competition on tenders, the real price of PV systems cannot be estimated with precision but simple LCOE calculations show that most announcements are now in line with feasible prices.[126]

Concerning installation, rooftop PV installations support almost three times as many jobs and Gross Value Added than ground-mounted installations. This can be explained by their installed capacities, unit cost per MW and labour needs for installation, maintenance and operations. e.g. installation and maintenance & operations are easier and less time-consuming for ground-mounted systems, having a lower cost per MW. This means that fewer jobs are supported per MW compared to rooftop PV systems.

The cost of operation and maintenance becomes increasingly significant with the decline of PV system prices. Experience tends to show that it could be more important than initially calculated and actually influences the LCOE. This seems to be valid especially in humid or desert and hot climatic countries where PV is expected to develop further now. Some uncertainties due to quality issues in these environments could increase the cost of operation and maintenance in several countries compared to the expected numbers. It appears more and more that PV installations should take into account the location of the plant, not only with regard to the energy yield but also to the additional costs incurred due to anticipated the failure of systems components (modules, inverters…).

The expected lifetime of PV plant is evolving in various ways, with the idea that PV plants could be completely refurbished, including new modules after a certain lifetime, in such a way that they could compete with conventional power plants with lifetimes greater than 40 years.

[126] *Global PV market report 2018 – 2022. PV Market Alliance, 2018*

2.4.3.2 System cost structure

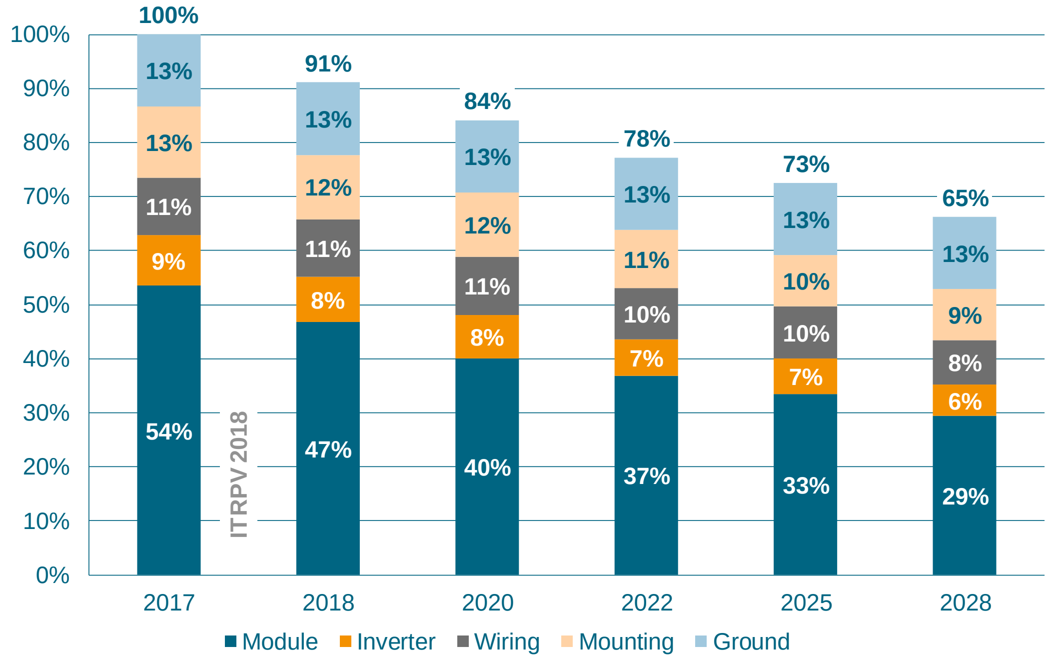
The cost structure of a photovoltaic system has until recently been dominated by the modules. With the entry into the market of Chinese mass producers this cost structure has both reduced overall and the Balance of System components have become more important as an overall proportion of system costs, as can be seen in Figure 56 which illustrates a projected continuation of the downward price trend, albeit for a generalised cost structure.

The proportion of system costs accounted for by Balance of system is projected to increase from 46% to 52% in 2020 and 55% by 2028. This represents only the elemental (capital) costs, as well as land (ground) costs in the case of ground-mounted systems and excludes 'soft' costs associated with system design, permitting and installation/commissioning. These costs have been estimated based on an analysis of completed projects in the Germany PV market (see Table 46). The breakdown dates to 2013, and further component cost reduction will have subsequently occurred[127], however it is useful as an insight into the whole cost of an installation.

In the case of BIPV systems the module cost may account for a greater proportion of the cost structure because the product must also fulfil the building component function. BIPV products are also more bespoke, being produced in much smaller production lots than modules, which to an extent have become more standardised. Figure 57 illustrates the possible ranges and outliers for different typical BIPV products based on a survey of 128 BIPV sector representatives conducted in 2013-14.

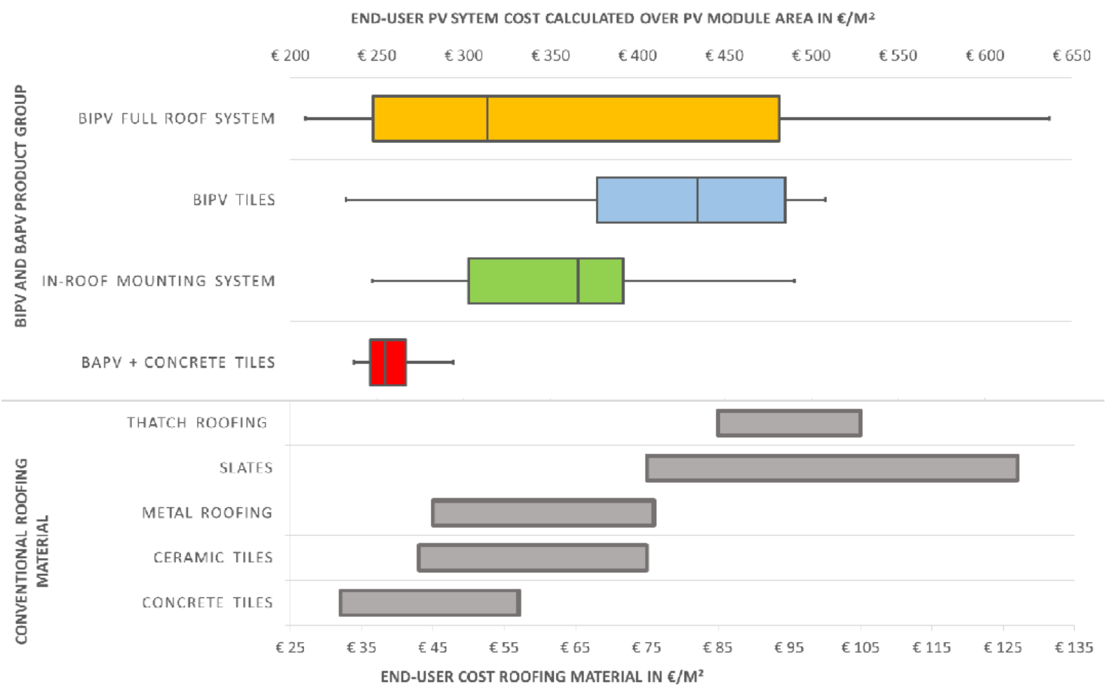
[127] IRENA Cost and Competitiveness indicators, Rooftop solar PV at: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Dec/IRENA_Cost_Indicators_PV_2017.pdf

Figure 56. System costs and cost projections



Source: ITRPV, 2017

Figure 57. Benchmark results from an end-user price survey, comparing conventional roofing materials with BAPV and BIPV roofing solutions



Source: Verberne et al (2014)

Table 46. Breakdown of labour costs and costs for 5 kWp add-on systems in Germany 2013.

Item	**Labour**	**Costs**		**Cost share**
PV module costs	[person-hours]	[EUR]	[EUR/kW_p]	[%]
Module (Si crystalline, Dec. 2013)	-	3000	600	37.8
"Hard" deployment costs	-			
Inverter (Dec. 2013)	-	1150	230	14.5
Mounting system	-	700	140	8.8
Cabling	-	100	20	1.3
"Soft" deployment costs and related transaction costs				
Customer acquisition (sales calls, site visits, system design, bid preparation, contract negotiation) *	5	175	35	2.2
Administrative processes related to building law*	0.67	23	5	0.3
Administrative processes related to grid connection permit*	1.5	53	11	0.7
Installation of PV system*	45	1575	315	19.9
Grid connection and commissioning*	2.5	88	18	1.1
Marketing and advertising		72	14	0.9
Overhead & profit installer firm		993	199	12.5
SUM		7929	1586	100
Time provided by building owner/client				
Information search	unknown	-	-	-
Site visit with installers	unknown	-	-	-
Contract negotiation with PV installer firm	unknown	-	-	-
Administrative processes related to financing	1	-	-	-
Corporate legal fiscal work	0.08	-	-	-
Registration to the federal Network agency	0.16	-	-	-
SUM	1.24	-	-	-

* Cost data calculated based on person hours and hourly rates

Source: Strupeit.L and Neij.L (2017)

2.5 Conclusions and recommendations

Initial conclusions and recommendations have been formulated in this section based on the work carried out in the present task. The definition of the product scope proposed in Task 1 for modules, inverter and systems is still considered to be valid in the light of these findings.

The main outputs provided by Task 2 are summarised according to the chapter headings used in this report. Barriers and opportunities for the implementation of eco-design and other policy measures are also highlighted and discussed.

2.5.1 Market and stock data

In the upstream segment of the market (i.e. component manufacturing), it is expected that the majority of jobs and GVA creation will shift from PV modules and inverters to other Balance of Systems (BoS) components over the 2016-2021 period, whereas downstream activities (i.e. services provided within the PV industry), which represent more than two thirds of the gross value added (GVA) in EU 28, are expected to rise again from more than 3500 M€ in 2016 to up to ca. 8000 M€ in 2021.

PV Modules

The total cumulative power of PV modules imported into Europe was approximately 87 GW up until the reference year, 2016. Adding the local production (23.92 GW) and subtracting the exports (9.43 GW), the installed base that constitutes the stock is estimated at 101.86 GW for year 2016. This figure represents one third of the cumulative global shipments up until the reference year (340 GW).

The six categories of PV modules with a market share greater than 1% are: multi-crystalline, mono-crystalline, amorphous silicon thin films, cadmium telluride films, and CIGS films. Until 2015 multi crystalline was dominant at utility-scale but since then prices for mono-crystalline have declined as production has expanded.

Although Cadmium telluride is the technology which has experienced the largest growth in the decade 2007-2016, in 2016 Multi silicon represented almost 70% of the market, Mono around 23%, CdTe ca. 4%, closely followed by high efficiency modules almost 3%, and CIGS 1.6% . Concentration and Ribbon PV modules figures were found to be negligible.

Due to the lack of the official shipments data that is differentiated by module technology and pricing, it is not possible to estimate the monetary value of shipments.

Inverters for photovoltaic applications

Inverter capacity is generally expressed in watts of AC rated output (WAC). Because inverter market data is generally estimated from module DC capacity it is important to understand how the two may interrelate depending on the market segment. There also exists a mismatch between shipment data and sales because stock destined for Africa is shipped first to the EU.

In total 6,854 MW_{AC} of inverter capacity was shipped to the EU market in 2016. It can be seen that overall the EU market is dominated by three phase string inverter technology.

With an adjustment for the undersizing of inverter AC capacity in proportion to module DC capacity on larger systems, the installed new stock in 2016 is estimated to be in the range of 5,678 and 6,151 MW_{AC}. Using similar assumptions the total installed stock until the end of 2016 is estimated to be in the range of 94,400 and 96,913 MW_{AC}.

PV systems

In terms of the installed stock for systems, the ground mounted installations (which can be mainly considered as utility scale) experienced the largest growth in the years 2001-2016, followed by the industrial and commercial sectors where there were years especially between 2008 and 2011 when the growth doubled (over 100% each year).

The total installed system stock in 2016 was 101,788 MW_{DC}. The majority of this stock was accounted for by commercial (32%) and ground mounted (31%) systems. Residential and industrial systems accounted for 19% and 18% respectively.

2.5.2 Market trends

According to the insight from the trends given in section 2.3, the main EU and global trends are identified and categorised as relating to:

- the structure of global module production and supply,
- the type of the financial incentives and market arrangements that will be used by Member States to support further market growth,
- the relationship of utilities with their consumers and their extent of their role in providing solar PV systems,
- the extent to which self-consumption models will shape system designs in the future,
- a diversification in the range of digital and operational support services available to system owners, and the benefits these can bring.

The seven main trends identified from four authoritative market analysis reports are summarised in Table 47.

Table 47. Identification and evaluation of global market trends

Trend	Time horizon	Degree of uncertainty
Continued overcapacity in global module production	Short term	Medium
Phasing out of financial support schemes	Medium term	Low
Increased use of solar auctions to drive down prices	Medium term	Low
An increase in Corporate Power Purchase Agreements for solar energy	Medium term	Low
An increased focus on operation & maintenance services	Medium term	Medium
An increase in the number of utilities that provide solar PV services	Medium term	High
An increase in self-consumption by system owners	Medium term	Medium to high
Digitalisation of PV systems and components	Short term	Low

PV Modules

Market segmentation: The global market share for PV modules is dominated by crystalline silicon cell types for the reference year 2016 and projected to 2027. The PERC family of cell structures has quickly entered the market, achieving already a significant market share, and is projected to account for the largest market share by 2021. Bifacial cell types are projected to grow steadily, reaching approximately 20% market share by 2021, driven largely by large rooftop and utility scale system installations. The ITRPV projects that once PERC cell structures have become mainstream then bifacial modules will quickly follow in a 12-18 month period.

Product trends: Within a module, the number of cells is anticipated to increase, and despite the efforts to decrease the cost of encapsulants and back sheet materials these will be both main contributors in module manufacturing; new materials are being developed (EVA still having the major share). With the quality and durability of modules being a major focus, in line process control and automated optical inspections and testing/sorting are rising techniques in modules and cells manufacturing.

For thin film technologies information on trends is rather limited. Improvements for the mainstream products mainly refer to cost reduction and improving material efficiency, i.e. solar cells with less material but with higher efficiency. Moreover,

because of the encapsulation techniques used thin-film technologies fulfil most of the architects' and constructors' requirements for the building skin, hence the BIPV market is expected to gain importance for these technologies.

Competitive analysis: The world PV modules market is dominated by the production of silicon technologies. China in particular can be seen to dominate the whole value chain, including polysilicon production, ingot production, wafer production and cell/module production. The country accounts for almost half of global module supply and deployment today. The seven companies that dominate the silicon market are grouped in what is known as Silicon Module Super League and six of them are headquartered in China.

The photovoltaic modules market is highly competitive, which means that there are limited margins which in turn restricts the number of intermediaries. Manufacturers' channels to market for conventional modules are generally limited to:

- Direct sales to developers or large installers,
- Sales via local subsidiaries,
- Sales via distributors then to installers
- Products then sold under the brand name of another company.

The market share of distributors in the large-commercial and industrial segment is rather small, due to the small margins, and larger installations do not normally use distributors for cost reasons.

Inverters

Market segmentation: The European inverter market is dominated by single and three phase string inverter technology (73%). The remaining portion of the market is accounted for by centralised inverters (26%), delivered either as a standalone unit or packaged with other power conditioning equipment such as transformers, and micro-inverters (1%).

Product trends: With the exception of micro-inverters, which still appear to have potential for efficiency improvements, inverter efficiency has increased to the point where the majority of system-level inverters have a declared efficiency in the region of 98%.

In the field of string inverters with a power rating of up to 100 kW, transformerless circuit topologies with high switching frequencies and Maximum Power Point Tracking devices represent the state of the art. Although still limited, the application of three phase string inverters to larger utility scale systems is an important application trend. Reducing the bill of materials through the introduction of silicon carbide (SiC) and gallium nitride (GaN) switching components (transistors) is a main trend in inverters. As was identified in the analysis of module trends, there are indications that the integration of power electronics at module level will continue to increase. This will see the further development of modules with integrated micro-inverters and DC power optimisers.

Competitive analysis: Global solar PV inverter shipments grew 23% on 2016 (34% in EU), reports GTM Research in its latest Global Solar PV Inverter Market Shares and Shipment Trends 2018 report. Revenues, meanwhile, increased by 11%. European manufacturers play an important role in the market, being estimated to account for just over 50% of shipments in 2016. The European inverter market is led by three companies (SMA, Fronius and ABB) that are also in a favourable position in the world market. SMA Solar (Germany) is the world's highest ranked company with regard to R&D investment in the PV sector.

Channels to market: for systems of a size greater than 100 kW, the system developer will in general tend to go directly to the manufacturer. The regional or country representatives of manufacturers are in general subsidiaries of the manufacturers. Distributers tend to be well established companies (e.g. Krannich solar in Germany) that sell mostly to the residential and commercial segments.

PV systems

Market segmentation: The early demand for systems came from a relatively small group of so-called pioneers who were committed to PV's environmental, energy security, and self-generation benefits. The PV industry has now evolved to so-called 1st Generation PV business models where the product is more attractive to a broader market, moving into the so-called early adopter customer category. 2nd Generation business models have yet to emerge, but will emphasise greater integration of the PV systems into the grid because emerging technologies and regulatory initiatives are likely to make such integration more viable and valuable.

Product trends: New market demands are being created by customers e.g. new technologies, contracting services, and maintenance services. In the EU, there are two major applications for grid-tied PV: residential and utilities with 22% and 38% of the total EU capacity, respectively. Residential prosumers are anticipated to increase although the remuneration conditions are not uniform across EU. For large installations, the major investments portfolios are principally located in three countries, UK, Germany and France.

The trends in systems can be seen at two main project stages: *design* and *operation*:

At the *design stage* it is expected that dynamic energy simulation grows, especially for large installations where it is already common its use, but also in small installations. Also in the design stage, 1 axis trackers are foreseen to increase a 50% by 2020, coupled together with bifacial modules, and eventually becoming the dominant design. The expected increase in the self-consumption will stimulate further storage options to be developed. There are already some manufacturers offering inverter products combined with batteries, or their integration at module level. Also at module level, there is a trend to include power electronic solutions. To then connect the modules, the trend expected to continue is the use of combiner boxes.

At *operational stage*, monitoring and data analytics are increasingly forming part of operation and maintenance contracts. These services are growing in complexity and range from vegetation trimming to modules cleaning.

Competitive analysis: Europe has strong firms in more specific PV domains such as the manufacturing of connectors, (sun) trackers, encapsulants and polymers in general, and solar glass. Most of these companies invest heavily in research and development (R&D). While there has been an overall downturn in residential installations, for example in the major EU markets of Germany, Italy and the UK, a diversified offer of components and services for 'prosumers' has emerged and there is evidence that it is growing. The leading market for battery storage systems is Germany, where the introduction of financial incentives has led to the installation of more than 75.000 PV + storage systems by the end of 2017.

Among the top five tracker manufacturers companies globally, two are European, Soltec (SP) and Convert Italia (IT). With diminishing utility-scale site availability and rapidly increasing tracker competition, the commercial and industrial segments seems poised for substantial growth in tracking technology.

Channels to market: As seen for previous PV components, when dealing with systems, the channels to market can be quite diverse depending also on the scale of the system, whether it is large scale or small residential installer market. Project developers and engineering procurement and construction (EPC) companies are normally present in large installations, while system installers normally act at all scales. The main developers in Europe are found in Germany (with an accumulated value of 2,040 MWp), France (811), Austria (469), the UK (358) and the Netherlands (307). In the case of EPC contractors, the Member States whose firms have the highest accumulated capacity are Germany (3,569 in MW_{AC}), Spain (631), the UK (585), Austria (466), France (369) and Portugal (318).

PV system trends and competitive analysis

Stakeholder consultation points

2.1 Are there any significant trends that haven't been captured for PV modules, inverters and systems?
2.2 Is there any trend amongst those presented for PV modules, inverters and systems that you do not agree with? If so, please give your reasoning.
2.3 Does the description of routes to market for PV systems match the experience across different EU Member States?

Requests for information and case studies

- Further information on which market segments are anticipated to create demand for the new silicon technologies identified in this study.
- For conducting a competitive analysis we would like further information on monitoring and data analytics, and operation and maintenance services
- Further information on BIPV products trends, segmentation of products

2.5.3 Consumer expenditure

The cost structure of a photovoltaic system has until recently been dominated by the modules. With the entry into the market of Chinese mass producers both the overall cost structure and the proportion accounted for by modules have reduced.

Module price evolution in the selected countries (Germany, Italy and Spain) has followed the same trend along 2001 to 2016. They all had a peak around 4.5-5 EUR/Wp in 2005/06 and then a continuous reduction down to 0.5 EUR/Wp, which is an average of a -90% decrease.

In terms of future inverter price forecasts, up until 2022 prices of all type of inverters are estimated to decline. The most notable trend for inverters prices is however the sharp decline in micro-inverter pricing, which reflects aggressive cost reductions by the market leader Enphase Energy, as well product innovation, such as dual module inverters. It is anticipated that further moves towards AC module integration will contribute to the downward price trend.

The final system price has declined in the recent years even faster than the module price and for ground-mounted systems, prices below 0.70 EUR/Wp in Europe and below 0.65 USD/Wp have been registered in emerging markets such as India, thanks to very low cost for manpower. However, the price decrease hasn't been as marked in all countries and market segments. In countries where the level of incentives remains sufficiently high, the decrease of prices was less significant. In comparison with most competitive countries such as Germany, prices for rooftop system have declined more In Japan and in the USA, . The potential for price decline is still high in many segments and countries, while the current price of ground-mounted installations will continue to decline at a slower pace.

System cost structure

Stakeholder consultation points

2.1 What could be the variance in the PV system pricing at the smaller end of the scale compared to the headline figures presented *i.e. commercial and residential*?
2.2 What are the factors that can influence this price variation?

Requests for information and case studies

- Module price evolution for EU countries other than those analysed: by technology (e.g. Si based, thin film) and by segment (residential, commercial, utility scale),
- Microinverters integrated in modules prices
- Updates on 'soft' costs[128] for PV systems, especially for utility scale. Further price information on operation and maintenance costs

[128] According to Strupeit and Neij (2017) soft costs relate to 'customer acquisition, technical and legal-administrative planning, installation work as well as the transaction costs associated with financing'.

3 Task 3: User Behaviour and System Aspects

This report forms the third task in Preparatory Study for the product group 'solar modules, inverters and systems'. The aim of this task is to:

- analyse users, procurers and installers behaviour and practices;
- identify recent changes and trends;
- understand to what extent they are captured by the existing regulations and standards for the product group or service analysed;
- provide inputs and assumptions for the assessment in later tasks of the environmental impact and cost of the product and how the standard measurement conditions may vary.

User requirements can be influenced by product design and product information. Relevant user-parameters are an important input for the assessment of the environmental impact of a product during its use and end-of-life phase, in particular if they are different from the standard measurement conditions as described in existing test standards for the product (see Task 1).

In line with previous Tasks, the provisional scope of this analysis of user practices and related system aspects will comprise grid connected systems of the following type:

- residential (up to $10\ kWp$);
- commercial (private/public $\leq 1\ MWp$);
- ground mounted/utility scale ($> 1\ MWp$).

With respect to the previous objectives some factors to consider are the relationship between capital cost, the solar resource and performance.

The analysis, carried out at a first stage through literature research and a later stage through direct contact with stakeholders, aims to identify any distinct variation in user requirements linked to the type of installation or end-user and any related variation from the measurement conditions specified in standards.

3.0 Photovoltaic users, procurers and their requirements

Users of photovoltaic systems can be anyone that uses electricity from the grid because those systems generate electricity which becomes a commodity that can be bought, sold and/or traded. Electricity is from the end user perspective never the final application but only a means to activate energy services which are needed, for example to provide hot sanitary water (HSW). For the end users there are also several alternatives to generate electricity[129] or even to supply the end application (see 3.1.6). As a consequence many photovoltaic system 'users' can be identified.

Over the last decades photovoltaic systems gained an increased share in renewable energy generation (see Task 2). Compared to other renewable energy sources, photovoltaic systems are attractive because they do not generate nuisance under operation, e.g. such as potential risks for shading and noise nuisance with wind turbines (Abbasi, Monazzam, Akbarzadeh, Zakerian, & Ebrahimi, 2015[130]). With regard to investment cost they are becoming increasingly price competitive[129] (Carlsson et al., 2014[131]) and also their operational cost is very low (see Task 2). A major potential short-coming of photovoltaic systems and their user expectations is its weather dependency, meaning that the produced electricity do not necessarily match

[129] *https://setis.ec.europa.eu/system/files/ETRI_2014.pdf*

[130] *Abbasi, M., Monazzam, M. R., Akbarzadeh, A., Zakerian, S. A., & Ebrahimi, M. H. (2015). Impact of wind turbine sound on general health, sleep disturbance and annoyance of workers: a pilot- study in Manjil wind farm, Iran. Journal of Environmental Health Science and Engineering, 13(1), 71. https://doi.org/10.1186/s40201-015-0225-8*

[131] *Carlsson, J., Fortes, M. del M. P., Marco, G. de, Giuntoli, J., Jakubcionis, M., Jäger-Waldau, A., … Weidner, E. (2014). ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050. JRC Science and Policy Reports. https://doi.org/10.2790/057687*

the demand. This is because some users may place an importance on self-sufficiency, which is a theme that will be discussed in more detail in section 3.2.3.

Photovoltaic systems are also attractive to many users because they can be easily installed either in small or large systems on various locations. Figure 58 shows for example a large utility scale plant with ground mounted systems. An important benefit of this larger type of system is the easier grid integration in the medium voltage distribution grid and reduced losses, see 3.2.2 and 3.4.1.5. In such an installation the modules are also more easily accessible for repair and maintenance.

Smaller installations can be installed closer to the end user and/or electricity user for example on a flat or gable roof (Figure 59 and Figure 60). A flat roof allows more freedom to select the slope and azimuth, which can be beneficial to optimise the yield. Module repair can be relatively more expensive for roof mounted systems because of the need to access many small installations. This can result in a need for higher module quality and lifetime requirements.

Also building integrated photovoltaics (BIPV) can introduce aesthetic requirements (e.g. full black) which are less important for large ground mounted systems. The inverter is usually installed on a location where it is easily accessible for indoor maintenance and repair, for example in the attic (Figure 61). The lifetime requirements for inverters attached on roofs may therefore be less demanding compared to modules on ground mounted sites, where the inverter may be more exposed to ambient conditions.

The subsequent section will explain who are the typical stakeholders directly involved in PV systems and what are their typical requirements.

Figure 58. Large utility scale plant (3077 kWp) with ground mounted PV systems on 8 acres in Lommel (BE) (source: IZEN)

Figure 59. Medium sized PV system (386 kWp) installed on a flat roof.

Figure 60. Small sized PV system (1,75 kWp) installed on an gable roof.

Figure 61. Small wall mounted photovoltaic inverter (1,75 kWp) indoor on an attic.

3.0.1 Overview of stakeholders involved in PV system use

There are several stakeholders involved in the PV market although their nomenclature is not uniform among the different literature. It is however possible to identify typical primary stakeholders such as end-users, system owners, the distribution utility, wholesale generators, the regulator, the transmission company. PV component manufacturers, investors, architect and designers and building owner (if other than the end-user or system owner) can be identified as secondary stakeholders (R2M, Onyx Solar, Flisom, BEAR-iD, & Acciona, 2016[146]).

The widespread deployment of distributed PV has distinct effects on the primary stakeholders since their interest and power of influence is different. Figure 62 relates the interests and power of influence for some of the previously mentioned stakeholders. Stakeholders relevance, challenges and benefits from PV deployment are summarized in Table 48.

The PV industry has been slowly moving away from business models in which the end-user financed, owned and managed the installation of the PV systems towards models in which these types of systems are attractive to a broader market.

According to (Frantzis, Graham, Katofsky, & Sawyer, 2008[110]), and although this publication is not recent, the expected evolution of business model was considered to be one which would allow a greater integration of the PV systems into the grid and would accommodate a more proactive role from the utility (Figure 63). This is still true in the present context and part of this has already been introduced to the market as will be explained later (see section 3.0.2). The utility involvement is motivated mainly by concerns for grid infrastructure, safety and possible revenue loss.

Figure 62. Classification of different stakeholders (power vs. interest) – adapted from (R2M et al., 2016[146])

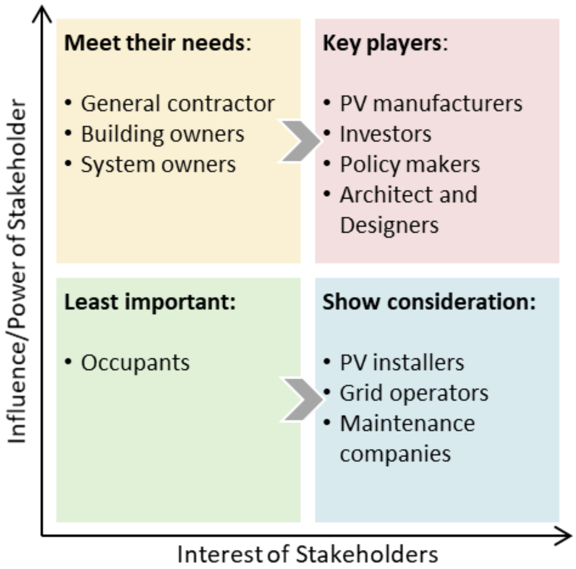
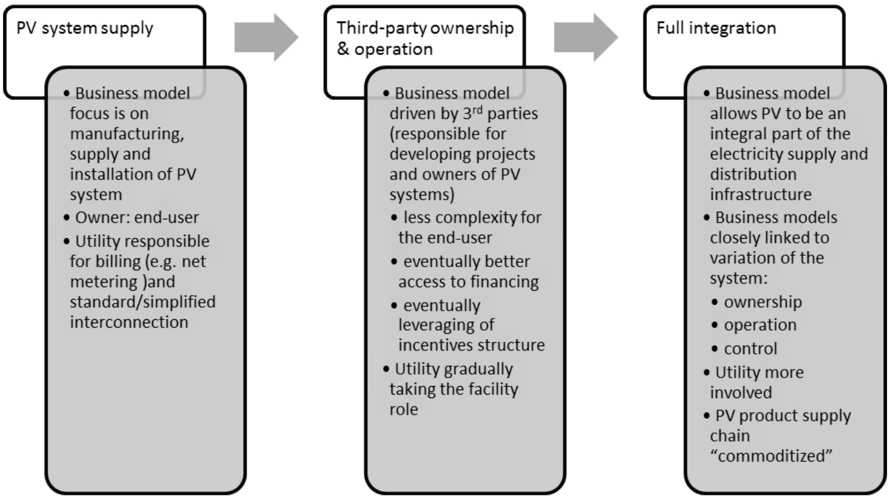


Table 48. Stakeholders' relevance, challenges and benefits from PV deployment

Stakeholder	**Relevance**	**Challenges & Benefits**
Prosumer - system owner	Usually also the owner of the PV system (system owner) and building.	Need to invest in PV systems. Cost-effective alternative to the grid.
Building owner (if other than the end-user)	Key stakeholder to be convinced to invest in PV technologies or to rent available roof for PV installation.	Needs to be aware of the advantages of PV deployment and receive an adequate payment/incentive.
Distribution utility	High penetration of the PV market influences the revenue associated with traditional tariff structures.	Need to ensure safety, operational integrity and reliability of the distribution grid. PV deployment can open the market to new products and services to be sold to customers.
Wholesale generator	High penetration of the PV market would compete in the wholesale market with other generating assets.	Need to be competitive. In a market environment competition is *per se* a benefit.
Regulator & Policymakers	Responsible for standards, rules, legislation. Policy enablers.	Need to create incentives and schemes balancing the needs of distinct sector and lobbies. Can positively impact on renewable energy penetration, among other aspects.
Transmission Company	Responsible for transmission.	High penetration of PV can impact on the demand for transmission services.
ESCOs	Responsible for designing and implementing projects.	Evolving legislation can be seen as a challenge. Return on investment.
PV manufacturers	Main investors on production and possible R&D of BIPV technology.	Need to meet any existent legislation + design and building specifications (mainly for BIPV). Revenues.
Investors	Financing the several stakeholders.	Evolving legislation can be seen as a challenge. Return on investment.
Architects and designers	Responsible for defining design features and specifications. Important role, especially in the case of BIPV.	Required knowledge on the optimal design. The fact that standard products are often the most cost effective can be seen as a challenge depending on the timescale and also on the type of PV systems (BAPV or BIPV). Building green can bring revenues and more clients.

Figure 63. Expected evolution of PV business models - adapted from (Frantzis, Graham, Katofsky, & Sawyer, 2008[110])



Typical current PV ownership application models are presented in Table 49. Herein prosumers are PV system owners who are simultaneously energy consumers and producers. PV systems for producers only can be either self-owned or have third-party ownership. In Table 49 new *versus* existing (retrofit) buildings are discriminated according to the Energy Performance of Buildings Directive (EPBD) which strives towards Nearly Zero Energy Buildings for new constructions as of 31 December 2020 and as explained in section 3.1.6 BIPV/BAPV can be an option for this. Moreover on new buildings there can also be some synergy with other construction works and therefore cost benefits.

Table 49. Current PV ownership application models (source: own estimate)

	Application				
Ownership	BIPV/BAPV Residential buildings		BIPV/BAPV Non-residential buildings		Ground mounted systems
	New building	Building retrofit	New building	Building retrofit	
Prosumers	•••	••	•••	••	○
Energy producers only Self-owned	••	•	••	•	•••
Energy producers only Third party	•	○	••	•	••

•••: well established and promoted by the Energy Performance of Buildings Directive (EPBD)
••: well established
•: emerging
○: minimal activity

An example of the value chain for residential end-users in a retrofitting case (existing building) is illustrated in Figure 64 while an overview of downstream sector (utility PV application) is illustrated in Figure 65.

Figure 64 shows the main stakeholders involved in retrofitting and some of the transactions and flows of value between them. The main stakeholders are the prosumer; the utility; the regulator; the financier (if needed); the aggregator (facultative) and the government. The upstream supply side is comprised of the operation, maintenance and monitoring providers (when hired), the PV system distributor and the installer. Most of these stakeholders are also present in the case of:

- end-user owned systems in new residential constructions (the key difference is the home builder),
- third-party owned in the case of commercial retrofitting (key difference is the third-party owner),
- third-party owned in the case of a grid sited project (key difference when compared to the previous type is the payment scheme which can rely on power purchasement agreements – PPAs).

Figure 64. Example of value network: residential end-user - retrofitting case - adapted from (Frantzis et al., 2008[110])

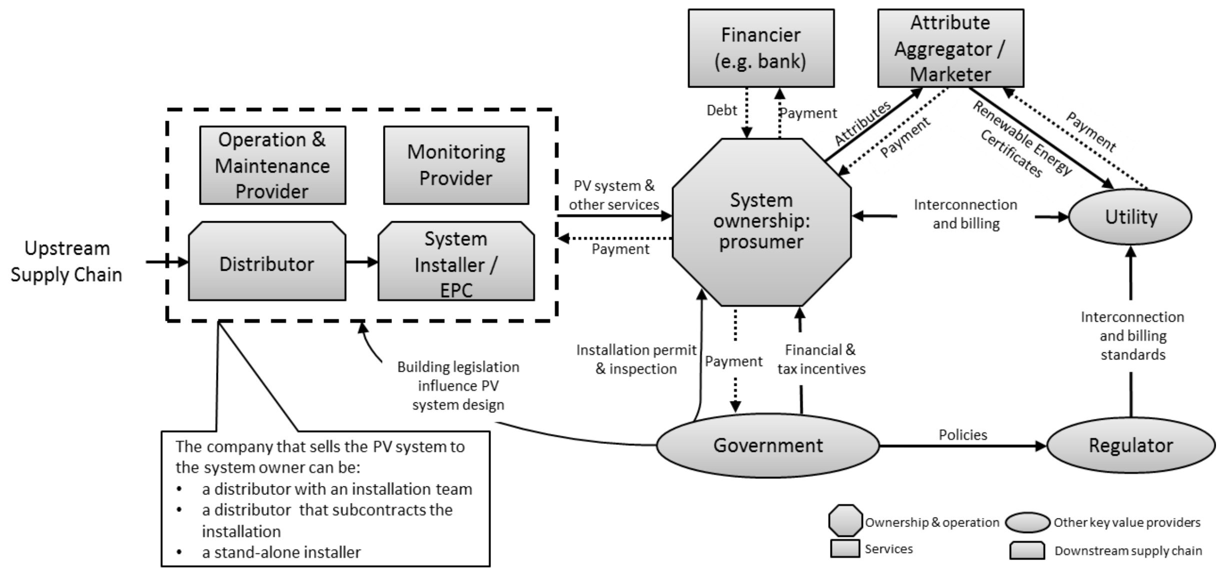
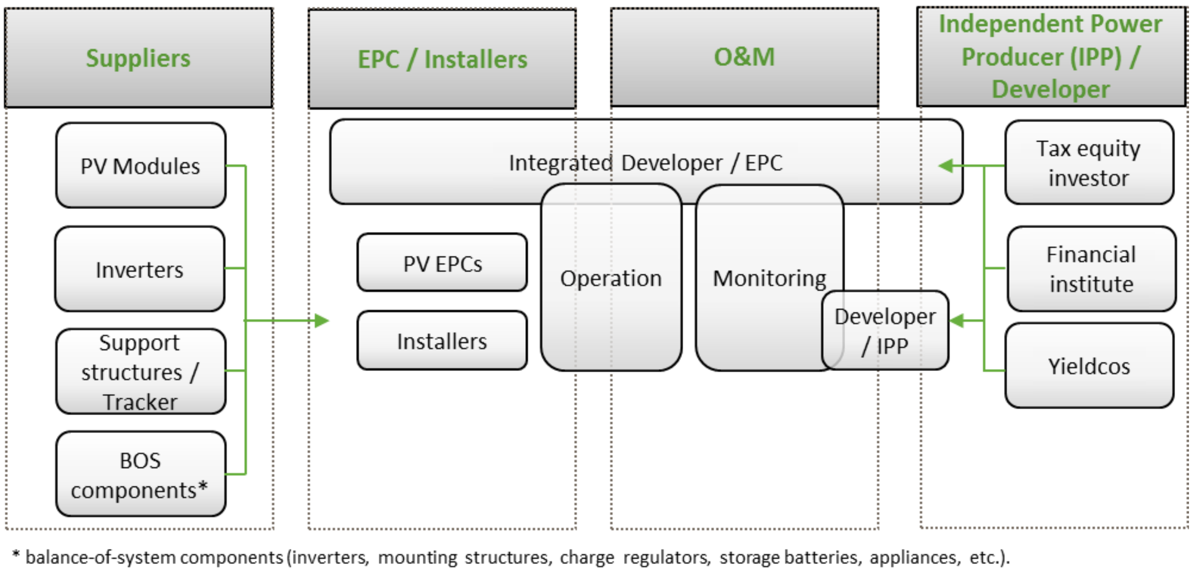


Figure 65. Overview of downstream sector (utility PV application) (IEA PVPS, 2017b[132])



3.0.2 Owners of PV systems

3.0.2.1 Ownership by energy producers only

In this section we discuss "Users of PV systems" or PV system owners who are only or exclusively energy producers, that is they do not consume the energy themselves. They will have a separate meter for measuring the production and this is probably the most common form of ownership today. They mostly rely on Feed-in Tariffs (FiT), Power Purchase Agreements (PPA) and/or Green Energy Certificates (GEC).

As was described in Task 1, FiTs are increasingly being awarded a result of a so-called "RES auction", which is a procurement auction, acting as a RES support allocation instrument, and in which power or energy are offered up for bidding (Mora et al., 2017[133]). Bidders compete for delivering the volumes "on the basis of their required support level" usually in €/MWh. Those

[132] *IEA PVPS. (2017b). Trends 2017 in Photovoltaic Applications - Report IEA PVPS T1-32:2017.*

[133] *Mora, D., Kitzing, L., Soysal, E. R., Steinhilber, S., del Río, P., Wigand, F., ... Woodman, B. (2017). Auctions for renewable energy support – Taming the beast of competitive bidding Final report of the AURES Project. Report D9.2. Retrieved from http://auresproject.eu/sites/aures.eu/files/media/documents/aures-finalreport.pdf*

with the lowest required support level for the project generally win this type of auctions. They are then granted the right to construct the winning RES project and receive a support payment for a given period of time. This type of bidding process has been used in several countries in Europe, and due to the complexity of the bidding procedure and the pressure to drive down capital and operating costs it is generally used for the larger systems. Such Renewable energy auctions are based on competitive bidding processes, which aim to (Mora et al., 2017[133]):

- identify the most adequate RES projects to be deployed within a certain time frame and geographical area;
- allocate appropriate support payments to the aforementioned projects.

3.0.2.2 Independent Power Producers

Independent Power Producers (IPPs) are entities, privately-held and thus not public utilities, which own facilities to generate electric power for sale to utilities and end-users. According to the definition are responsible for developing, building and operating power plants. They have, however, no affiliation to a transmission or distribution company (Global Capital Finance & Clean Energy Pipeline, 2014[134]).

IPPs can also sell power to utilities under a long-term Power Purchase Agreements (PPA). Usually these agreements involve an entity (e.g. a single buyer or the distribution company) who buys the power generated by the IPP according to the terms specified in the contract. Whilst utilities may own transmission or distribution assets and sell electricity directly to retail or other small consumers, IPPs do not (Global Capital Finance & Clean Energy Pipeline, 2014[134])

For the IPPs there is a significant financing risk since projects under development have a higher risk profile than operating assets which turns into higher cost of capital. Also if revenues are lower than expected then cumulated debt service can be at risk (Global Capital Finance & Clean Energy Pipeline, 2014[134])

3.0.2.3 Third party ownership such as Energy Service Companies (ESCO)

An alternative ownership structure to IPPs is that the land or building on which the PV system is installed have different or mixed ownership.

In Belgium and Germany for example this arrangement is used for some public buildings in the form of an Energy Service contract[135,136]. It is an emerging area. The benefit is that the ESCO takes over all services and risks involved in installation and exploitation of PV systems but often also part of the complexity of tendering

An extra benefit of an ESCO is that they can deduct taxes and avoid that the client has to invest in upfront taxes in the PV system long before the benefit, see 3.4.1.1. In Belgium municipalities have to pay Value Added Taxes (VAT) on their expenses and therefore such a construction with an ESCO can avoid this upfront VAT investment cost.

Another option is to rent a PV installation for your building, e.g. which can be found in Germany[137]. It is a relatively new market segment the key difficulty being due to the shared ownership and contracts, for example in relation to equipment damage. For potential market and stock data please consult Task 2.

Third party ownership can complicate subsidy schemes(see 3.4.1.2) because these are often linked to ownership. Subsidy schemes providing revenue are a major driver for installing PV system (see 3.0.1) but vary across Europe and/or Regions (see Task 1).

Third party ownership is of relevance to public procurement because of the potential to reduce upfront capital costs, see 3.0.5.

3.0.2.4 Ownership by prosumers

In this section we discuss users of PV systems who simultaneously produce and consume energy behind the electricity meter. They are also referred to as ‘prosumers’. Prosumers can combine the benefits of energy producers as were discussed in the previous sections.

Examples of prosumers include:

- residential prosumers producing electricity at home mainly through the use of PV panels installed on the rooftop;
- citizen-led energy cooperatives;

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[134] *Global Capital Finance, & Clean Energy Pipeline. (2014). The European Renewable Energy Investor Landscape.*

[135] *http://www.escolimburg2020.be/files/BROCHURES_2014/brochure_esco_EN_LR.pdf*

[136] *SAG Solar, Germany: http://www.sagsolar.com/en/solar-plant-lease*

[137] *https://www.dz-4.de/*

- housing associations;
- commercial and industrial prosumers whose main business activity is not electricity production;
- public institutions.

Moreover, evolving electricity market legislation has introduced the concept of communities of prosumers – collective self-consumption. In this way each prosumer may have a different geographical location, but they may agree to share the self-produced electricity.

Defining what is a prosumer

According to the International Energy Agency (IEA) and cited by (GfK Belgium Consortium, 2017[138]), prosumer installations below 10kW is defined as belonging to the residential sector. Typical residential PV systems do not exceed 20 kW and are usually roof mounted according to (IRENA, 2012[139]). However, according to (GfK Belgium Consortium, 2017[138]), this number is lower: "residential prosumer installations across Europe are generally lower than 10kW".

The legal definition of residential prosumers is not clear or harmonised among different countries. According to (GfK Belgium Consortium, 2017[138]), a regulatory definition of that term or a piece of legislation to specifically fully regulate this type of use is inexistent, at least concerning the countries analysed in that report. Also the definition of self-consumption or auto-consumption may differ and include different attributes. Some countries also refer to active consumers and self-producers[140]. In some countries, residential prosumers are defined according to the size or the capacity of the installation. However, in some countries the size or capacity is stated as being "small" without putting any numbers on it. The generation capacity used as a cap in prosumer-related national legislations, when clearly stated, is not the same in the different countries (GfK Belgium Consortium, 2017[138]).

More recently there are also collective prosumers which perform collective self-consumption. In France for example in 2016 a law has been introduced to allow for this[141]. Article L 315-2 of the French energy code defines that self-consumption is collective when the electricity exchange is made between one or more electricity producers and one or more final consumers, linked together by a legal entity, and from which the injection and exit points are on the same low-voltage loop of the public distribution grid. The key benefit of such an approach is that it enables electricity users who have no suitable or a collective roof (e.g. apartment) to become photovoltaic prosumers.

Market testing of prosumer attitudes

In the context of the EU funded CLEAR project (Consumers Learn Engage Adopt Renewable Energy Technologies) a market enquiry was launched in Spain, Portugal, Italy and Belgium to identify *"the best approach to implement a group offer with regard to Renewable Energy Systems (RES)"* (Test-Achats/Test-Aankoop et al., 2015[142]). The sample consisted of a target group mainly composed by intenders and thinkers and a basic level of adopters. 5012 respondents were gathered. According to the responses, the two aspects that a user most values concerning renewable energy solutions (RES) are how much money could be saved if they had a RES compared to their current energy source and total running costs. These two aspects are common in the four countries in which the survey was conducted.

For Spain, Italy and Portugal the least important information needs were information about performance warranties and the possibility to personalise the offer. For Belgium, the least important information was a tool to provide personalised solution and payment possibilities.

A major study on prosumers commissioned by DG Justice (GfK Belgium Consortium, 2017[138]) has carried out a similar analysis and has included market enquiries in, amongst other Member States, Germany, France, the Netherlands and UK (Figure 66). This study also identified that the main driver that leads an end-user to invest in solar PV systems is saving money. Environmental impact and government subsidies play also an important role. The choice and purchase of PV systems from the end-users perspective would depend on price, aesthetics and payback time (GfK Belgium Consortium, 2017[138]).

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[138] GfK Belgium Consortium. (2017). Study on "Residential Prosumers in the European Energy Union" - JUST/2015/CONS/FW/C006/0127. Retrieved from https://ec.europa.eu/commission/sites/beta-political/files/study-residential-prosumers-energy-union_en.pdf

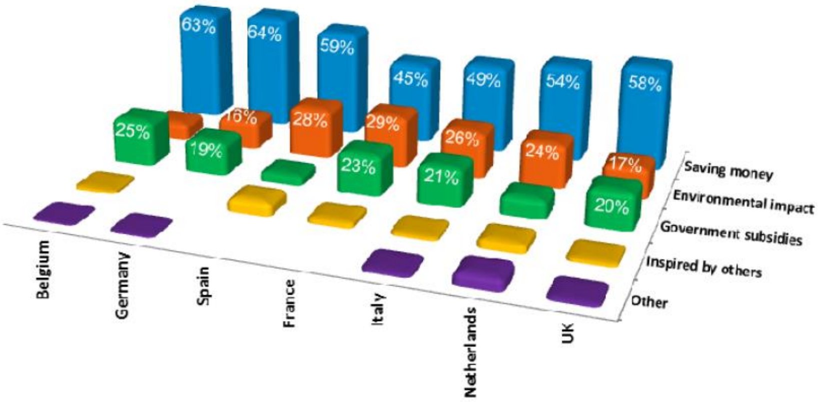
[139] *IRENA. (2012). Renewable Energy Technologies: Cost Analysis Series. Solar Photovoltaics, (4).*

[140] A table summarizing that information can be found in (GfK Belgium Consortium, 2017): Table 1 - Definition of residential prosumers (page 37).

[141] http://www.pv-financing.eu/wp-content/uploads/2016/10/4.-Collective-self-consumption-in-France.pdf

[142] Test-Achats/Test-Aankoop. (2015). Zonnepan e elen, (september), 62–66.

Figure 66. Main drivers for residential prosumers to invest in solar PV by country (GfK Belgium Consortium, 2017[138])



Concerning the product characteristics of PV solar panels, (GfK Belgium Consortium, 2017[138]) conducted an experiment to identify which characteristics or combinations of characteristics are considered most important to the end-user when buying a PV system. Details of the experiment can be found in that report. The sample consisted of respondents owning a house with PV systems but interested in purchasing a PV system. Selected product features included:

- aesthetics,
- costs per solar panel,
- inverter type,
- installation,
- efficiency,
- lifetime, and
- maintenance costs

Other factors to be considered included the resale value of the houses after the PV system installation. The main conclusions from this part of the study are not yet available.

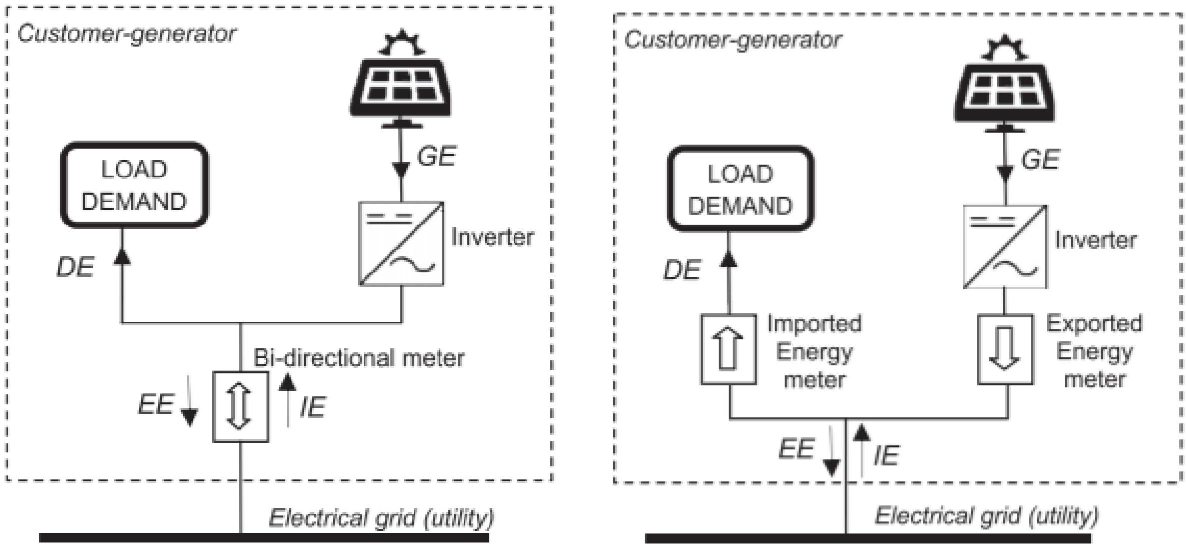
Defining self-consumption

An important practical parameter in seeking to define and meter self-consumption (SC) is the minimum time period to elapse between generation and consumption. This is typically 15 minutes, 30 minutes, 1 hour, over one day/night or per year depending on the billing scheme, which may differ per EU region or country[143]. The shorter time intervals are usually accounted for a system of net-billing i.e. electricity generated and consumed is metered separately and then reconciled on the bill. Aiming for self-consumption below a 15 minutes time period is generally not considered useful because the peak loads of a group of domestic houses are easily averaged out. Amongst others, for this purpose the IEC or local grid code uses a diversity factor (e.g. IEC61439, NFC 14-100).

The longest time period used to define self-consumption is per year which is also commonly called 'net metering' (e.g. as used in Belgium, and the Netherlands). In this case the electricity grid acts as a free storage all year long and it can therefore act or compete to a certain extent with other technical solutions such a demand side management or batteries. Instead, it can be considered as being performed by a bidirectional running mechanical meter (running forward during times when net electricity consumption dominates, and backwards when net generation dominates). The main difference between net-metering and net-billing is illustrated in Figure 67.

[143] 2014, European Commission: Cost-benefit analyses & state of play of smart metering deployment in the EU-27. Table 7 and 10 in: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014SC0189&from=EN

Figure 67. Net-metering and net-billing schemes (Dufo-López & Bernal-Agustín, 2015[144])



The prosumer market can be influenced by local support policies, see 3.4.1.2, and retail electricity prices, see 3.4.1.3, which can differ strongly between member states and hence also the incentive to become a prosumer (see 3.4). More recently, batteries are becoming more competitively priced, and in some Member States receive investment subsidy. Battery storage systems can assist prosumers in increasing their self-consumption by storage as well as demand side management to control local loads, see 3.4.2.1.

According to (ACCIONA, NOBATEK, 2016[145]), due to the progress towards grid parity and policies aiming to facilitate self-consumption, innovative business models have been slowly emerging (Table 50). Grid parity is achieved when the levelised cost of the PV electricity matches the net electricity price. When this parity exists, PV projects usually do not need financial support or incentives to be economically viable.

3.0.3 Different options for installing PV systems

Building attached (BAPV) photovoltaic systems refers to PV systems installed on an existing building (Figure 68) while Building integrated (BIPV) photovoltaic systems are integrated in the building envelope replacing typical building materials by PV ones (Figure 69). The Energy Performance of Buildings Directive (EPBD) is an important driver for BAPV and BIPV as it establishes targets for Nearly Zero Energy Buildings BIPV/BAPV can be an option to meet such targets, which vary between Member States. Moreover, on new buildings there can also be some synergy with other construction works and therefore cost benefits.

Building integrated (BIPV) photovoltaic systems and the market for architectural BIPV in Europe have been growing in the last years according to (R2M et al., 2016[146]) and (IEA PVPS, 2017b[132]). The dominant PV technology in BIPV is crystalline silicon (c-Si) although a relatively high percentage of the product offerings uses thin film (TF) PV technology (Zanetti et al., 2017[147]). Typical trends namely in The Netherlands include the use of prefab mounted BIPV in social housing renovation programs. In this context poorly insulated social housing get a new building skin using prefab constructed façade and roof elements. According to (Zanetti et al., 2017[147]) coloured façades may also gain market share mainly due to their ability to reduce their visibility which contributes to a broader market acceptance of PV façades[148]. Solar glazing is another expectable trend although this technology is not new.

144 *Dufo-López, R., & Bernal-Agustín, J. L. (2015). A comparative assessment of net metering and net billing policies. Study cases for Spain. Energy, 84, 684–694. https://doi.org/10.1016/j.energy.2015.03.031*

145 *ACCIONA, NOBATEK, C. (2016). European regulatory framework for BIPV.*

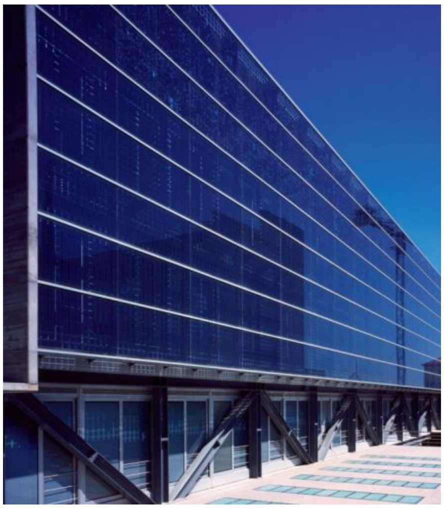
146 *R2M, Onyx Solar, Flisom, BEAR-iD, & Acciona. (2016). PVSITES: BIPV market and stakeholder analysis and needs.*

147 *Zanetti, I., Bonomo, P., Frontini, F., Saretta, E., van den Donker, M., Vossen, F., & Folkerts, W. (2017). BIPV Status Report 2017, 76. Retrieved from https://www.seac.cc/wp-content/uploads/2017/11/171102_SUPSI_BIPV.pdf*

148 *Coloured PV façades have however the disadvantage of a "shading" over the PV cells which impacts negatively on the energy production (Zanetti et al., 2017).*

Figure 68. BAPV at EnergyVille, Genk, Belgium (Yordanov et al., 2017[149])

Figure 69. BIPV – La Salle, Barcelona, Spain (Rasker, 2017[150])



[149] Yordanov, G. H., Smolders, F., Olaerts, A., Verbeek, G., Baert, K., & Driesen, J. (2017). A 368-kWp Grid-connected PV System : Known and Hidden Losses. In EU PVSEC Programme Planner (pp. 1909–1914). Amsterdam.

[150] *Rasker, E. (2017). Belgian BIPV-Workshop. REYNAERS.*

Table 50. Range of emerging business models from the prosumers' perspective - adapted from (ACCIONA, NOBATEK, 2016[145]) and (GfK Belgium Consortium, 2017[138])

	Production-based: FiT. No self-consumption	**Self-consumption + constraints**	**Self-consumption + FiT**	**Net-billing**	**Net-metering**	**Self-consumption + premium**
	No right to self-consumption. Support mechanism such as FiT in place.	Grid-connection and self-consumption allowed with some fees or taxes. Usually no compensation for the excess electricity fed into the grid.	Self- consumption allowed. Prosumer can benefit both from bill reductions but also from support mechanisms, such as FiT. (e.g. Bulgaria)	Self- consumption without support mechanisms. Net-billing, considers both energy flows between the PV system and the grid. Different prices for energy consumed from the grid and excess electricity injected into the grid may be used. time-scale: 15 min to 1h (e.g. Portugal)	Net-metering business model compensates the excess energy fed into the grid. The price is equal to the electricity retail price. Some taxes might usually charge for the grid availability and maintenance. time scale: over a long period (month/year) (e.g. Belgium)	There might be an additional payment for on-site self- consumption, or a compensation for the excess exported electricity at a higher price than retail electricity. (e.g. Czech Republic)
Right to self-consume	Not allowed	Yes	Yes	Yes	Yes	Yes
Revenues from self-consumed PV	-	Savings on the electricity bill	Savings on the electricity bill	Netting of production revenues and consumption costs	Savings on the electricity bill	Savings on the electricity bill
Additional revenues on self-consumed PV	-	No	No	No	No	Premium
Charges to finance transmission & distribution cost	-	Yes	No	No	No	No
Revenues from excess electricity	-	Zero	< retail price	<= retail price	= retail price	> retail price
Maximum timeframe for compensation	-	Real-time	Real-time	Long period	Long period	Real time

According to (IEA PVPS, 2017b[132]), incentives for BIPV have been decreasing with the exception of a few countries such as France and Austria which still maintain support schemes to favour the development of BIPV. Higher FiT rates for BIPV systems are made available with the final aim of promoting structural integration of PV systems in the built environment (R2M et al., 2016[146]).

3.0.4 Consumer requirements in the design stage of a PV installation

As documented before, by far the main driver for procuring a PV system is saving money (Figure 66). Therefore, the most important consumer requirement is to calculate the annual Energy output from PV system (AC) (Eout). Based on the annual Energy output (Eout) forecast and the subsidy scheme, the return on investment or money saved can be calculated, see 3.4.1 or Task 2. However, in order to achieve realistic lifetime cost and energy output calculations for the specific circumstances of the prosumer they would need to include a calculation of all investment and running costs at the beginning of and throughout the expected lifetime of the system, considering the risk of failure of components and days of downtime.

This PV system energy output (Eout) is related to the Performance Ratio (PR), the reference yield (Yr) [hours/year] and the total PV array power rating in DC(P0) [kWp]. Therefore, the following formula applies:

Eout [kWh/y] = PR x Yr[hours/y] x P0[kWp]

A more detailed insight on all factors that could affect the Performance Ratio (PR) and hence the annual Energy output (Eout) of a PV system is given in a later section 3.1.5 and a more complete overview of contributing derate factors[151] (IEC 61724-1) in Table 52. It should be clear from the later section 3.1.6, that not all parameters will contribute to the real measured AC output power under control of the installer and therefore there will always remain some margin of uncertainty left between what can be forecasted during the quoting and the real output. Therefore, quality programs and procurement specifications also tend to focus on what can be controlled in standard conditions in the strict product scope, as explained in detail in section 3.1.3.

Potentially the most important part of the design process is therefore the energy yield forecast (Ey), which is discussed in detail in later section 3.1.4. A high-quality engineering project requires the selection of a reliable solar resource database, correct energy simulation, a good layout, and adequate electrical and mechanical dimensioning[152]. Depending on the size of the installation, type of mounting (roof-mounted or ground-mounted) and aim, several design aspects should be taken into consideration (see section 3.1.7).

A summary of the link between the performance parameters and energy yield calculations of a PV system is included in the subsequent section 3.1.7 and Table 58, while more technical details and reference data in its respective preceding sections (see 3.1.4 and 3.1.5).

Hereafter is a brief discussion per market of some typical consumer requirements during procurement. More background information and a detailed introduction for those who are not familiar with the topic can be consulted in dedicated literature (Luque & Hegedus, 2012[153]).

3.0.4.1 PV design processes in the residential market

The previously described design process can look relative elaborate and expensive for small residential PV systems. However, it can be automated and linked to predefined packages of module/inverter combinations. Already today many large retailers start to offer PV systems to the residential market[154, 155, 156]. They carry out the design procedure mostly for free during the quoting procedure, mainly related to the analysing the roof orientation and shading risk. These retailers can also differentiate the amount of service that is included in the package deal, e.g. provide loans, insurance, extended warranty, maintenance, etc. The analysis of which roofs are suitable can also be automated by processing satellite/airplane images and laser range sensor data for a complete region[157]. Consumer expectations can also bring into the design process a range of other considerations

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[151] *Derate factors quantify individual sources of loss with respect to the nameplate's DC power rating (IEC 61724-1).*

[152] *http://www.etip-pv.eu/fileadmin/Documents/ETIP_PV_Publications_2017-2018/PV_Quality_report_ETIP_PV_SolarUnited_August_17.pdf*

[153] *Luque, A., & Hegedus, S. (Eds.). (2012). Handbook of Photovoltaic Science and Engineering. John Wiley & Sons, Ltd.*

[154] *http://ikea.solarcentury.com/*

[155] *https://www.vattenfall.de/de/sonnendach.htm*

[156] *https://www.engie-electrabel.be/nl/energie-besparen/zonnepanelen/opbrengst*

[157] *https://vito.be/en/media-events/press-releases/how-suitable-is-your-roof-for-the-installation-of-solar-panels-or-a-solar-boiler-see-for-yourself-on-the-solar-map*

such as aesthetics (e.g. the appearance of modules or the visual effect of a system on a roofline) as well as considerations of longer term aspects such as access to modules for cleaning and inverters for repair/replacement (Which? 2018).

From the user perspective, various aspects may be of concern due to their influence on performance. The choice of the inverter is an important aspect. String inverters are usually cheaper but since they connect the panels in series, if one of the panels fails, it will impact in the whole system. Micro-inverters, usually more expensive, don't have this drawback and any problems will be potentially better identified through the power-monitoring system. The location of the inverter is another important aspect to take into account. Being placed near the panels minimises possible energy losses due to long cabling. The heat from solar irradiation however might have a negative impact on its performance. The colour of the panels, besides the aesthetic aspect, may or not influence their performance. Black panels without front surface busbars might, for example, see their efficiency decreased due to an associated temperature rise.

The choice between roof mounted or integrated, depends on the type of construction: for new constructions, BIPV is an option, but for old construction the only option left might be BAPV. In the case of retrofitting, it will be dependent on the depth of modifications: for example, replacement of roofs might allow the installation of BIPV. It is important to highlight that one advantage of BIPV is related to their positioning: they sit flush with the roof which leaves no room for birds to nest underneath. Birds nesting is a problem reported by several PV owners and thus the importance of making them aware of this possible situation ("Make the most of your solar panels - Which?," n.d[158].).

Additionally, and although PV panels might be self-cleaning through the rain when the roof has the right incline, some additional actions might be required if there are birds, trees or even a high amount of traffic in the area.

3.0.4.2 System and product tests made by selected consumer organisations

Hereafter is a brief selection of some other examples of different types of information and tests that *consumer organisations* carry out to support residential consumers in installing PV systems.

The Belgian consumer organisation 'Test-Achats' for example provides extensive support to their members for purchasing PV systems (Test-Achats/Test-Aankoop, 2015[159]). They audit PV module manufacturers and check production samples on uniformity, compliance with the rated power, soldering errors with electroluminescence camera, visual errors in the back sheet laminates or frames and the quality system in place. They also offer group purchase promotions in which they audit the production accordingly. Moreover their requirements are:

- PV modules must comply with IEC 61215 (crystalline cells) or IEC 61646 (thin film cells) IEC 61730 (BAPV) with a third party certification (BELAC, TUV, ..), as detailed in Task 1.
- They refer to a reference contract proposed by the local authorities[160] for installers (Service Public Wallonie, 2015[161]), see a later section in this task for more details.
- Minimum warranty in modules and inverter of 10 years.
- At least one of the installers must have followed the Rescert PV installer course[162.]
- During installation the consumer organisation will perform regular audits.

The British consumer organisation Which?[163] provides similar information to its members based on module manufacturer audits and inspection combined with paid expert advice for selecting a PV systems. Another approach from the Spanish consumer organization OCU is to recommend a selection of tested PV systems or kits[164], which are preselected combinations of modules with inverters which are then given a scoring or rating based on their tested performance.

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[158] *Make the most of your solar panels - Which? (n.d.). Retrieved from https://www.which.co.uk/reviews/solar-panels/article/best-solar-panel-brands/make-the-most-of-your-solar-panels*

[159] *Test-Achats/Test-Aankoop, DECO, Altroconsumo, OCU, Consumentenbond, ICRT, … APERe. (2015). Clear - Consumers Learn Engage Adopt Renewable Energy Technologies. Retrieved March 20, 2018, from http://www.clear-project.eu/home/the-project/reports*

[160] *https://energie.wallonie.be/fr/installations-photovoltaiques-qualiwatt.html?IDC=8797*

[161] *Service Public Wallonie. (2015). contrattypeversion311decembre2015. Service Public Wallonie.*

[162] *https://www.rescert.be/fr/certificats-possibles*

[163] *https://www.which.co.uk/reviews/solar-panels/article/best-solar-panel-brands/solar-panel-brand-reviews*

[164] *https://www.ocu.org/vivienda-y-energia/gas-luz/test/comparar-kits-fotovoltaicos*

There are also international initiatives that developed collaboratively[165] PV system testing for their member consumer organizations. In principle what consumer organisations do is very close to what some retailers are doing [166, 167], the key difference is that they are also the contractor and single point of service. In many cases retailers and/or installers make proposals or quotes free of charge. Of course, test can also be done by third party accredited laboratories, as detailed in Task 1.

Of general interest are the technical terms of Walloon Reference contract for PV systems (Service Public Wallonie, 2015[161]). It stipulates that the installer should estimate the AC output of the PV system (see 3.1.5.1) and compare it to the metered annual energy consumption of the client from the most recent year. This AC output is related to the Final Yield (Yf) which depends on the Performance Ratio (PR) and the Reference Yield (Yr) see 3.1.5.1 or standard IEC 61724-1.

The AC output must be projected for a lifetime of 25 years taking into account module degradation (see 3.1.4.5). It is also required to make a detailed listing of all object that could contribute to shading (see 3.1.5.2) and inform the client about potential consequences. The AC output must be compared to a system with optimum inclination angle (35°), south orientation (see 3.1.4) and without shading effects (see 3.1.5.2). This will make it more easy to compare tenders disregarding their often subjective estimate of the impact from shading.

3.0.5 Public procurement criteria and requirements for PV systems

3.0.5.1 General introduction to public procurement

During the procurement process a public authority will select a contractor for installing the PV system. The entity responsible for on-site system installation based on the intended design, equipment specifications is called herein the contractor. The Contractor can thus be seen as one of the entities with the greatest impact on the quality of the asset in terms of safety and actual system performance (Doyle et al., 2015[168]).

The procurement process can vary according to the ownership. In the particular case of public authorities and green procurement, or Green Public Procurement, it means the process whereby public authorities seek to procure goods, services and works with *'a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured'*[169]. It is one of the objectives of this study to explore the potential for GPP criteria for PV modules, inverters and systems. Therefore this task will look for a set of representative examples according the different types[170] of criteria that are usually described or set so as to analyse how the priorities of public sector clients may influence technical requirements:

Selection Criteria (SC): Selection criteria refer to the tenderer, i.e., the company tendering for the contract, and not to the product being procured. It may relate to suitability and capability to pursue the professional activity, e.g. training. etc.

Technical Specifications (TS): Technical specifications constitute minimum compliance requirements that must be met by all tenders..

Award Criteria (AC): At the award stage, the contracting authority evaluates the quality of the tenders and awards points that will have a weighting together with to the price bid.

Contract Performance Clauses (CPC): Contract performance clauses are used to specify how a contract must be carried out. It may be linked to penalties or bonuses under the contract in order to ensure compliance.

The structure of the tender process is also linked to the preferred type of contractual arrangement, as illustrated by recent EU GPP criteria for Office Buildings (European Commission 2016). Figure 70 is taken from a guide developed for public authorities by the US Department of Energy and illustrates the different contracting routes that can be followed. Although the diagram is in a US context, the same broad options are available in a EU context.

Careful consideration of the contracting route is important because it may have implications for the types of GPP criteria that can be used, and when they will be applied during the bidding and contract execution process.

[165] *http://www.international-testing.org/*

[166] *https://www.ikea.com/gb/en/ikea/solar-panels/*

[167] *https://www.eon.de/de/pk/solar/aura/photovoltaikanlagen.html*

[168] *Doyle, C., Truitt, A., Inda, D., Lawrence, R., Lockhart, R., & Golden, M. (2015). Best Practices in PV System Installation. Retrieved from http://www.nrel.gov/docs/fy15osti/63234.pdf*

[169] *http://ec.europa.eu/environment/gpp/what_en.htm*

[170] *http://ec.europa.eu/environment/gpp/glossary_en.htm*

3.0.5.2 Public procurement – some initial examples

The Office Journal of the EU's tenders database was consulted in order to review the types of criteria that are set when publishing calls for tender for PV systems. Relatively few European public tenders were found to be published[171], with 46 tender documents for a period from 7/2015 until 4/2018. The most active country was Poland followed by France, Germany, UK, Ireland, Italy and Switzerland. Note that public authorities can also procure green electricity but apparently do not often procure and/or own the PV systems used to generate this electricity themselves.

There was also one tender from the European Commission services, in Ispra (JRC) (2018/S 030-064302). Worth noting that in the technical specifications sometimes also monitoring is required, for example the tender from JRC 2018/S 030-064302 requires a monitoring system according to new standard IEC 61724-1: 2017 class B.

Examples of Award Criteria were based on the price per kWp but sometimes combined with extra points[172] for (Main-Kinzig(D)) the following were specified: a longer warranty on modules and inverter, installation time, reaction time in case of failure and how long spare parts are kept for repair of the inverter. Repair response times and installation time are sometimes specified only in the Contract Performance Clauses instead of the Award Criteria.

Another Tender (Monthey-Switzerland) combined the price (35%) with the forecasted AC output power (35%) combined with the judging on the technical quality of the proposal (10%), the project management (10%) and previous references (10%). Note that in these example elements such as project management and references that are usually Selection Criteria were taken into account in the Award Criteria.

Important in all tenders reviewed were the minimum quality requirements and/or the valuation of quality, which are related to performance as discussed in the subsequent section 3.1 but also trained staff (see 3.4.1.8.

Apart from directly procuring a PV installation there are also other procurement routes. A special form of public procurement is using an Energy Service Company (ESCO) with Third Party Ownership, which is discussed in the previous section 3.0.2.3 wherein also the example of the Flemish municipalities was given. This can be done by roof contracting to a Third party, for example in Germany the Berliner Energy Agentur[173] is doing this. In both the UK (Reading) and in Germany (Freiburg) renewable energy investment co-operatives have been established to finance systems that have been installed on a range of public and community buildings [174] [175].

As explained in section 3.0.2.3 an important benefit of third party energy service or ownership models is avoidance of Value Added Taxes (VAT) on the installed PV installation. In Belgium the Distribution Company offers ESCO services to the local municipalities for their buildings[176] meaning that they organise the tendering, servicing an financing. Finally, public authorities can simply also procure green electricity. A hybrid of this approach is being used in some cases due to the absence of FiTs Power Purchase Agreements (PPAs). For example in the case of Portsmouth City Council in the UK [177].

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[171] *OJEU Tenders Electronic Daily, http://ted.europa.eu/TED/*

[172] *http://www.versorgungsservice-main-kinzig.de/Ausschreibung-2018.2031.0.html*

[173] *Berlin Energy Agency, http://www.berliner-e-agentur.de/en/services/photovoltaic-contracting*

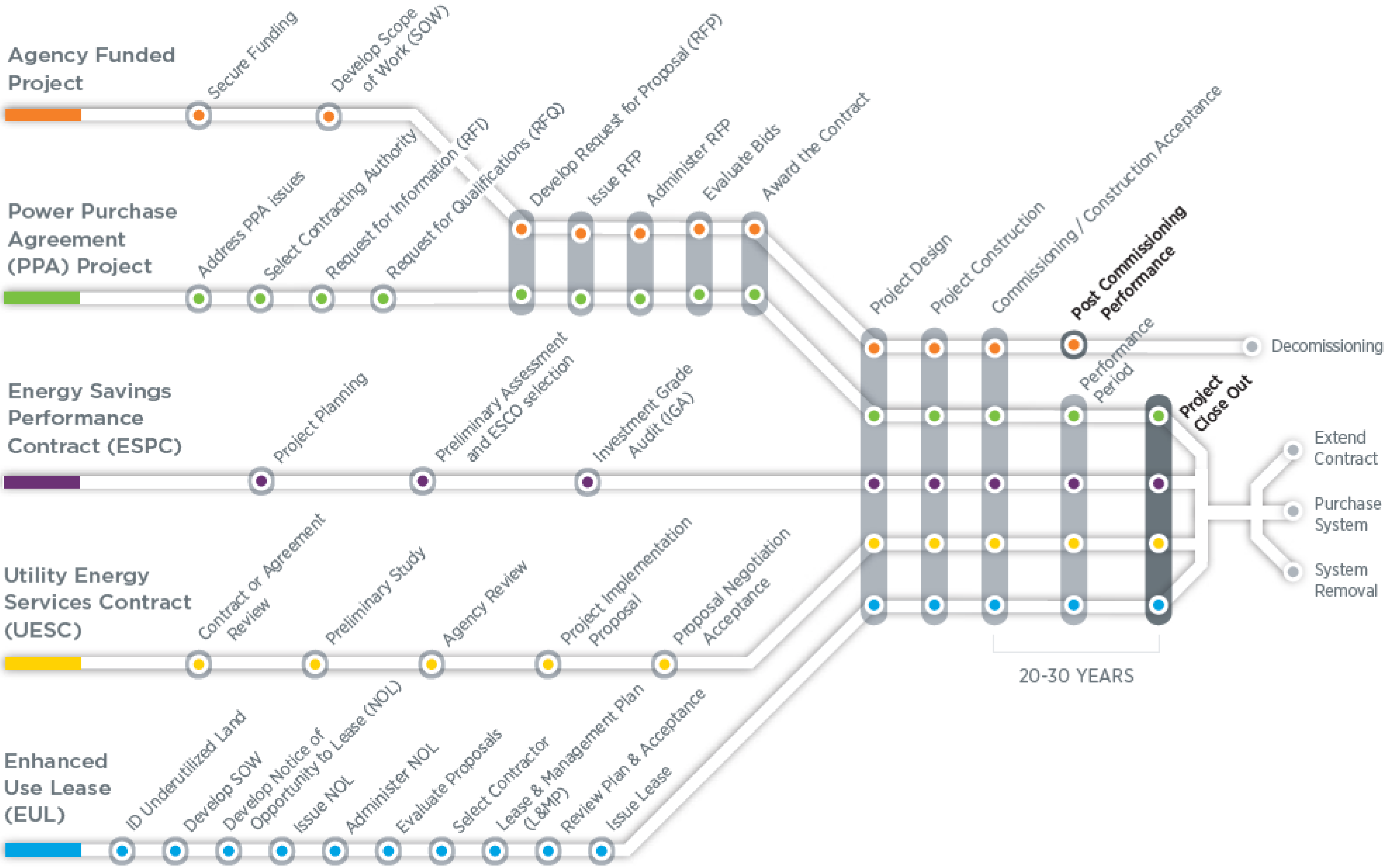
[174] *Reading Community Energy Society, readingenergy.coop*

[175] *see FESA www.fesa.de and Regiosonne www.regiosonne.solar-monitoring.de)*

[176] *http://www.eumayors.eu/about/covenant-community/signatories/key-actions.html?scity_id=5310*

[177] *Solar power portal, Solar PPAs and the public sector, 7th July 2016 https://www.solarpowerportal.co.uk/blogs/solar_ppas_and_the_public_sector_7834*

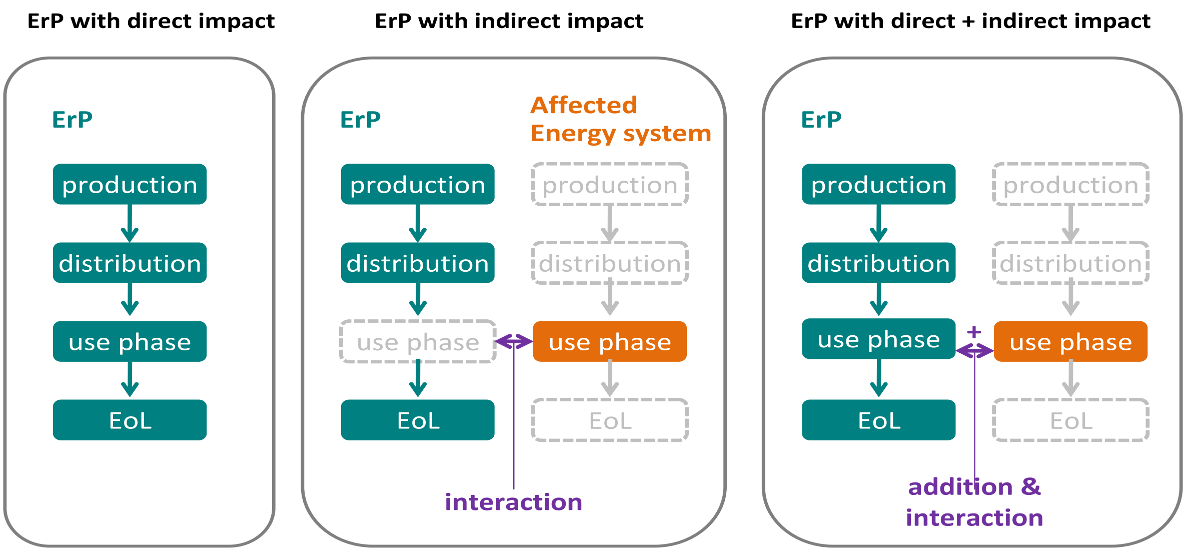
Figure 70. Diagram illustrating different financing and contractual arrangements for public procurement (Source: US DoE, 2010)



3.1 Subtask 3.1: Systems aspects in the use phase of solar photovoltaics with direct impacts on the energy production

For the purpose of introducing the MEErP method [178] the concepts of: Energy related Products (ErP) with direct impact, ErP with indirect impact and ErP with direct + indirect impact, are illustrated in Figure 71.

Figure 71. Ill (Source: MEErP, 2011)



The MEERP guidance (2011) refers to **direct impacts** as those related to energy consumption in the use phase. Given that solar PV is an energy generating product it might be needed to consider direct impacts in negative terms i.e. those parameters that may constrain or reduce the amount of electricity generated during the use phase, or which may be considered as direct losses from a system during the use phase. Direct impact for PV systems herein means any impact that is directly related to the PV system itself and it can therefore be interpreted as relating to the system design and specification decisions which can have a direct impact on the performance of a module, inverter or system. Consequently this are mainly those aspects taken into account in the **Performance Ratio (PR)** of the PV system and **the in plane irradiation(Hi)**.

In the case of **indirect impacts** the MEErP guidance refers to these as being related to an 'affected energy system'. Solar photovoltaic electricity generation will therefore displace or **substitute centralised non-renewable electricity generation**, thereby indirectly reducing environmental impacts. **Other** indirect impacts are also possible. For example, local on-site production will also indirectly **reduce transmission and distribution losses**. It also has to be taken into account that not all indirect impacts have a positive indirect benefit for example **matching the local load profile**. More details on these indirect impacts and the modelling thereof will be discussed in a subsequent section 3.2

A summary overview of direct and indirect impacts related to the use phase is in Table 51, see section 3.1.2 and later for more detailed technical definitions.

The analysis is based on different scoping levels in the subsequent section; starting with a strict product scope, and then extending this perspective to an extended product approach, thereafter proceeding to a technical system approach and finally discussing lifts from a functional system approach.

[178] *http://www.meerp.eu/*

Table 51. Direct and indirect impacts

Direct impacts	**Indirect impacts**
related to energy production in the use phase	**related to an affected energy system**
– Performance Ratio(PR), which is is the quotient of the system's final yield Yf to its reference yield Yr, and indicates the overall effect of losses – Derate Factors (DRx) to decompose Performance Ratio (IEC 61724-1:2017): $DR_{capture}$ for capture losses DR_{BOS} for BOS losses – In plane irradiation(Hi) [kWh/m^2] over the specified time period	– Environmental impacts due to substitution of non-renewable electricity with photovoltaic energy – Transmissions and distribution losses associated with the grid – Increased need for demand side management – Increased need for grid storage – Increased use of storage and therefore losses – Ancillary grid support, e.g. congestion management. – Substitute hot water production with fossil fuel in a building. – Provide renewable energy for local consumption (HVAC, home appliances, etc., ..)

3.1.1 Scoping levels with their system boundaries and functional unit

According to the MEErP method there are typically four different scoping levels:

- **Strict product approach**: In the strict product approach, the system boundary just contains the PV installation with its components. The operating conditions are nominal as defined in traditional standards.
- **Extended product approach**: In the extended product approach, the influence of real-life deviations from the testing standard will be discussed.
- **Technical system approach**: When viewed from the technical system perspective, the PV system is embedded in the surrounding building system or site.
- **Functional approach**: In the functional system approach, only the basic function of a photovoltaic, i.e. producing renewable energy, is maintained, yet other ways to satisfy this basic function are reviewed, as well. For example wind turbines can be installed at grid scale for RES or a solar collector for DHW at building level.

The **users or procurers will consider PV system design and specification first before they decide later on the product requirements,** which is more or less the reverse order of these sections.

The following boundaries can be defined (see also Task 1):

The **module 'product' boundary** includes all integrated components up to the DC terminals. For the module, the functional unit (see Task 1) is defined as a 1 kWh of DC power output from a reference system under fixed climatic conditions for 1 year and assuming a service life of 25 years.

The **inverter 'product' boundary** includes all integrated components between the DC supply to the inverter and up to the AC terminals. For the inverter, the proposed functional unit is defined as a 1 kWh of AC power output from a reference system (excluding the efficiency of the inverter) under fixed climatic conditions for 1 year and assuming a service life of 10 years.

The **'PV system'** encompasses all components required to deliver the functional unit. An extension of the boundaries of the system used to supply AC electricity should be done if storage options, like for example batteries, are included.. If a transformer is required, for example on larger utility scale installations, it is proposed that it is excluded from the boundary, but in the case that it is may require allocation if only part of its capacity is used. For the PV system, the proposed functional unit(see Task 1) is defined as a 1 kWh of AC power output supplied under fixed climatic conditions for 1 year (with reference to IEC 61853 part 4) and assuming a service life of 25 years.

The **'higher level' system** mainly refers to the electricity grid, but possibly also domestic hot water systems (in the case of PV powering a heat pump and thermal storage tank) and the petrol/diesel fuel supply chain (in the case of PV supplying an electric car battery).

3.1.2 The Performance Ratio(PR) of a PV system and the Derate factors(DR_k) for the scoping levels and product boundaries

The standard IEC 61724-1:2017 defines **the Performance Ratio (PR)** as the quotient of the system's final yield Yf [hours/period] to its reference yield Yr [hours/period] and indicates the overall effect of losses on the system output due to both array temperature and system component inefficiencies or failures, including balance of system components.

According to informative Annex C of IEC 61724-1:2017 the performance ratio can be defined as a series of multiplicative factors contributing to the performance ratio (PR) whereby DRk are individual deratings corresponding to different loss mechanisms.

In general, elements which reduce/determine performance losses in PV systems are:

- Effective solar irradiation available, therein taking into account:
  - diffuse radiation
  - direct sunlight
  - orientation, this especially relevant for BIPV but also others
  - shading, this especially relevant for BIPV but also others
- Ambient temperature
- Inverter Clipping which is efficiency derating when the expected output of the inverter is higher than the manufacturer-specified maximum
- Power Factor Correction, If the maximum inverter capacity is larger than the vector sum of the reactive power and real power produced by the inverter then a similar situation to that of inverter clipping can occur and losses in the inverter can increase due to this function.
- Excessive Soiling
- String/Module faults
- Degradation
- Mismatch between the string voltage and the input voltage range of the inverter
- Mismatch between the maximum power of the modules and the inverter

It should be noted, that some of these factors could also be regarded as design features for a system (i.e. inverter clipping) - the DC:AC ratio design is typically optimized depending on the use and application case, hence, clipping can be used as a design featured and might be desired for some use cases.

Taking into account the MEErP approach with its scoping levels and product boundaries (see 3.1.1) for the purpose of this study derate factors are defined in Table 52. The proposed **derate factors** in Table 52 are defined and explained in more detail in subsequent sections. This Table 51 has been elaborated based on IEC 61724-1:2017 terminology with the references to other standards included herein, and is considered to provide a good fit with the decomposition requested by the MEErP. Despite this we are aware that in literature non standardised terminology and ad hoc approaches are often used for decomposing the Performance Ratio depending on the data available and the purpose of the analysis. This may complicate the data collection for this study (see 3.1.7.)

Table 52. Overview of Derate factors for a PV system and relation to the scoping levels and product boundaries wherein STC means Standard Test Conditions.

Derate Factor(DF) Performance Ratio = $DR_{capture}$ x DR_{BOS}	PV system		Extended Product (non STC)		Strict product (STC)	
	overall	**detailed**	**overall**	**detailed**	**overall**	**detailed**
array capture losses derating	$DR_{capture}$	-	-	-	-	-
shading losses	-	$DR_{shading}$	-	-	-	-
snow cover losses	-	DR_{snow}	-	-	-	-
soiling losses	-	SL	-	-	-	-
DC array cable losses	-	DRarraywr	-	-	-	-
array mismatch losses	-	DR_{MISM}	-	-	-	-
optical reflection losses	-	DRrefl	-	-	-	-
other module level capture losses	-	$DR_{cap-mod}$	$DR_{cap-mod}$	-	-	-
module thermal capture loss	-	-	-	DR_{therm}	-	-
module degradation capture loss	-	-	-	DR_{degrad}	-	-
optical reflection losses	-	-	-	DRrefl	-	-
spectral effects	-	-	-	DRspect	-	-
module derating at STC	-	-	-	-	1	-
Balance of system (BOS) efficiency	DR_{BOS}	-	-	-	-	-
AC wiring losses	-	DRacwire	-	-	-	-
AC transformer losses (if available)	-	DRtrafo	-	-	-	-
losses due to network availability (curtailment)	-	DRcurt	-	-	-	-
losses due to inverter failures (drop out)	-	DRinv-fail	-	-	-	-
inverter losses (= DR_{inv-ns} x η_{inv})	-	DRinv	-	-	-	-
derating non standard inverter total	-	-	DRinv-ns	-	-	-
derating non standard inverter loading	-	-	-	$DR_{inv-load}$	-	-
derating non standard MPPT transients	-	-	-	$DR_{inv-MPPT}$	-	-
total inverter efficiency standard conditions	-	-	η_{t-inv}	-	η_{t-inv}	-
static inverter converter efficiency	-	-	-	-	-	ηconv
MPPT inverter efficiency	-	-	-	-	-	η_{MPPT}

Standard Test Conditions (STC): irradiation: 1000 W/m², temperature: 25°C, air mass: 1,5

Non-Standard Test Conditions (Non-STC)

3.1.3 The strict product approach

3.1.3.1 Standard Test Conditions for PV modules and main rating parameters

Standard Test Conditions (STC) refers to reference values of in-plane irradiance (1000 W/m²), PV cell junction temperature (25 °C), and the reference spectral irradiance (AM1.5) defined in IEC 61853-1.

In line with this STC the main module product performance parameter is the '**Maximum Power at STC' P_0 [kWp]** (see Task 1). It is the input parameter For estimating the annual yield(Yf) of a PV system. Typical PV module performance data is in Figure 72.

When the total area of the PV installation matters, the efficiency of converting solar radiation into electricity or **'Module Efficiency' n_A[%]** is an important secondary parameter. A typical commercial PV module today has an efficiency of 18 %, which means that a module of 1.60 m² will have a maximum power at STC of 290 Watt. Acceptable deviation range (0%-5%) from the nameplate rating is also stated in the datasheet. Further electrical properties measured at STC: maximum power point voltage and current, open-circuit voltage and short-circuit current as well as maximum operating voltage are also specified in a module datasheet.

Figure 72. Typical PV module data sheet

PERFORMANCE UNDER STANDARD TEST CONDITIONS (STC)*

Maximum power	P_{max}	280 Wp
Open circuit voltage	V_{oc}	39.0 V
Maximum power point voltage	V_{mpp}	31.8 V
Short circuit current	I_{sc}	9.45 A
Maximum power point current	I_{mpp}	8.93 A
Module efficiency	η_m	16.7 %

Measuring tolerance (P_{max}) traceable to TUV Rheinland: +/- 2% (TUV Power controlled, ID 0000039351) *STC: 1000W/m², 25°C, AM 1.5

PERFORMANCE AT 800 W/m², NOCT, AM 1.5

		SW 280
Maximum power	P_{max}	.
Open circuit voltage	V_{oc}	36.0 V
Maximum power point voltage	V_{mpp}	29.4 V
Short circuit current	I_{sc}	7.74 A
Maximum power point current	I_{mpp}	7.22 A

Minor reduction in efficiency under partial load conditions at 25 °C: at 200 W/m², 97% (+/-3%) of the STC efficiency (1000 W/m²) is achieved.

PARAMETERS FOR OPTIMAL SYSTEM INTEGRATION

Power sorting	-0 Wp / +5 Wp
Maximum system voltage SC II / NEC	1000 V
Maximum reverse current	25 A
Number of bypass diodes	3
Operating temperature	-40 to +85 °C
*Maximum design loads (Two rail system)**	113 psf downward, 64 psf upward
*Maximum design loads (Three rail system)**	178 psf downward, 64 psf upward

*Please refer to the Sunmodule installation instructions for the details associated with these load cases.

COMPONENT MATERIALS

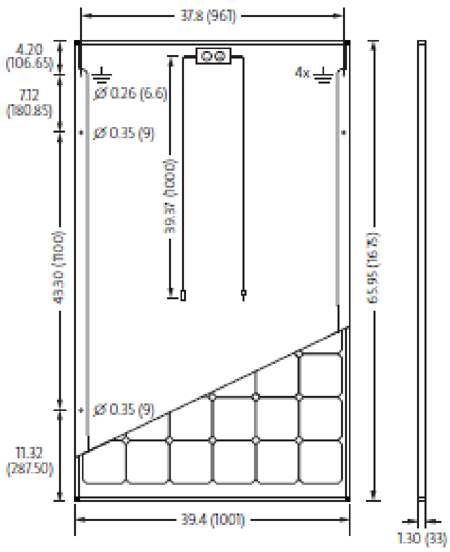
Cells per module	60
Cell type	Monocrystalline PERC
Cell dimensions	6 in x 6 in (156 mm x 156 mm)
Front	Tempered safety glass with ARC (EN 12150)
Back	Multi-layer polymer backsheet, black
Frame	Black anodized aluminum
J-Box	IP65
Connector	PV wire (UL4703) with Amphenol UTX connectors
Module fire performance	(UL 1703) Type 1

DIMENSIONS / WEIGHT

Length	65.95 in (1675 mm)
Width	39.40 in (1001 mm)
Height	1.30 in (33 mm)
Weight	39.7 lb (18.0 kg)

THERMAL CHARACTERISTICS

NOCT	46 °C
TC I_{sc}	0.07 % /C
TC V_{oc}	-0.29 % /C
TC P_{mpp}	-0.39 % /C



All units provided are imperial. SI units provided in parentheses.

ORDERING INFORMATION

Order number	*Description*
82000246	Sunmodule Plus SW 280 mono black

CERTIFICATES AND WARRANTIES

Certificates	IEC 61730	IEC 61215	UL 1703
	IEC 62716	IEC 60068-2-68	IEC 61701
Warranties	Product Warranty		20 years
	Linear Performance Guarantee		25 years

3.1.3.2 Standard Test Conditions for Inverters and key performance parameters

The inverter efficiency or so-called Euro-efficiency for standard load profiles is defined in the standard EN 50530 (year to define, under review[179]) and EN 50524 for data sheet and name plate for photo-voltaic inverters, see Task 1.

The **Overall efficiency (η_t)** is ratio of the AC energy output to the theoretically available energy in the Maximum Power Point (MPP) within a defined measuring period.

The **conversion efficiency (η_{CONV})** is ratio of the AC energy output to the DC energy input within a defined measuring period. The conversion efficiency depends on the load profile of the inverter and for this purpose standard load profiles are defined, it is a static efficiency not taking into account load variations die to changing weather conditions.

179 *https://www.researchgate.net/publication/228652218_prEN_50530-the_new_European_standard_for_performance_characterisation_of_PV_inverters*

The **MPPT efficiency (η_{MPPT})** is the ratio of the energy drawn by the device under test within a defined measuring period T_M to the energy provided theoretically by the PV simulator in the **(**MPP**)**. A photovoltaic system is only rarely operated under constant ambient conditions, because the sun's radiation values are subject to changes related to the weather and the time of day. Since the solar inverter is responsible for managing the output of the entire PV system, it must react dynamically to these changes. The standard EN 50530 defines standard transient load profiles for inverters.

Typical inverter efficiencies[180] are 96% conversion efficiency and 99,9 % MPPT efficiency. More details on inverter efficiency will be discussed in Task 4.

3.1.4 Extended product scope

This complements the previous strict product approach.

3.1.4.1 Impact of real life weather conditions on the final system yield(Yf)

Components and systems respond to climatic variations, i.e. where in the EU a system is located. This means that the same PV module and inverter will have a different performance based on the intensity of solar radiation, ambient temperature and wind speed and other weather factors. These environmental factors are inherently varying which in turn leads to changes in the PV system performance. For precise performance assessment of PV systems this requires the use of recorded weather data over entire year to capture the hourly, daily, and seasonal variations. The time interval of the data used will influence the accuracy of design simulation of a PV system performance.

The **final system yield (Yf)** (IEC 61724-1:2017) [hours/period] is defined as is the net energy output of the entire PV system (AC) per rated kW (DC) of installed PV array. This yield forecast is necessary for an owner to estimate his annual revenue, for example based on a subsidy scheme with feed-in-tariffs (FiT).

The final system yield is dependant (IEC 61724-1:2017) on the performance ratio (PR), which is subject of other sections, but also on **the reference yield (Yr**) [hours/period].

The following formulas apply:

$Y_f = PR \times Y_r$

Yr = Hi/Gi,ref

Wherein,

Yf = system yield which is the energy output divided by the array power rating.

Yr = reference yield which are the equivalent hours of solar radiation at Gi,ref

Hi = in plane irradiation [kWh/m^2] over specified time period or Plane-of-array (POA)

Gi,ref = in plane reference irradiance which is 1 kW/m^2 due to STC definition

PR = Performance ratio (pollution, degradation, thermal loss,..)

In order to estimate the reference yield this various calculation tools are available, e.g. the European Solar Atlas provided by JRC[181] (Figure 73).

PV syst[182] is the most widely used PV system design tool by project developers for commercial and utility scale projects. This tool is the most trusted by investors and insurance companies for historic reasons. This commercial software allows for the calculation of more complex systems that include for example geographic location, orientation, shading, module efficiency, module technology, inverter efficiency, etc. Weather data with hourly resolution are used in this simulation tool.

Fine-grain temporal simulation (hourly and shorter time series without averaging) of the PV system performance improves its precision. Relative errors up to 5% in precision are found for annual energy yield simulation between using either hourly or averaged weather input (Thomas Huld, Gottschalg, Beyer, & Topič, 2010[115]). This is particularly important for PV system design integrated with batteries or connected to a congested electrical grid.

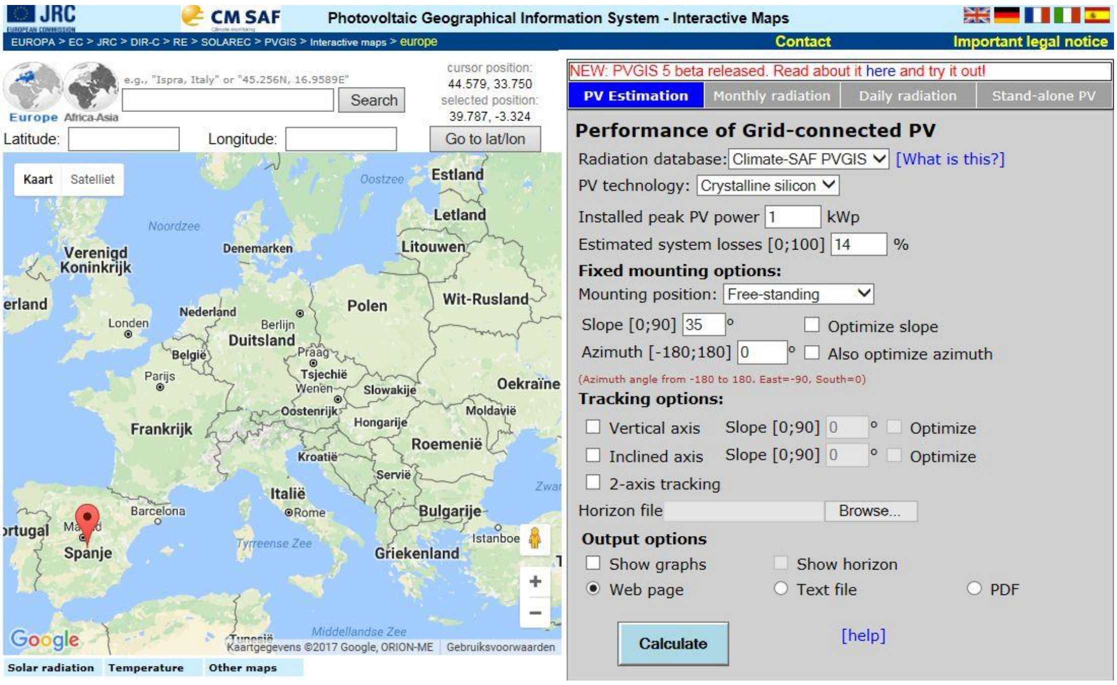
[180] *For example: https://www.fronius.com/en/photovoltaics/products/all-products/inverters/fronius-galvo/fronius-galvo-3-1-1*

[181] *http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php*

[182] *http://www.pvsyst.com/en/*

One should equally consider that significant uncertainty in the PV power generation arises from the difference between irradiation databases. Use of long-term dataset and/or combination of values from different databases are recommended[183]. To further improve the precision of solar irradiance measurements relevant tools and methods are have been developed by the Performance Plus project[184].

Figure 73. Tool for PV yield estimation (source: PV GIS Tool JRC)



The reference Yield (Yr) depends on the location's climate mostly due to variation in solar irradiance, duration of days and temperature. To enable systematic comparison between studies for different PV application based on simplified version of the Koppen-Grieger climatic zones (Figure 74) the current draft IEC61385-4 lists 6 reference international climates covering different irradiance, temperature and humidity conditions. These climate zones are the following:

- Humid tropical,
- Subtropical arid,
- Subtropical costal,
- Temperate coastal,
- High altitude,
- Temperate continental.

By way of comparison, and considering mostly the irradiance, the PVsites project which focussed on BAPV and BIPV module design and assessment in Europe has narrowed this selection to 4 climates: Southern, Western, East and North Europe as shown in Figure 75.

[183] *Solar Bankability project: Technical risks in PV projects*

[184] *FP7 PErformancePlus project final report: https://cordis.europa.eu/docs/results/308/308991/final1-308991_perfplus_finalreport_20151219_f.pdf*

Figure 74. Koppen-Grieger climatic zones

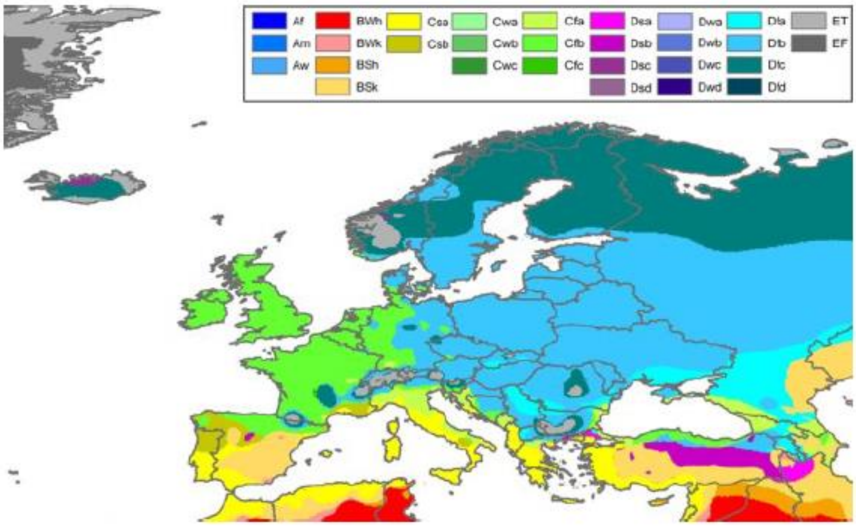
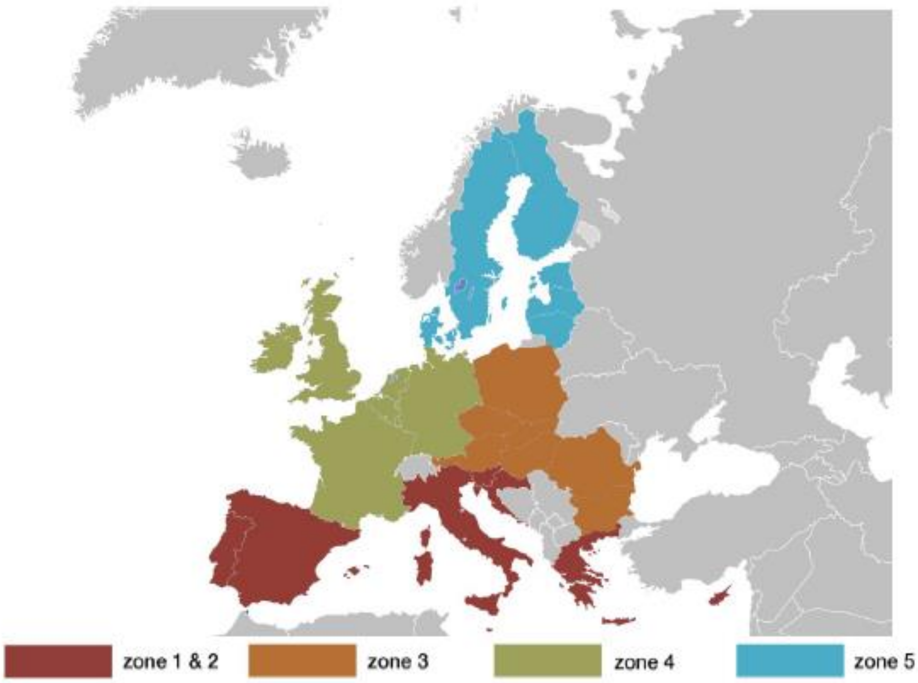


Figure 75. Climate zones defined by PVsites project



For Ecodesign and Energy Labelling Regulations for air conditioners and solar heaters the temperature was the most critical factor. The EU regulation 812/2013 defines 3 climate zones for labelling solar heaters which are average climate conditions, colder climate conditions and warmer climate conditions. An overview and corresponding categories between the different climates is listed in the table below.

For accurate energy yield assessment it is important to consider both irradiance (and relevant soiling, snow cover) and temperature hence it is proposed to consider a four climate zone. For each climate zone a specific location has been suggested based on the availability of high-quality weather and module power measurement data for detailed assessment. The typical irradiation values for these locations are indicated in Table 53.

Table 53. Overlay of climate zones and corresponding location options

IEC61385 (latitude)	PVSites	EU Regulation 812/2013	Location options
Subtropical arid (33°N33')	Southern Europe	Warm	Madrid, Rome, Athens
Temperate Coastal (56°N)	Western Europe	Average	Dijon, Paris
Temperate Continental (57°N)	Eastern Europe	Average	Berlin, Budapest
Temperate Continental (34°N)	Northern Europe	Cold	Helsinki, Stockholm

3.1.4.2 Module capture losses due to temperature impact (parameter: DRtherm)

Potentially one of the greatest impacts on real module performance comes from technology specific temperature effects in comparison to Standard Test Conditions (STC) when temperature is 25°C. In the case of crystalline silicon cells the module performance decreases as the temperature increases. The module power decreases by approx. 0.5%/°C. This technology specific parameter is listed on the module datasheet and further comparison between simple and more advanced crystalline silicon cells and other thin-film PV technologies is also possible using the planning software, e.g. the PVGIS tool from JRC[181]. It is important to note that temperature coefficient of certain thin-film PV technologies are positive, i.e. meaning that their performance improves at higher temperature.

Table 54. Capture losses due to temperature impact and low irradiance (source: PVGIS tool[181])

	Berlin (D)		Dijon	Rome
	optimum	BIPV	optimum	optimum
Slope angle [°]:	33	45	35	35
Azimuth angle [°]:	0	-45	-7	-8
Temperature and low irradiance [%]:	-5	-8	-8	-11,3
DRtherm	0,95	0,92	0,92	0,89

The average operating temperature of a PV system is 45-50°C in residential roof or ground mounted PV panel. The temperature increase compared to ambient temperature arises due to radiative heating for the sun and the environment, ambient temperature, heat generation within the PV module linked to resistive losses to name a few elements. The temperature of the PV module can be mostly lowered through natural and forced convection, e.g. wind. Therefore, installation conditions play a critical role in determining the front and back ventilation of the PV modules. In certain cases where ventilation of the PV panel is limited for example in BIPV installation the module temperature can raise up to 70-80°C.

3.1.4.3 Module capture losses due to spectral differences (DRspect)

Spectral variations refer to difference in the bandgap and absorption coefficient of the photo-active material used in the PV module. In single-junction crystalline silicon cell based modules the variation linked to spectral variations is minimal and largely averages out between the different seasons on yearly basis. This effect can become more important in various thin film PV (TFPV) technologies and tandems. Consumers may also choose to purchase higher performance heterojunction cell-based modules which incorporate more complex combined crystalline and thin film structures. For a set of reference applications data is included in Table 55.

Table 55. Capture losses due to spectral effects (source: PVGIS tool181)

	Berlin (D)		Dijon(F)	Rome(IT)
	optimum	BIPV	optimum	optimum
Slope angle [°]:	33	45	35	35
Azimuth angle [°]:	0	-45	-7	-8
Spectral effects [%]:	1,5	1,5	1,5	1
DRspect	1,015	1,015	1,015	1,010

3.1.4.4 Module capture losses due to reflection and angle of incidence (parameter: DRrefl)

The reflection losses in PV modules is linked to reflection from the glass surface as optical constants of all other materials is well optimized. This reflection loss can amount to 4% in case the glass has no surface treatment However, the use of anti-reflective coating to eliminate these losses is rapidly becoming industry standard[185]. Reflection losses can have significant seasonal variation, also depending on orientation and location. Certain effects average out over the year and studies estimate that losses amount to approx. 1%[186]. For a set of reference applications data is included in Table 56.

Table 56. Capture losses due to reflections (source: PVGIS tool181)

	Berlin (D)		Dijon(F)	Rome(IT)
	optimum	BIPV	optimum	optimum
Slope angle [°]:	33	45	35	35
Azimuth angle [°]:	0	-45	-7	-8
Angle of incidence [%]:	-3	-2,9	-3	-2,6
DRrefl	0,970	0,971	0,970	0,974

3.1.4.5 The impact from module degradation over lifetime (parameter: DRdegrad)

Typically crystalline silicon modules will degrade in performance at up to 1.0% per year which in turn influences the module lifetime which is further discussed in a later section 3.3.1. This is a technical issue that will be even further elaborated into more detail in Task 4.

All market players requires as minimum a certification of the PV module by an independent organisation based on IEC 61215 standard. Further application and installation condition demands complementary certification of the PV module following these standards: IEC 62804, Complementary testing for PID resistance, IEC 62716: Ammonium and IEC 61701 salt mist corrosion tests (depending on location, installation) and later with the new standards in preparation (see reports prepared by JRC).

Furthermore industrial players often require extended testing compared to conditions listed in the IEC 61215 and demand an extensive factory inspection.

3.1.4.6 The impact from inverters in non-standard conditions (parameter: DRinv-ns)

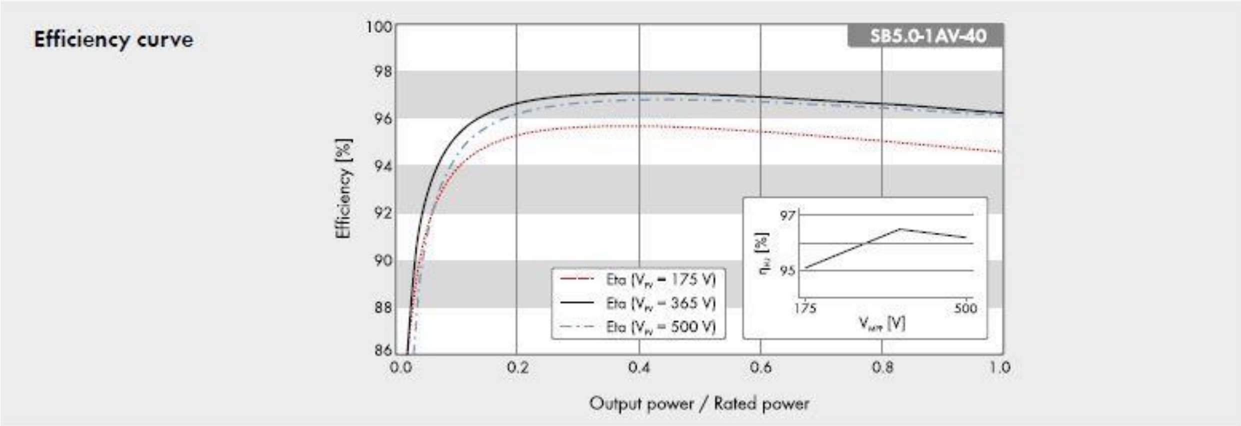
The energy efficiency of an inverter (%) can be measured according to standard EN 50530. This information is included in the datasheet of manufacturers or sourced from a well-documented online database[187], for example Figure 76. As can be seen from the example in the data sheet in Figure 76.

[185] *ITRPV Edition 2017*

[186] *D. L King et al., IEEE PVSEC 2002*

[187] *http://www.photon.info/photon_site_db_wechselrichter_en.photon*

Figure 76. Typical inverter data sheet



Technical data	Sunny Boy 3.0	Sunny Boy 3.6	Sunny Boy 4.0	Sunny Boy 5.0
Input (DC)				
Max. generator power	5500 Wp	5500 Wp	7500 Wp	7500 Wp
Max. input voltage	600 V			
MPP voltage range	110 V to 500 V	130 V to 500 V	140 V to 500 V	175 V to 500 V
Rated input voltage	365 V			
Min. input voltage / initial input voltage	100 V / 125 V			
Max. input current input A / input B	15 A / 15 A			
Max. input current per string input A / input B	15 A / 15 A			
Number of independent MPP inputs / strings per MPP input	2 / A:2; B:2			
Output (AC)				
Rated power (at 230 V, 50 Hz)	3000 W	3680 W	4000 W	5000 W 1)
Max. apparent power AC	3000 VA	3680 VA	4000 VA	5000 VA 2)
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V to 280 V			
AC power frequency / range	50 Hz, 60 Hz / −5 Hz to +5 Hz			
Rated power frequency / rated grid voltage	50 Hz / 230 V			
Max. output current	16 A	16 A	22 A 2)	22 A 2)
Power factor at rated power	1			
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited			
Feed-in phases / connection phases	1 / 1			
Efficiency				
Max. efficiency / European Efficiency	97.0% / 96.4%	97.0% / 96.5%	97.0% / 96.5%	97.0% / 96.5%

The European Efficiency (EN 50530) and the maximum Efficiency can deviate from the real life efficiency because:

- The real string voltage might be different depending on the selected type and amount of PV modules compared to those used in the standard;
- Real weather conditions and production profile;
- The standard does also not cover all new inverter topologies in detail, in particular inverters that incorporate charge controllers for battery storage (see next paragraph).

In principle an inverter converts DC (direct current) from PV modules into AC grid power, see Task 1. Because batteries are also working on DC, an opportunity exists to integrate the storage battery with the inverter and avoid conversion losses, see 3.4.2.1. Several manufacturers such as SMA already start to bring these inverters with combined battery storage on the market. In this case it will impact and complicate the definition and calculation of the inverter efficiency, and development of metrics and standards is ongoing[188] (see also Task 1).

Moreover it is also possible to integrate BAPV with storage and loads on a DC building network. Recent research found that relative to a conventional AC system, a DC network improves energy efficiency by approximately 2% without storage and 4% with storage for a simulated single family low energy home with heat pump located in central Europe[189]. The technology behind this will be further explained in Task 4.

[188] *http://www.bves.de/wp-content/uploads/2017/04/Effizienzleitfaden_V1.0.4_April2017.pdf*

[189] *https://infoscience.epfl.ch/record/213389/files/7_HOFER.pdf*

3.1.5 Technical system approach

This complements the previous extended product approach at system level.

3.1.5.1 Annual AC output energy of the PV system

The **final annual AC output energy(Eout)** is simply related to the final system yield (Yf) and the rated array power rating (Po) with the following formula:

Eout = Yf x Po

For the final system yield (Yf) definition, see section 3.1.4.1.

3.1.5.2 The impact from shading (parameter: DRshading)

PV system shading in the different categories can arise liked to inter-array or nearby objects (trees and buildings). Shading is particularly critically important in residential PV and BIPV application. Although the effect of shading can be simulated, its impact on the PV system is more complex to estimate as it depends on the plant configuration, and the use of Module level Power Electronics such as bypass diodes, DC optimisers and micro-inverters must be considered. This factor is described by DRshading. More details on these technologies will be discussed in Task 4 on technology.

To decrease the impact from shading, bypass diodes are standardly implemented in all PV modules. Furthermore DC power optimisers added between each module and the inverter are becoming common in residential PV installation. They will be discussed in Task 4 on technology. This is particularly the case for residential PV installation BIPV systems.

3.1.5.3 The impact from snow cover (parameter: DRsnow)

Snow coverage is considered as a specific case of soiling, naturally linked to the local climate. Models for its assessment given weather conditions are proposed as well as yield loss analysis studies. In general snow coverage leads to <1% annual energy yield loss[190].

3.1.5.4 The impact from soiling and regular cleaning (parameter: SL)

PV module soiling is caused by pollution, bird droppings, the accumulation of various forms of dust and local growth of moss. Soiling effects largely vary according to local rain fall and pollution. In temperate climate regions with regular rainfall losses 0-5% are estimated while in arid climate this can increase up to 25%[191]. This impact is related to maintenance that is also discussed in section 3.1.7.2. Especially larger PV systems do regular cleaning services and these are requested by owners and investors in order to maximise yield. For larger buildings this can be combined with the cleaning cycles for windows. In the residential market some installers now offer aftercare services that include periodic cleaning. Some companies in the market are specialised in cleaning[192]. Cleaning is usually done with distilled or demineralized water without using detergents because they could harm the anti-reflective coating. Demineralized water can be for example obtained with mobile reverse osmosis water purification system. A number of dry cleaning options are as well available that may be more efficient.

3.1.5.5 Impact of other PV system losses in cables and transformers behind the meter (parameters: DRacwire and DRtrafo)

When the system is connected to the low voltage distribution grid, transformer and AC cable losses are indirect losses which are discussed in section 3.2.2. Large installations (≥ 250 kVA) can be directly integrated into the Medium Voltage (MV) distribution or transmission grid. In these large installations it is possible that those transformer losses are taken into account in the energy bill of the PV system owner when the meter is located at the medium voltage and grid side of the transformer. In large installations with their own step up transformer it is possible to disconnect the transformer after curfew to eliminate no-load losses.

Transformer losses are regulated by Commission Regulation 548/2014 on Commission Regulation 548/2014 "On Ecodesign Requirements For Small, Medium And Large Power Transformers" and did set maximum loss requirements on transformers since July 2015 (Tier 1). For example in Tier 1 a 400 kVA transformer can have maximum 430 W no-load losses and 4600

[190] R. W. Andrews et al., http://digitalcommons.mtu.edu/materials_fp

[191] Solar Bankability Project: Technical Risks in PV projects

[192] http://www.solarclean.be/en/references/

Watt load losses, hence they are low (<1%). Total transformer losses (Ptot) are a combination of load and no-load losses (Tichelen et al., 2011[193]).

3.1.5.6 Impact from system unavailability due to grid curtailment and other system failures (DRcurt)

These derate factors are related to the down time of the installation. They are related to the impact from catastrophic module and inverter failures are discussed in sections 3.3.1.2 and 3.3.1.4. It can also be result from grid curtailment due to for example grid congestion and over voltages, which is discussed in section 3.4.1.5.

3.1.6 Functional approach

This complements the previous technical system approach.

3.1.6.1 Design trade-offs for achieving Nearly Zero Energy Buildings(NZEB) with PV

The Energy Performance of Buildings Directive (EPBD) (see Task 1) requires all new buildings to be Nearly Zero Energy Buildings as of 31 December 2020.

The EPBD's article 2 defines 'nearly zero-energy building' as a building that has a very high energy performance, as determined in accordance with Annex I of the Directive.

For buildings there exist a choice of different technologies that can be used to deliver either:

- a specific level of reduction in primary energy use and CO_2 emissions, or
- a specific proportion of a buildings energy from renewables.
- a high level of self-consumption as an alternative to an external energy supplier.

It says also that the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. Therefore photovoltaics can be in important design option to achieve NZEB (Adhikari, Aste, Pero, & Manfren, 2012[194]; Attia, 2018[195]; D'Agostino & Parker, 2018[196]; Salom et al., 2013[197]). However one should be aware that this is not the only option to achieve NZEB[198]. For example passive heating/cooling design options for windows and shading can be compared with increasing photovoltaics. Another important comparison that can be made is between installing a solar collector for Domestic Hot Water (DHW) versus photovoltaics with a heat pump. The design of such buildings is outside the scope of this study. Building energy calculation tools today already include photovoltaic solar forecasting tools[199] making it easy for the architect to compare design those options.

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[193] Tichelen, P. Van, Peeters, E., Goovaerts, L., Stevens, M., Geerken, T., Vercalsteren, A., … Faninger, T. (2011). LOT 2: Distribution and power transformers. Tasks 1 – 7. Retrieved from https://transformers.vito.be/sites/transformers.vito.be/files/attachments/EuP_TransformersTask_1_7_V60.pdf

[194] Adhikari, R. S., Aste, N., Pero, C. D., & Manfren, M. (2012). Net Zero Energy Buildings: Expense or Investment? Energy Procedia, 14, 1331–1336. https://doi.org/10.1016/j.egypro.2011.12.1097

[195] *Attia, S. (Ed.). (2018). Net Zero Energy Buildings (NZEB): Concepts, Frameworks and Roadmap for Project Analysis and Implementation. Butterworth-Heinemann.*

[196] D'Agostino, D., & Parker, D. (2018). A framework for the cost-optimal design of nearly zero energy buildings (NZEBs) in representative climates across Europe. Energy, 149, 814–829. https://doi.org/10.1016/j.energy.2018.02.020

[197] *Salom, J., Marszal, A. J., Candanedo, J., Widén, J., Lindberg, K. B., & Sartori, I. (2013). Analysis of Load Match and Grid Interaction Indicators in Net Zero Energy Buildings with High - Resolution Data.*

[198] https://ec.europa.eu/energy/sites/ener/files/documents/nzeb_executive_summary.pdf

[199] http://passivehouse.com/04_phpp/04_phpp.htm

https://www.cadvilla.com/de/index.php

https://sustainabilityworkshop.autodesk.com/buildings/pv-panel-factors-revit

3.1.7 Summary of typical performance ratios for a set of European reference installations and impact from design, construction and monitoring/ maintenance

3.1.7.1 Design and construction stages

The role of the system designer and the general concept was already discussed in the previous section 3.0.4. Some examples of design aspect to be considered are presented in Table 57.

Table 57. Some of the design aspects to be considered – based on (Doyle et al., 2015[164]) and updated

General Site	**Roof** (if roof-mounted)	**Structure**	**Electric**	**New equipment location**
Building footprint	Dimensions	Wind speed or snow load	Service type and size, main service panel, and breaker size	Inverter
Distance to property lines	Required minimum roof dimensions	Design roof snow load	Service panel make and model	Conduit run
Age of roof covering (if roof-mounted)	Type of roof covering	Rafter or truss spacing	Availability of breaker spaces	PV modules
Age of home (if roof-mounted)	Underlayment type and lap dimensions	Framing lumber dimensions	Meter location relative to the building	Service disconnect
Easements, restrictions, open permits	Roof condition	Rafter or truss spacing		
	Existence of obstruction locations	Max. rafter span or longest truss top chord panel length between struts		Monitoring equipment
	Safety & liability considerations	Lumber species and grade		
		Sheathing thickness and type		

All mentioned design tasks should aim to maximize the overall Performance Ratio (PR) within the local boundary conditions, i.e., in other terms carefully minimising the impact of each Derate factors (DFx) listed below and the reference yield (Yf).

Table **58** contains an overview of the impact of PV plant layout, connection to the grid as well as factors linked to design monitoring and maintenance on the various factors that were described in detail in previous sections. Table 59 presents typical values for PV system performance parameters.

These data will be elaborated in a further review after deciding on the typical reference locations.

Table 58. Summary of impacts from design, monitoring, maintenance on the PV system performances (source: own estimate)

Derate Factor(DF) Performance Ratio = $DR_{capture}$ x DR_{BOS}	impact from design /specification	impact from maintenance	impact from monitoring
array capture losses derating	x (specify monitoring)		xxx
shading losses	xxx	x	xxx
snow cover losses			xx
soiling losses		xxx	xx
DC array cable losses	xxx		
array mismatch losses	xx	xx	xx
optical reflection losses			
other module level capture losses	x (module selection)		xxx
module thermal capture loss			
module degradation capture loss			
optical reflection losses			
spectral effects			
module derating at STC			
Balance of system (BOS) efficiency			
AC wiring losses	xx		
AC transformer losses (if available)			
losses due to network availability (curtailment)			xxx
losses due to inverter failures (drop out)			xxx
inverter losses (= DR_{inv-ns} x η_{inv})			x
derating non standard inverter total	xx (match string voltage/inverter)		
derating non standard inverter loading	x		
derating non standard MPPT transients	x		
total inverter efficiency standard conditions			
static inverter converter efficiency	xxx		
'Module Efficiency' ηA[%]	x (fit with available area)		
Annual Reference Yield Yr[KWh/KWp]	xxx		xxx

Table 59. Typical PV system performance parameters (TBD to be defined)

Derate Factor(DF) **Performance Ratio = $DR_{capture}$ x DR_{BOS}**	**PV system**		**Extended Product (non STC)**		**Strict product (STC)**		**typical value (range)**		
	overall	**detailed**	**overall**	**detailed**	**overall**	**detailed**	**residential**	**commercial**	**utility scale**
array capture losses derating	$DR_{capture}$	-	-	-	-	-	0,75	0,8	0,8
shading losses	-	$DR_{shading}$	-	-	-	-	TBD	TBD	TBD
snow cover losses	-	DR_{snow}	-	-	-	-	TBD	TBD	TBD
soiling losses	-	SL	-	-	-	-	TBD	TBD	TBD
DC array cable losses	-	DRarraywr	-	-	-	-	TBD	TBD	TBD
array mismatch losses	-	DR_{MISM}	-	-	-	-	TBD	TBD	TBD
optical reflection losses	-	DRrefl	-	-	-	-	TBD	TBD	TBD
other module level capture losses	-	$DR_{cap-mod}$	$DR_{cap-mod}$	-	-	-	TBD	TBD	TBD
module thermal capture loss	-	-	-	DR_{therm}	-	-	TBD	TBD	TBD
module degradation capture loss	-	-	-	DR_{degrad}	-	-	TBD	TBD	TBD
optical reflection losses	-	-	-	DRrefl	-	-	TBD	TBD	TBD
spectral effects	-	-	-	DRspect	-	-	TBD	TBD	TBD
module derating at STC	-	-	-	-	1	-	TBD	TBD	TBD
Balance of system (BOS) efficiency	DR_{BOS}	-	-	-	-	-	TBD	TBD	TBD
AC wiring losses	-	DRacwire	-	-	-	-	TBD	TBD	TBD
AC transformer losses (if available)	-	DRtrafo	-	-	-	-	TBD	TBD	TBD
losses due to network availability (curtailment)	-	DRcurt	-	-	-	-	TBD	TBD	TBD
losses due to inverter failures (drop out)	-	DRinv-fail	-	-	-	-	TBD	TBD	TBD
inverter losses (= DR_{inv-ns} x η_{inv})	-	DRinv	-	-	-	-	TBD	TBD	TBD
derating non standard inverter total	-	-	DRinv-ns	-	-	-	TBD	TBD	TBD
derating non standard inverter loading	-	-	-	$DR_{inv-load}$	-	-	TBD	TBD	TBD
derating non standard MPPT transients	-	-	-	$DR_{inv-MPPT}$	-	-	TBD	TBD	TBD
total inverter efficiency standard conditions	-	-	η_{t-inv}	-	η_{t-inv}	-	TBD	TBD	TBD
static inverter converter efficiency	-	-	-	-	-	ηconv	TBD	TBD	TBD
'Module Efficiency' ηA[%]							20%	18%	16%
Annual Reference Yield Yr[KWh/KWp]							site dependent		

3.1.7.2 Operation, monitoring and maintenance practices

The key to the successful operation of a PV plant is the monitoring system. Without accurate monitoring with suitable time resolution that enables downloading any available parameters from any collection of plant elements across any time span, there is little possibility for optimizing operational activities. With a quality monitoring system, it is possible to optimize maintenance tasks such as e.g. module washing frequency and ascertain if string fuses have blown before and detect any other need for intervention. Preventative maintenance activities should thus take place in order to assure the good performance of the system (IEA PVPS, 2017a[200]).

The following references have been identified as detailing good practices for installing monitoring to support maintenance and repair:

- IEC 61724 – Photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis
- Operation and Maintenance guidelines from Solar Power Europe (2017): http://www.solarpowereurope.org/reports/o-m-best-practices-guidelines/
- Best Practices in Photovoltaic System Operation and Maintenance 2nd Edition, from NREL (2016)
- Analytical Monitoring of Grid-Connected Photovoltaic Systems: Good Practices for Monitoring and Performance Analysis from IEA PVPS (2014)
- There are internet forums on data logging of PV for small and residential users, e.g.: https://www.photovoltaikforum.com/datenlogger-f5/ or https://www.zonstraal.be/forum/
- There are also tools for data analytics based on artificial intelligence and machine learning which can be used to verify the performance behavior of PV plants and at a later stage improve and automate the optimization of performance (http://www.3e.eu/data-services/pv-health-scan/ and http://www.3e.eu/pv-performance-verification-meets-big-data/). The use of this type of tools may detect early faults and performance degradation give actionable recommendations on the root causes.

The standard IEC 61724-1:2017 defines three classes (A, B, C) of monitoring systems. The practical implementation of monitoring and maintenance depends on the size of the installation. Especially the cost for a local weather station for solar irradiation and wind can be expensive, as well as the cabling for monitoring individual cell temperatures. A power meter hence it is mainly a data logger that needs to be added[201], when a digital meter is present from the utility it can often be used. Measurements per module exists and technology will be further discussed in Task 1. Detailed monitoring can reveal the origin of a low performance ratio (see 3.1).

In its most simple and low cost form, people can compare their annual yield as calculated free online with PVGIS[202,203] in kWh/kWp and compare it with their annual metered data. To correct for annual weather variation data from the nearby weather station can be consulted[204] or compared to similar installations in the neighbourhood[205]. This remains however inaccurate and does not reveal much details about the causes for underperforming, e.g. soiling, degradation, defected module in a string, shading, .. Therefore several commercial companies offer O&M services, each with their own technology, some of them do not require a local weather station and use advanced weather modelling tools. Professional operation and maintenance (O&M) of a PV system lowers the levelized cost of electricity and results in a better return on investment. These benefits have been recognised by most players in the value chain as listed above.

Both preventive and corrective maintenance are generally considered as part of contracts for larger PV systems. For preventive maintenance detailed visual and physical inspections (e.g. aerial IR imaging, on-site characterization for selected modules) are required and checklists are proposed in the guidelines for the various installation types. Maintenance services can also include cleaning, vegetation cutting and eventually snow/sand removal. To minimize downtime of the PV system

[200] *IEA PVPS. (2017a). Technical Assumptions Used in PV Financial Models. Review of Current Practices and Recommendations. Retrieved from http://www.iea-pvps.org/index.php?id=426*

[201] *https://www.photovoltaikforum.com/datenlogger-f5/*

[202] *http://re.jrc.ec.europa.eu/pvgis/*

[203] *PVGIS allows the user to do a geographical assessment of solar resource and performance of photovoltaic technology. It has been developed at the European Commission Joint Research Centre, at the JRC site in Ispra, Italy.*

[204] *For example https://www.dwd.de/DE/Home/home_node.html*

[205] *https://pvoutput.org/l*

critical spare part stock is also listed as indispensable. Part of the maintenance contract is the data recording and monitoring which enables remote supervision of the energy flow and early detection of any sub-optimal performance. Similarly to maintenance detailed guidelines on the data collection, key performance indicators to extract are also available.

Guidelines also cover personnel and their training as adequate training is indispensable for safe and responsible for work. Furthermore the rapid evolution in the field and variety of the products ask continuous formation of the technical teams on the field.

Projects developers and investors usually look for certification and quality insurance at all steps of a PV project. This also includes the qualification of the technical personnel during installation and maintenance. Following the EU Directive (2009/28/EC) Member States (MS) are encouraged to develop a mutual acknowledged certification scheme. Across Europe the availability of certification schemes for PV installers has rapidly increased however it varies greatly between countries[206]. PVTRIN and other European projects aimed to harmonise these systems but they remain fragmented[207] (PVTRIN, 2013[208]).Its Europe wide acceptance has not followed until now. Equivalent certification scheme has been developed in the US with the NABCEP Solar PV Installation Professional Certification[209].

Table 60 gives an overview of some operation and maintenance services already available in the market and which are intended to keep the performance of the PV system as high as possible through its lifetime.

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[206] *Belgium: https://rescert.be/fr/lists; France: https://www.qualit-enr.org/annuaire;*

[207] *PVTRin project final report, 2013 https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/final_report_pvtrin_en.pdf*

[208] *PVTRIN. (2013). Training of photovoltaic installers in Europe: The PVTRIN training and certification scheme. Retrieved from https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/final_report_pvtrin_en.pdf*

[209] *http://www.nabcep.org/*

Table 60. Example of some O&M services already available in the market (Solarsense 2018)

<table>
<tr><td rowspan="2"></td><td colspan="2">Operation & Maintenance services</td></tr>
<tr><td>Commercial</td><td>Domestic</td></tr>
<tr><td>System Health Check</td><td>— Visual check of all rails and mountings
— Visual check of module condition
— Full string test
— Visual & physical check of all module connectors
— Interrogation of inverter display error codes and logs
— Full inverter diagnostic testing and checking of monitoring connectivity
— Visual check of all system AC & DC electrics
— Inverter & fan dust and clean
— Irradiance test and other tests using Seaward diagnostic technology
— Full report of system condition & operation provided to system owner</td><td>— Visual check and test of key connections, switches and electrical components;
— Visual check of panels, mountings and other hardware components;
— Inverter diagnostics;
— Irradiance & DC circuit test;
— Clean inverter and fan;
— AC electrical safety certificate compliant with BS7671 (for thermal systems)
— Report and recommendations</td></tr>
<tr><td>Solar Panel Cleaning*</td><td colspan="2">— Use of specialist equipment and super-clean water to clean the panels (with low water usage)
— Extremely pure water produced on-site by mobile 3 stage filtration, reverse osmosis and de-ionisation equipment to ensure near zero deposits
— Specialist brushes clean and rinse panels thoroughly without damaging delicate mysophobic coatings
— Water-fed pole system offer up till a certain lateral reach
— Visual check of array condition</td></tr>
<tr><td>System Upgrades</td><td></td><td>— Battery Storage technology
— Air Source Heat Pumps
— Immersion Controllers (to convert the excess electricity produced by the PV system into piping hot water)</td></tr>
</table>

* The majority of solar panels have a mysophobic coating (i.e., self-cleaning surface) to resist dirt and contaminants. Further anti-soiling coating are in development by most major glass/coating suppliers. Nevertheless in periods of low rainfall or in locations near busy roads or with a high number of birds, proximity to trees, farms, etc, panels may accumulate deposits which may impact on the performance of the system.

3.2 Subtask 3.2 – The indirect impacts from solar photovoltaics

General objective of subtask 3.2:

This task complements the previous task 3.1 as both direct and indirect impacts must be addressed within the Preparatory Study according to the MEErP methodology. It is therefore important to read the introduction in section 3.1.1 as it illustrates the difference between direct and indirect impacts as defined in the MEErP[210] methodology as well providing clear examples. Please see Table 51 for an overview of the aspects addressed under direct and indirect impacts.

3.2.1 The substitution effect of non-renewable energy or primary energy from fossil fuel on the grid

This study follows the Methodology for the Ecodesign of Energy-related Products (MEErP[210]) for which a spreadsheet tool for Life Cycle Analysis (LCA) is made available. The discussion hereafter is on how to model the positive impact from PV systems herein.

PV modules or systems are in a strict sense not energy using products because they produce instead of using electricity. Therefore the suggested approach in later tasks is to consider the positive impact from the produced electricity due to the substitution effect of average electricity. The MEErP tool has modelled the average impact from EU electricity, hence it can be simply adapted for this in Task 5.

Important metrics here are the:

- Primary Energy Factor: for a given energy carrier, non-renewable and renewable primary energy divided by delivered energy, where the primary energy is that required to supply one unit of delivered energy, taking account of the energy required for extraction, processing, storage, transport, generation, transformation, transmission, distribution, and any other operations necessary for delivery to the building in which the delivered energy will be used.
- GfK Warming Potential[211] (GWP): term used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere.

For modelling purposes, the MEErP tool uses the default Primary Energy Factor for electricity:

- "Primary Energy" as defined in the EED (2012/27/EU) means gross inland consumption, excluding non-energy uses.

In practice the concept of Primary Energy means that the energy utilised in generating electricity is used, i.e., 2.5 Mtoe Primary Energy including generation for every 1 Mtoe of final electricity used.

For 2014 the average GWP of electricity was 276 gCO_2eq/kWh[212] while for PV this is obviously lower[213], e.g. about 40 gCO_2eq/kWh only (2020 forecast).

As a conclusion, such a substituted average grid energy approach is proposed in order to model all positive impacts from photovoltaics in Task 5.

3.2.2 Indirect impact on grid operation

3.2.2.1 Distribution and transmission grid losses

Grid losses can increase or decrease when the load profile does not match with the production, this is often the case as explained in more detail in section 3.2.3.

The average losses in transmission networks (TNs) in EU (2015) vary between 1%-2.6% while for distribution networks (DNs) between 2.3%-13.4%[214] (Figure 77). This variation has mainly to do with the historical development and current state of the grids in each country with regard to age, design, etc. Therefore, in general, distribution networks present the highest losses and therefore can be further considered for this study. This European study (2016) also identified that the starting conditions of grids (e.g. voltage level; number of transformers) and potentials for energy efficiency improvement vary widely in the EU. A list

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210 http://ec.europa.eu/growth/industry/sustainability/ecodesign_nl

211 http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Global-warming_potential_(GWP)

212 https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment

213 https://setis.ec.europa.eu/system/files/ETRI_2014.pdf

214 https://ec.europa.eu/energy/sites/ener/files/documents/GRIDEE_4NT_364174_000_01_TOTALDOC%20-%2018-1-2016.pdf

of factors that have a key impact on the level of losses in the system were identified, including: loading (including peak demand), number of energized transformers, lengths of the feeders, presence of distributed energy resources.

A more detailed example is given in Figure 78 comparing Germany, France and UK. Herein, one should be aware that transformers have load and no-load losses and can therefore be optimized to match the loading profile (Tichelen et al., 2011)[193] Power cables are easier from an energy saving point of view because the larger their cross section the lower the losses (Tichelen, Ectors, Stevens, Chung, & Peeters, 2015)[215].

Figure 77. Percentage of losses in transmission and distribution networks in selected EU countries (source: Tractebel (2016)[216])

Country	Average % of losses in TNs	Average % of losses in DNs
France	2.3%	5.0%
Austria	1.5%	4.5%
Czech Republic	1.5%	7%
Slovakia	1%	8.3%
Romania	2.6%	13.5%

The FP7 Parity project studied in more detail the impact from photovoltaics and demand response (DR) on distribution grid losses, see Figure 79. It also shows that Demand Response (DR) can evidently further reduce distribution grid losses (<0,2%). As explained later on in section 3.4.1.4 demand response can also be a good value proposition. Other Ecodesign studies already focus on implementing demand response functionalities for smart appliances (Lot 33[217]). The EC is also investigating the development of a new Smart Readiness Indicator (SRI)[218] within the context of the ongoing review of EPBD [219]. This indicator will amongst others also cover Demand Response at building level, which is useful for buildings that use electricity for heating/cooling for example with a heat pump. This shows that for low PV penetration (<10%) there is a decrease in grid losses because energy can be consumed locally and less distribution is needed. For higher penetration rates the losses rise again and for large penetration rates losses increase due to unbalance with local consumption resulting in a reverse power flow. This study did not calculate the impact from local storage (see 3.4.2.1), which could have a similar impact compared to Demand Response or in combination with Demand Response. This study did not yet consider new opportunities for inverters to provide grid ancillary services to grid operators, e.g. inject reactive power to avoid congestion, which are discussed in later section 3.4.2.4 and it's technology in Task 4.

High penetration rates in terms of annual energy generation do also not match with the average load factor of distribution transformers. In the Lot 9 Eco-design study on transformers[220] the base case transformer had an average load factor of 15 %(α) only with a load form factor(Kf) of 1,07. Installing significantly more in the low voltage grid could result in grid congestion, see section 3.4.1.5.

The large difference between losses in the Transmission Network (TN) or grid and Distribution Network (DN) indicates that for high PV penetration rates it may be a better option to install grid scale PV compared to residential PV in order to keep grid losses low and/or to avoid congestion.

It is suggested to use as base case no impact on grid losses in later tasks but +/- 2 % can be used in a sensitivity analysis in Task 7. When comparing the benefits of local consumption it is suggested to use the average grid loss of 9 %, see Figure 79.

Demand response for local consumptions is potentially an efficient solution since can reduce grid losses and cording to some sources it can also provide a good value proposition[217,218].

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215 *Tichelen, P. Van, Ectors, D., Stevens, M., Chung, L. W., & Peeters, K. (2015). Preparatory Studies for Product Group in the Ecodesign Working Plan 2012-2014 : Lot 8 - Power Cables Task 1 -7 report. Retrieved from www.erp4cables.net*

216 *https://ec.europa.eu/energy/sites/ener/files/documents/GRIDEE_4NT_364174_000_01_TOTALDOC%20-%2018-1-2016.pdf*

217 *http://www.eco-smartappliances.eu/Pages/welcome.aspx*

218 *https://smartreadinessindicator.eu/*

219 *http://www.europarl.europa.eu/legislative-train/theme-resilient-energy-union-with-a-climate-change-policy/file-energy-performance-of-buildings-directive-review*

220 *https://www.eceee.org/static/media/uploads/site-2/ecodesign/products/distribution-power-transformers/final-report-feb2011.pdf*

It can be concluded that grid losses are much lower compared to storage losses reported for pumped-hydro[221] or batteries today (typically 80 %)[222]. Hence, it will be difficult for new emerging local battery storage solutions (see 3.4.2.1) to compete on energy efficiency grounds with using the distribution and transmission grid to average out local generation and production, see also subsequent sections 3.2.3.

Figure 78. Mapping of losses based on voltage level and components for different EU countries (source: Tractebel (2016[223]))

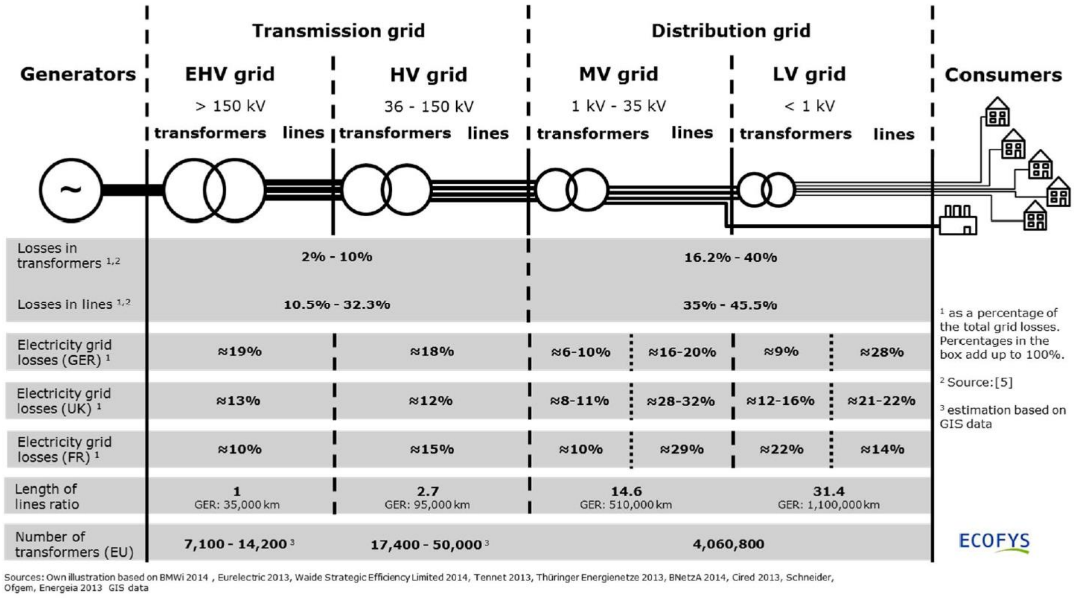
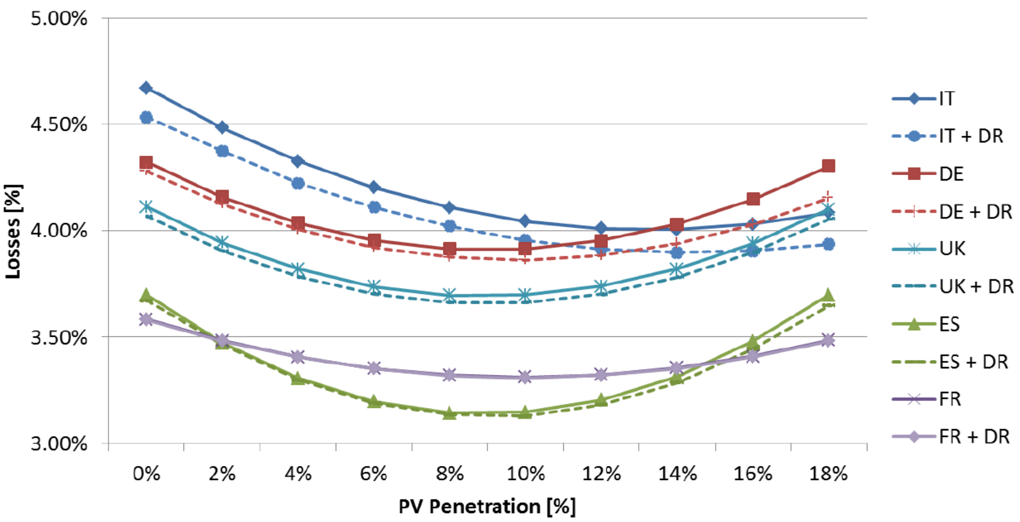


Figure 79. Impact of increased PV penetration and combination with Demand Response (DR) on distribution network losses in Germany, Spain, France, Italy and the UK (source: PV Parity project [224]).



[221] *It cannot be neglected the fact that pumped hydro storage can be expensive to install and use, depending on government imposed tariffs.*

[222] *https://setis.ec.europa.eu/system/files/ETRI_2014.pdf*

[223] *https://ec.europa.eu/energy/sites/ener/files/documents/GRIDEE_4NT_364174_000_01_TOTALDOC%20-%2018-1-2016.pdf*

[224] *https://helapco.gr/pdf/PV_PARITY_D44_Grid_integration_cost_of_PV_-_Final_300913.pdf*

3.2.2.2 Electricity grid management

3.2.3 Self-sufficiency and self-consumption by prosumers

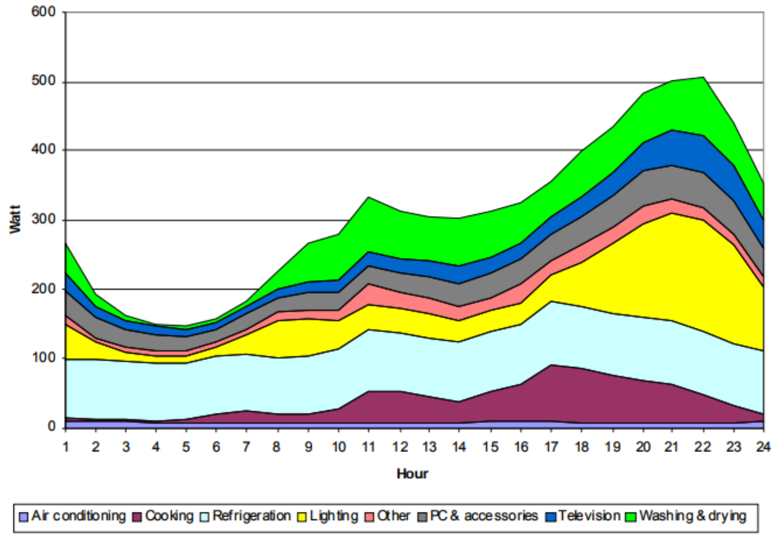
As explained section 3.0.2.4, prosumers are a new category of PV system owners. They will be motivated to increase their self-consumption due to the deployment of PV systems and consequent energy generation. As a rule of thumb for planning cost-effective self-consumption systems, the system yield should be adjusted to about the level of annual electricity consumption[225]. The opportunities and barriers for this are explained into more detail in sections 3.4.2.1 but they are linked to demand response as explained in lot 33 on smart appliances[226] but also to new PV systems that are coming on the market that include:

- monitoring (4-noks, 2018[227]) and/or
- some type of optimization (Huawei, 2018[228]; Panasonic, 2018[229]) and/or
- battery storage (see Task 2).

Technology options will be discussed in Task 4 but the section hereafter looks at the typical load profiles and PV generation profiles to quantify typical self-consumption.

Prosumers were introduced in section 3.0.2.4 as well as the issue on defining the minimum time period for metering which will be supposed hereafter 15 minutes. Energy generated from local PV is dependent on the location, orientation efficiency of the panel and several other parameters already mentioned. The usage of the energy locally produced could be important to take advantages from the deployment of PV systems.

Figure 80. Typical average residential electricity profile disaggregated by end-usage ("REMODECE," 2008[230])



[225] *Typically the rate of self-sufficiency in simple PV systems does not go above 30-40%.*

[226] *http://www.eco-smartappliances.eu/Pages/welcome.aspx*

[227] *4-noks. (2018). Solar Photovoltaic. Retrieved from https://www.4-noks.com/product-categories/solar-photovoltaic-en/?lang=en*

[228] *Huawei. (2018). FusionHome Smart Energy Solution. Retrieved from http://solar.huawei.com/eu/Residential*

[229] *Panasonic. (2018). Aquarea + PV PANELS.*

[230] *REMODECE. (2008). Retrieved from http://remodece.isr.uc.pt/*

In the **residential** sector there is typically a mismatch between generation and consumption. An average disaggregated residential power profile is represented in Figure 80. Three illustrative examples of this mismatch in the residential sector are displayed in Figure 81 and Figure 82.

Figure 81 presents the estimated annual distribution of demand and PV generation for a residential building in Ireland and two specific examples for winter and summer daily distribution of PV generation and demand. It is important to highlight that this specific example in Ireland might exclude the use of air conditioning systems and thus strongly differ from the typical summer distribution of demand in southern countries.

Figure 82presents as an illustrative example real data from the REnnovates project ("REnnovates," n.d.[231]), in another geographical location, for a whole week in 4 distinct periods of the year.

From these facts above, it can be concluded that the degree of self-sufficiency or autarky for residential users is not large without additional measures. Hence, this creates opportunities for increased self-sufficiency that are discussed in section 3.4.2.1.

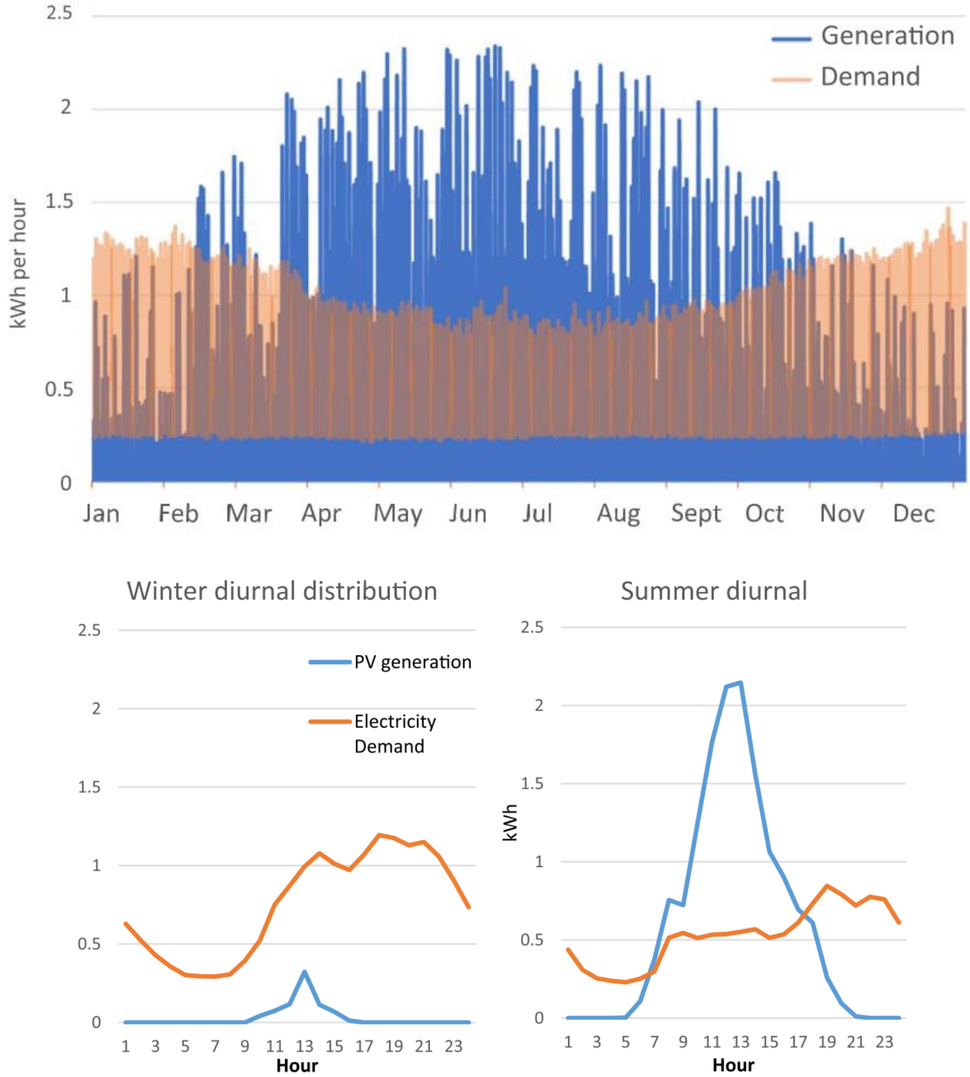
On a cloudy day quarterly solar production can become irregular while over a larger region this will be averaged out due to clouds movements (Luthander, Lingfors, Munkhammar, & Widén, 2015[232]). Averaging out cloud effects requires a larger spatial distribution of the PV generation but this is solved by the electrical grid and its load aggregation. An alternative solution is using a battery as discussed in section 3.4.2.1.

Concerning **commercial** prosumers, such as department stores and office buildings, often a better match between the energy consumption profile and onsite renewable generation may be possible. An illustrative example, for a sunny day with a high amount of energy locally generated and assuming clear sky conditions, can be seen in Figure 83.

[231] *REnnovates. (n.d.). Retrieved from http://www.rennovates.eu/*

[232] *Luthander, R., Lingfors, D., Munkhammar, J., & Widén, J. (2015). Self-consumption enhancement of residential photovoltaics with battery storage and electric vehicles in communities. Proc. of Eceee Summer Study on Energy Efficiency, 991–1002.*

Figure 81. Annual distribution of demand and PV generation in Ireland and two examples for winter and summer daily distribution of PV generation and demand.(La Monaca & Ryan, 2017[233])



NOTE: According to (La Monaca & Ryan, 2017) "Ireland has a relatively low solar resource and only a negligible amount of residential PV currently exists".

[233] *La Monaca, S., & Ryan, L. (2017). Solar PV where the sun doesn't shine: Estimating the economic impacts of support schemes for residential PV with detailed net demand profiling. Energy Policy, 108(December 2016), 731–741. https://doi.org/10.1016/j.enpol.2017.05.052*

Figure 82. Illustrative example with real data from one house in The Netherlands in 4 distinct periods of the year- PV generation (total local energy generation), consumption (total energy consumption), injection in the grid (total energy injection in the grid) and offtake (total energy consumption which was not covered by local PV energy generation)

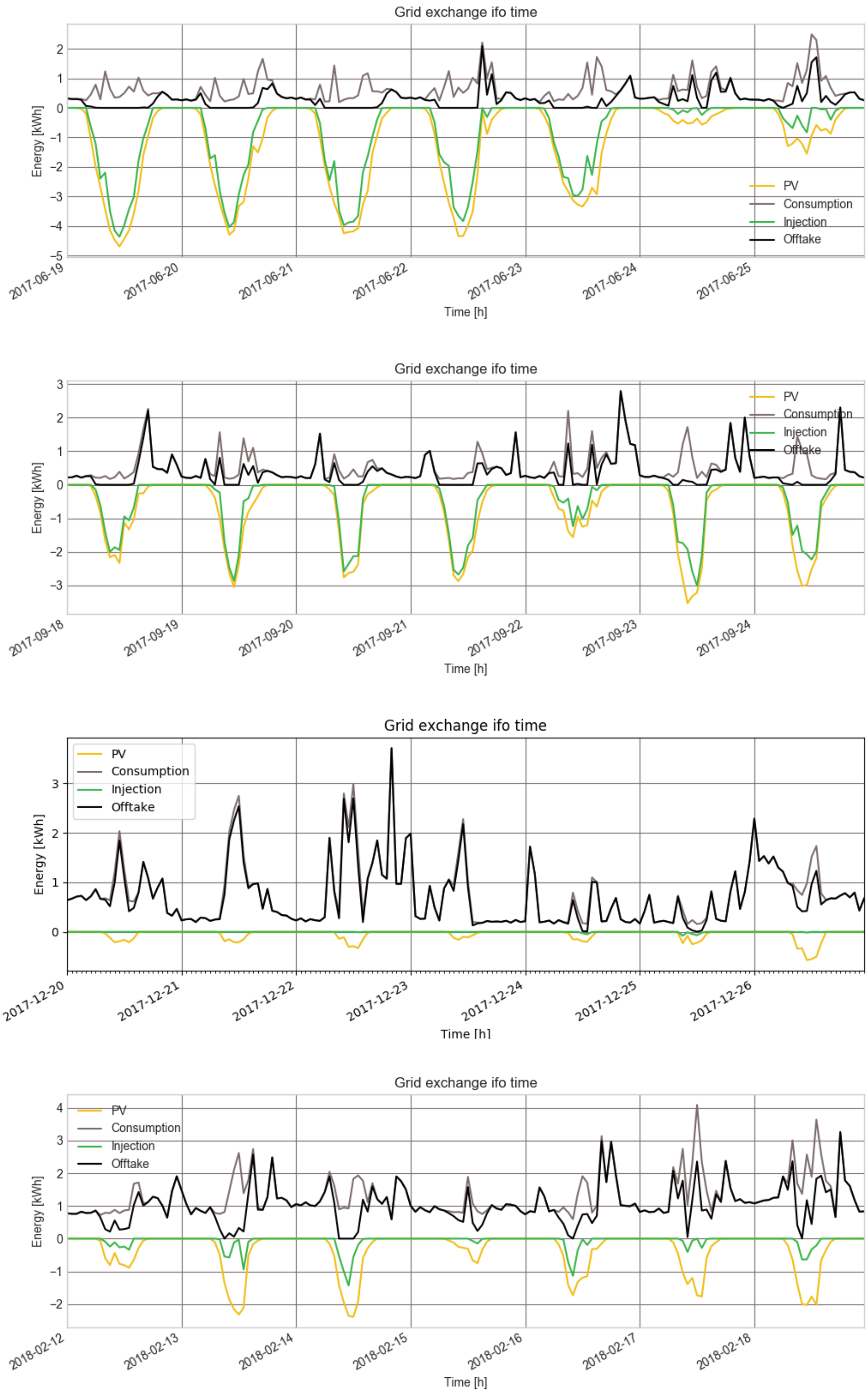
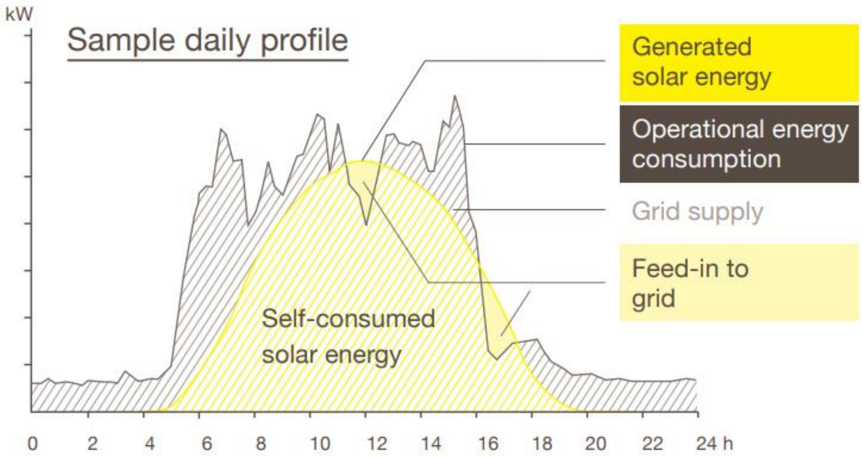


Figure 83. Illustrative example of the matching between consumption and solar generation (Kraftwerk, 2013[234])



Conclusion:

Self-sufficiency for residential consumers is not large without employing additional measures that will be discussed in 3.4.2.1. However, the electricity grid can act as storage up to a certain degree of PV penetration, since electrical grids are efficient, and therefore the impact on grid losses is also moderate (see 3.2.2). Previous section 3.2.2 also showed that a small degree of PV penetration will reduce losses when it matches local loads reducing therefore loading on the distribution grid.

3.3 Subtask 3.3 –End-of-Life behaviour

General objective of subtask 3.3:

Identification of actual user requirements (average across the EU) regarding end-of-life aspects. This includes:

- Product use & stock life (i.e., time between purchase and disposal)
- Present fractions to recycling, re-use and disposal;
- Present fraction of second-hand use and refurbishment.
- Repair & maintenance practice (frequency, spare parts, trip km, other impacts)
- Collection rate (by fraction, consumer perspective)
- Second-hand use, fraction of total and second hand life
- Available good practice in product use.

In this subtask the focus has been placed on user choices and system/component specification data that can have an impact on forecasting future waste volumes in later Tasks 5-7. However due to the long lifetime of PV modules (>20 years) and inverters, reliable and representative data for this tasks is not yet available. The little evidence found today on user choices might be therefore be anecdotal and not yet representative for 2030 and beyond.

3.3.1 Lifetime of the PV system

Scope: The generation of waste or collection rate is inherently influenced by the time after which the product is replaced with a new one. Product lifetime will therefore have an important impact on Life Cycle Analysis (LCA) of photovoltaics because it will influence the negative impact from production and waste against the benefits of producing electricity. Therefore the subsequent sections will describe suitable input data, and these will be further processed in Task 5 on LCA. However when looking at the lifetime of a PV system there are several potential definitions serving various purposes which are briefly discussed hereafter.

In this section mechanisms leading to power losses additional to the derate factors defined in Section 3.1 are listed. Mechanisms are considered which lead to decreases or complete loss of the PV module and system performance that cannot be recovered upon cleaning and requires repair or replacement.

[234] *Kraftwerk. (2013). Case Study : Photovoltaic for commercial The path to more independence.*

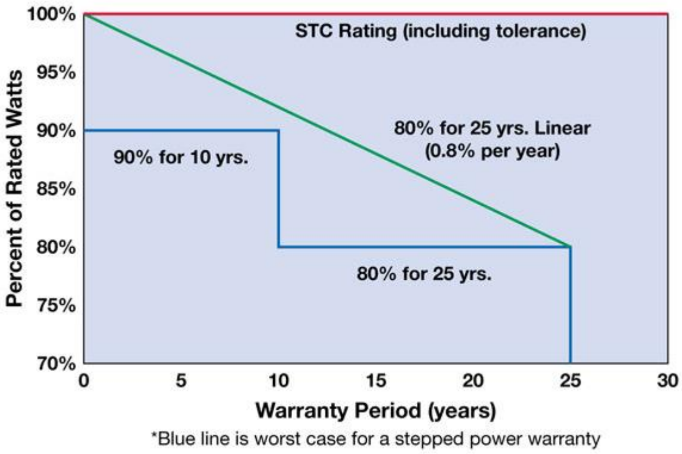
The technical aspects related to module lifetime will be discussed into more detail in section 4, herafter the focus is on the user and waste generation. Products can also have a second life, which is discussed in 3.3.1.8.

3.3.1.1 Definition of the name plate lifetime relative to degradation rates for modules

PV module lifetime is defined as 80% of the initial nameplate rating (M. Köntges et al., 2014; Meydbray & Dross, 2017[235]). This means that an annual degradation rate of 0.8%-1% enables a PV module to deliver the expected power for 20-25 years. Thus, similar length warranties are issued by PV module manufacturers. For novel generation of PV modules, especially with strengthened packaging even lower degradation rates are expected and hence also extended operational lifetime up to 30 years.

In today's PV module warranty either step-wise degradation or linear performance loss is assumed within the 20-25 years operational lifetime. For the purposes of this study the warranty duration is considered to reflect the economic lifetime. The PV system in reality can however maintain more than 80% of its initial lifetime beyond 20-25 years (Figure 84). According to (Meisel et al., 2016[236]), (recent) modules showing 0.5-0.6% annual degradation rate on the field, combined results of accelerated degradation studies and considering good operations and maintenance practices suggests that the PV system lifetime can be extended up to 35 years.

Figure 84. Example of PV Module Warranty



Annual PV module degradation rate is theoretically defined as the performance loss (maximum power measured at STC upon define years of operations of the PV module versus the maximum power measured at STC upon fabrication) averaged over the name plate lifetime of the PV module. It is expressed in relative power loss % over one calendar year in this study. Degradation rate refers to gradual power loss of the PV module and system over time. This metric is mostly extracted from outdoor measurement of the PV module and corrected for temperature, irradiation, and other variations. The degradation rate of PV module varies from year-to-year influenced by both weather and technology. Moreover adapted statistical approaches can influence the values and their uncertainty[237].

It is important to distinguish between degradation rate and failure rate. This later metric refers to complete loss of PV module or system performance, or its necessarily shut down due to safety reasons. Failure rate should be expressed as a 2 or 3 parameter Weibull distribution in order to provide meaningful information to end users.

[235] Meydbray, J., & Dross, F. (2017). PV Module Reliability Scorecard Report 2017. Dnv Gl. Retrieved from https://www.dnvgl.com/publications/pv-module-reliability-scorecard-2017-93448

[236] Meisel, A., Mayer, A., Beyene, S., Hewlett, J., Maxwell, K. N., Coleman, N., … Mayo, E. (2016). Photovoltaic Modules with 35 Year Useful Life, 1–22.

[237] (Phinikarides 2014) Alexander Phinikarides et all, RenewableandSustainableEnergyReviews40(2014)143–152, Review of photovoltaic degradation rate methodologies

3.3.1.2 Definition of life expectancy in function of catastrophic failure rate for modules

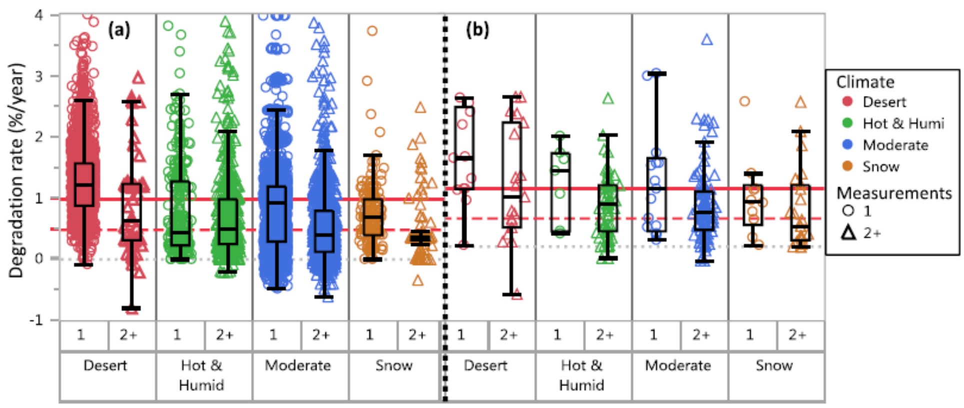
In the context of waste generation or Life Cycle Analysis the 'life expectancy' is a more relevant definition of lifetime (Fthenakis et al., 2011[238]) and it is not de facto equivalent to degradation. In principle the lifetime for a PV module will mostly depend upon technical lifetime of a system, meaning that the PV system is assumed to operate until it fails or is dismantled due to underperformance. A catastrophic failure means hereafter that the module stops functioning and/or cannot be installed or operated safely. This event often occurs suddenly and leads to entire loss of the power production capabilities. Hence it is considered as end of the expected lifetime. A purely cosmetic issue which does not harm the module power and its safety is not considered.

3.3.1.3 Degradation and catastrophic failure rate under operation

Flawed and poor quality modules in general fail rapidly upon installation and their replacement fall within the manufacturer's warranty. This still implies loss in energy production of the PV plant, and often requires early replacement of the panel, hence generates waste. German statistics from a German distributor based on 2 million modules over 2006-2010 indicate that 2% of the PV modules will not meet predicted performance upon ~10-12 years of operations. Major causes of the failure are linked to J-box and cabling, glass breakage and cell and interconnection damage[239].

Overview of the degradation rates for different PV module technologies and at various climates have been summarized from more than 40 studies by (Jordan, Silverman, Wohlgemuth, Kurtz, & VanSant, 2017[240]). The median annual degradation rate of - 0.5-0.6 %/year or average of -0.7%/year for c-Si PV modules is calculated from long-term fielded samples. This value has been extracted from over 10.000 data points of PV system which has been investigated for different durations, different x-si technology generation, climates. In this study the most common degradation modes for PV modules are hot spot, IC discoloration, glass breakage and encapsulant discoloration[241].

Figure 85. Degradation rate for x-Si Pv module depending on climate[242]



[238] *Fthenakis, V. M., Frischknecht, R., Raugei, M., Kim, H. C., Alsema, E., Held, M., & de Wild Scholten, M. (2011). Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity (Vol. IEA PVPS T). https://doi.org/IEA-PVPS-TASK 12*

[239] *http://www.iea-pvps.org/fileadmin/dam/intranet/ExCo/IEA-PVPS_T13-01_2014_Review_of_Failures_of_Photovoltaic_Modules_Final.pdf*

[240] *Jordan, D. C., Silverman, T. J., Wohlgemuth, J. H., Kurtz, S. R., & VanSant, K. T. (2017). Photovoltaic failure and degradation modes. Progress in Photovoltaics: Research and Applications, 25(4), 318–326. https://doi.org/10.1002/pip.2866*

[241] *Jordan et al. Progress in Photovoltaics 2017*

[242] *Jordan et al. Prog. Photovolt: Res. Appl, 2016*

Table 61. Key parameters of (a) silicon-based single-crystalline and (b) CdTe photovoltaic cells and modules and values used in the three scenarios BAU (Business as Usual), REAL (realistic improvement) and OPT (optimistic improvement) (source: IEA PVPVS Task 13 report on 'LCA of future photovoltaics electricity production (Stolz & Frischknecht, 2017)[243]')

Parameter	Single-Si				CdTe			
	TODAY	BAU	REAL	OPT	TODAY	BAU	REAL	OPT
Cell efficiency	16.5 %	25.0 %	27.0 %	29.0 %	15.6 %	22.8 %	24.4 %	26.0 %
Derate cell to module efficiency	8.5 %	8.5 %	6.8 %	5.0 %	13.9 %	10.0 %	7.5 %	5.0 %
Module efficiency	15.1 %	22.9 %	25.2 %	27.6 %	13.4 %	20.5 %	22.6 %	24.7 %
Wafer thickness / layer thickness	190 µm	150 µm	120 µm	100 µm	4.0 µm	2.0 µm	1.0 µm	0.1 µm
Electricity demand in CdTe laminate manufacture	-	-	-	-	100 %	86 %	81 %	74 %
Kerf loss	190 µm	150 µm	120 µm	100 µm	-	-	-	-
Silver per cell	9.6 g/m²	9.6 g/m²	5.0 g/m²	2.0 g/m²	-	-	-	-
Fluidized-bed reactor (FBR) Share of Poly Si Production	0 %	20 %	40 %	100 %		-	-	
Glass thickness	4.0 mm	4.0 mm	3.0 mm	2.0 mm	3.5 mm	3.5 mm	3.0 mm	2.0 mm
Operational lifetime	30 years	30 years	35 years	40 years	30 years	30 years	35 years	40 years

For thin-film technologies a more dispersed and smaller dataset is obtained spreading from 0.2 to 4.2%/year, although the average is typically around 1.5%/year according to (Meisel et al., 2016[231]). Another reference concludes that thin-film degradation rates have improved significantly during the last decade, although they are statistically closer to 1%/year than to the 0·5%/year necessary to support market expectations for a commercial performance warranty.

3.3.1.4 PV module degradation and catastrophic failure during shipment and installation

The EU funded project PV bankability ranked the major degradation and catastrophic failures based on their cost considering reduced/loss of power generation, repair etc. They have noted the most important elements both in utility and residential PV installation are incorrect installation and broken modules (Moser et al., 2016[244]). During transportation, solar modules can undergo mechanical stress that can lead to cracks that affect both their short and long-term performance. During transport, PV modules packed on pallet experience shock and vibrations which induced and/or accelerates the propagation of cracks in crystalline wafers. These defects are invisible to the eye, and trigger power loss on the longer term and are hence often unnoticed during installation. Previous study cites up to 5% damage linked to transport and installation (M. Köntges et al., 2014[245]).

The IEC 62759-1:2015 standard, conceived to assess the transportation risks of module package units, suggests shake and vibration tests. Several studies provide guidelines to minimize the risk of transportation damage(Marc Köntges et al., 2016[246]).

Next to packaging, and transport conditions, installers' knowledge is critical for the correct handling of the PV handles and safe and technically correct installation.

[243] *Stolz, P., & Frischknecht, R. (2017). Life Cycle Assessment of Photovoltaic Module Recycling. Retrieved from http://www.iea-pvps.org/index.php?id=275*

[244] *Moser, D., Del Buono, M., Bresciani, W., Veronese, E., Jahn, U., Herz, M., ... Richter, M. (2016). Technical risks in PV projects. Solar Bankability Project, 1, 1–109. Retrieved from http://www.solarbankability.org/results/technical-risks.html*

[245] *Köntges, M., Kurtz, S., Packard, C. E., Jahn, U., Berger, K., Kato, K., ... Van Iseghem, M. (2014). Review of Failures of Photovoltaic Modules. IEA-Photovoltaic Power Systems Programme. https://doi.org/978-3-906042-16-9*

[246] *Köntges, M., Siebert, M., Morlier, A., Illing, R., Bessing, N., & Wegert, F. (2016). Impact of transportation on silicon wafer-based photovoltaic modules. Progress in Photovoltaics: Research and Applications (Vol. 24). https://doi.org/10.1002/pip.2768*

3.3.1.5 Inverter catastrophic failure rate and average technical lifetime

Inverters have shorter lifetimes (5-20 years) and are comparable to other electronic products. The very limited number of independent reviews of inverter failure rates suggest 1%-15% yearly failure rate[247]. These are related to their electronic component reliability, mainly: DC bus capacitors; IGBT power module solder joint lifetime, main DC contactor (if any), cooling fans (if any), etc. In this context Design for Serviceability (DFS) to reduce "Mean Time To Repair" are important parameters, together with the projected inverter lifetime. Recycling of inverters is similar to other electronic converters and also has to follow the WEEE Directive.

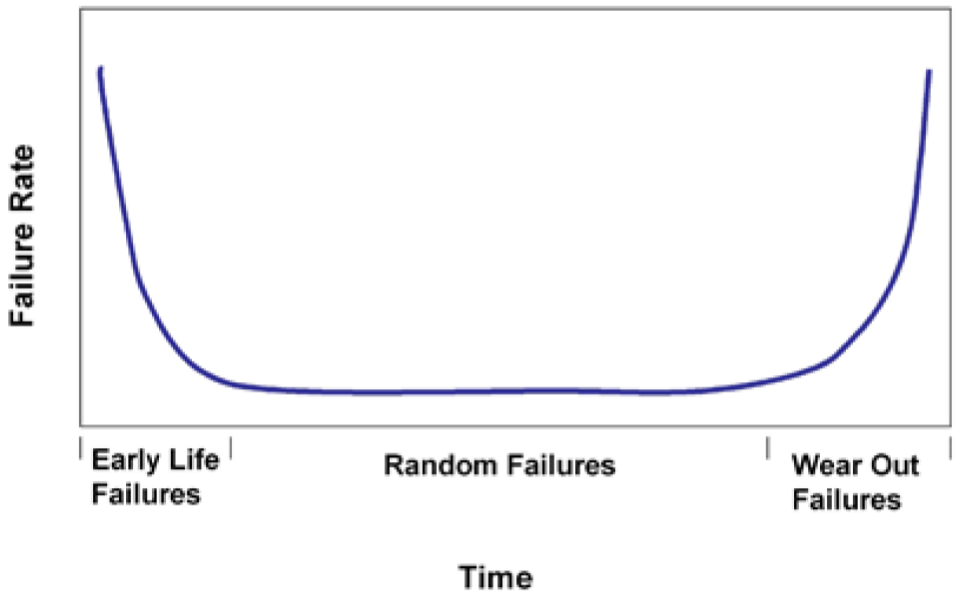
With these varying reports we assume in this study average 10 years of inverter technical lifetime, and in best up to 20 years of technical lifetime.

Next to failures considering replacement, one needs to consider downtime of the inverter linked to failure which should be serviced. This can be linked to both the software and/or hardware failure. Reports cite an average of 20 days/year downtime for string inverters and 3 days/year for central inverters. This difference simply arises from the service contract mostly purchased for the latter type (Golnas, 2013[248]; Kröger-Vodde, Armbruster, Hadek, Heydenreich, & Kiefer, 2010[249]).

Most common failures of inverter on the field go beyond an "*unknown error message*", to include the failure of the fan and other damage linked to overheating.

According to an IEA Task 13 report on financing PV (IEA PVPS, 2017a[200]) (p. 52), the life of an inverter is considered to be between 10-15 years. The technical lifetime of the PV system in general and the inverter in particular, follows a so-called "bathtub" failure profile shown in Figure 86.

Figure 86. Bathtub curve showing probability of failures over the technical lifetime (TL-tech) of a product or project (IEA PVPS, 2017a[200])



A warranty of two years covers the early life failure of a system when the failure probability is still high. These defects are most linked to production defects. It is obvious that the risk of failure in the flat line area of random failures is the lowest nevertheless several inverter manufacturers offer extended warranty services.

[247] *Laukamp et al., 2002*

[248] *Golnas, A. (2013). PV System Reliability: An Operator's Perspective. IEEE Journal of Photovoltaics, 3(1), 416–421. https://doi.org/10.1109/JPHOTOV.2012.2215015*

[249] *Kröger-Vodde, A., Armbruster, A., Hadek, V., Heydenreich, W., & Kiefer, K. (2010). Distributed vs. Central Inverters - A Comparison of Monitored PV Systems.*

3.3.1.6 Consumer average required lifetime and relation with maintenance costs

A recent enquiry was launched recently by (GfK Belgium Consortium, 2017[138]) to identify which characteristics or combinations of characteristics are most important to the end-user when buying a PV system (as mentioned in section 3.0.2.4). Based on the answers it may be possible to identify the average required lifetime from end-users' perspective. The relation between lifetime and maintenance costs are also a combined characteristic analyzed in (GfK Belgium Consortium, 2017[138]).

3.3.1.7 Additional system components failure

In the PV system the clamps, railing, cabling, and increasingly trackers should be considered. Their failure can lead to loss or significant reduction of the power generation. Among them trackers are one of the most critical to consider for the operational lifetime. Trackers are used to orient the PV panels towards the sun to reduce the angle of incidence using single or dual axis motorized system. Although still employed in ~10% of the current utility scale projects it is expected that up to 40-50% of newly installed system will integrate them[250]. This technology is currently nearly never deployed in commercial and residential application both for technical, safety and economical reasons.

Critical elements that can influence the reliability of trackers are the number and type of motors, power supply system and mechanical design considering snow and wind load. Last but not least, this part of the system also requires regular preventive maintenance.

3.3.1.8 Repair, refurbishment and second hand use of PV systems

When considering lifetime it is also important to look at the potential for repair and refurbishment, possibly also leading to a second hand use – a second service life. Upon maturity of the PV industry in the last 5 years in some EU Member States with a large PV deployment several companies are now offering 2nd hand PV modules. Notably pvXchange[251], SecondSol, Solar-Pur offer mostly for business to business PV module, component exchange platform. Both platform operators can provide quality control, repair and installation services.

In parallel several companies are specialized in repair, re-powering of PV modules. The following type of damage can be repaired:

- faulty bypass diodes and connectors,
- punctured backsheets,
- damaged frames.

The 'healing' of PV modules affected by Potential Induced Degradation (PID) is equally proposed by companies. Faulty connector sockets have been cited as one of the most common failure on the German market. For this later problem on-site repaid method have been developed to avoid de-installation, transport, re-installation cost and time. Failures that cannot be repaired are linked to damaged cell connection, delamination of the encapsulant and glass breakage to cite the most common ones. Most repair companies provide a 2 year warranty on their repair work[252].

Beyond repair, replacement of the damaged PV modules, adjusting the PV system design and eventually re-cabling of the PV string is necessary for optimal performance. In case of removal/replacement of a PV module a lower performing PV module can limit the performance of all other panels connected on the same string. Therefore, adapted system layout is equally important for overall system repair.

In general inverter repair on the field is less common, mostly faulty inverters are replaced. In order to maintain the (expensive) inverter warranty only the inverter providers or a company commissioned by them is allowed to intervene for repair. Second hand inverter similar to PV modules are little or not at all covered by warranties[253].Summary on lifetime of PV modules and inverters

[250] ITRPV, 2017 edition

[251] From eBay to pvBay – getting used to used PV, PV magazine, 2016 https://www.pv-magazine.com/magazine-archive/from-ebay-to-pvbay-getting-used-to-used-pv_100024935/

[252] Repairing solar modules: sometimes easier than buying new ones, PV Europe, 2017 http://www.pveurope.eu/News/Solar-Generator/Repairing-solar-modules-sometimes-easier-than-buying-new-ones

[253] Solar advice: Exchange or repair the inverters?, PV Magazine, 2018

http://www.pveurope.eu/News/Planning-Operation/Solar-advice-Exchange-or-repair-the-inverters

Previous sections defined the following lifetimes:

- 'Operational lifetime for stock modelling' relative to replacement rate, see Task 2.
- 'Name plate lifetime' for modules, relative to degradation.
- Catastrophic failure rate of lifetime of modules and inverter.
- Ecological 'life expectancy' can be defined for Life Cycle Analysis (Fthenakis et al., 2011[238])
- the average required lifetime from the users and the minimum warranty expected lifetime.

In this context it is important to be aware that lifetime is the reciprocal value of replacement rate, for example a lifetime of 50 years is equivalent to a replacement rate. Replacement rate is a metric often used in stock modelling, see Task 2.

Note that apart from these technical lifetimes related to waste also a 'financial lifetime' can be defined, for example for the calculating of the levelized cost of Electricity (LCOE) for PV systems, see section 3.4.1.1 (T Huld et al., 2014[254]).

A summary overview of data is given in Table 62.

Table 62. Types of lifetime for different components and corresponding values (NA means Not Applicable)

	PV system	Modules	Inverter	Task/source
	Typ. (y)	Typ. (y)	Typ. (y)	
'Operational lifetime for stock modelling'	NA	TBD	TBD	Task 2
Name plate lifetime for modules	NA	20	NA	Data sheets/ IEC61215
LCA Life expectancy	NA	30	Small(<15kVA): 10 Large: 30 +10%parts/10y	IEA PVPS Task 12 (Fthenakis et al., 2011[238])
Warranty	NA	≥10?	≥5?	Market data
Average required lifetime BIPV With central inverter	NA	≥10?	≥10?	Own estimate/stakeholder feedback
Average required lifetime BIPV With module level inverter	NA	≥20?	≥10?	Own estimate/stakeholder feedback
Average required lifetime BAPV With central inverter	NA	≥40?	≥40?	Own estimate/stakeholder feedback
Average required lifetime BAPV With module level inverter	≥40?	NA	≥NA	Own estimate/stakeholder feedback
Average required lifetime for ground mount systems	≥10?	≥10?	≥10?	Own estimate/stakeholder feedback
Technical lifetime (task 4)	>20 y	>20 y	5-10	Task 4

3.3.2 Recycling and disposal practices and the collection rate

The dismantling of photovoltaic systems and modules typically follow the logic of a business-to-business (B2B) waste management scenario. It can also be assumed that waste from private household photovoltaic systems could end up in both B2B and B2C contexts, depending on how equipment is handled and who carries out the decommissioning. The decision tree depicted the different options for dismantled PV systems which will be investigated further (see Figure 87).

Due to the long lifetime end-of-life of PV modules (>20 years) and inverters, recycling is mainly an aspect for the future. It might be incorrect to extrapolate the current recycling data because it is today a minor issue and work for setting up recycling is in progress as explained before. Waste projections will be needed, for example see Figure 88.

Data for Europe that is provided for each Member State in the new WEEE calculator tool has been brought together through the ProSUM project (Huisman et al., 2017[255]). This project resulted in the online Urban Mine Platform

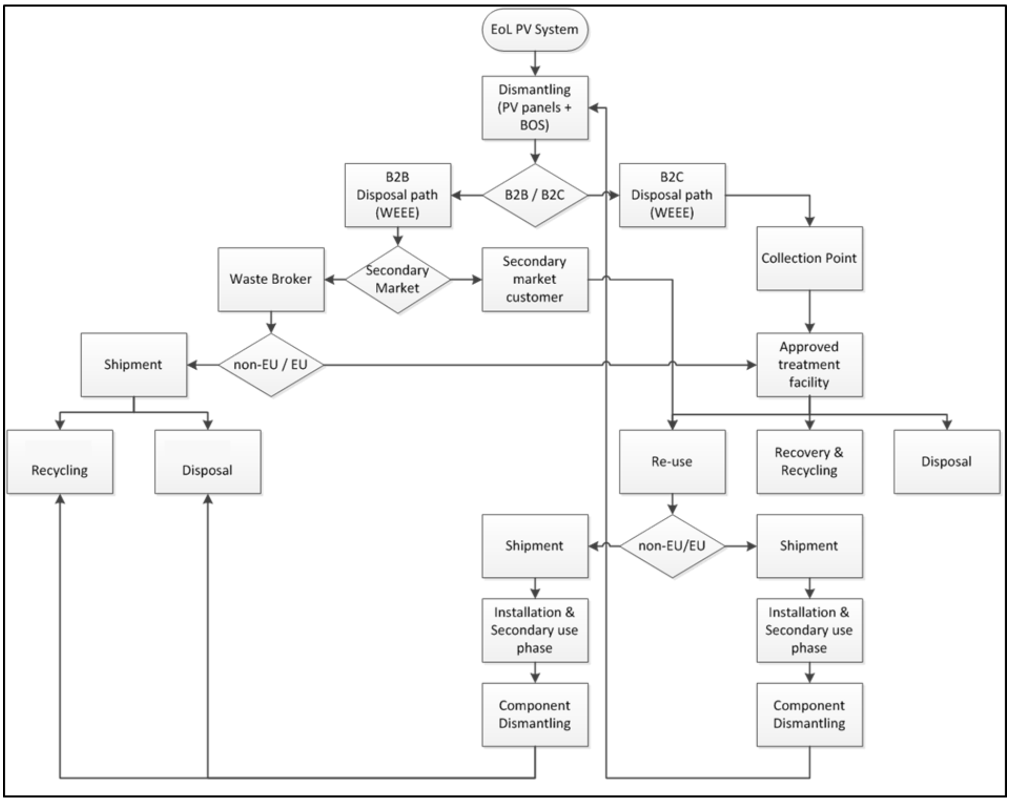
[254] *Huld, T., Waldau, a J., Ossenbrink, H., Szabo, S., Dunlop, E., & Taylor, N. (2014). Cost Maps for Unsubsidised Photovoltaic Electricity. European Commission.*

[255] *Huisman, J., Leroy, P., Tertre, F., Söderman, M. L., Chancerel, P., Cassard, D., ... Emmerich, J. (2017). Prospecting Secondary Raw Materials in the Urban Mine and mining wastes (ProSUM) - Final Report, ISBN: 978-92-808-9060-0 (print), 978-92-808-9061-7 (electronic), December 21. Brussels.*

(www.urbanmineplatform.eu). The platform has been consulted to get an overview of the waste projections for EU. Estimates are only available till 2020. 5000 tonnes of solar cell (Si-based) will become available in 2020 (see Figure 89). This source reports a waste release of 2500 tonnes solar Si cells in 2016 in the EU. This number is much lower than the global PV panel waste projection for 2016 (43 500 tonnes – see Figure 88). It will be further investigated in the project if the PV waste in the EU will follow a similar trend as the global waste projections from IRENA (2016) (Weckend, Wade, & Heath, 2016[256]).

In the framework of WEEE, PV producers are setting up PV module recycling schemes such as PV CYCLE257. It is also reported that PV Si-modules can be recycled up to 96 %258, meaning that not only glass and aluminum is recycled but also silicon. Important parameters are module lifetime, both from an economic and technical perspective. Also the market leader in thin film CdTe cells (First Solar), which contains hazardous Cd, have for many years operated a closed loop collection and recycling scheme. The IEA recently released a new report on recycling trends (Komoto & Lee, 2018[259]) and research to prepare for the future is ongoing.

Figure 87: Decision tree for the end-of-life management of a PV system installed in the European Union[260]



Hence for recycling rates potentially assumptions will need to be made based on similar products and data available from recycling technology.

[256] *Weckend, S., Wade, A., & Heath, G. (2016). End-of-life management - Solar photovoltaic panels. Retrieved from http://www.irena.org/DocumentDownloads/Publications/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf*

[257] *http://www.pvcycle.org/*

[258] *http://www.pvcycle.be/press/breakthrough-in-pv-module-recycling-3/*

[259] *Komoto, K., & Lee, J.-S. (2018). End-of-Life Management of Photovoltaic. Panels : Trends in PV Module Recycling Technologies. Report IEA-PVPS T12-10:2018.*

[260] *Wade, Sinha, Drozdiak, & Brutsch, 2017*

Figure 88. PV panel waste projections (Weckend et al., 2016)

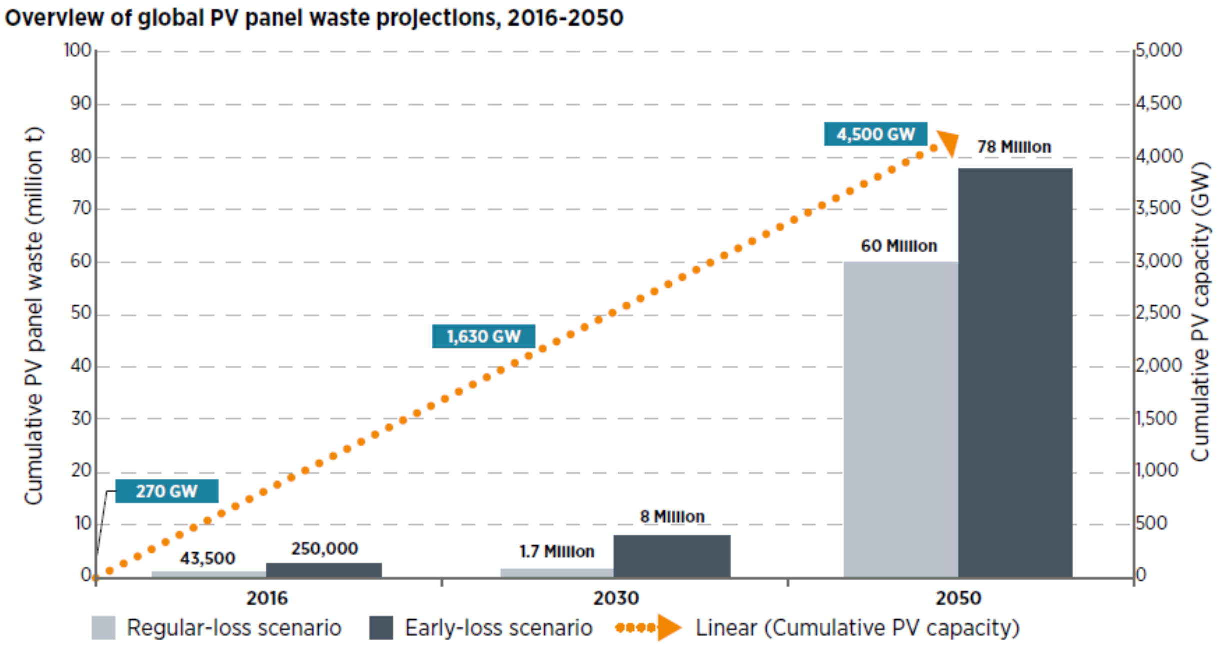
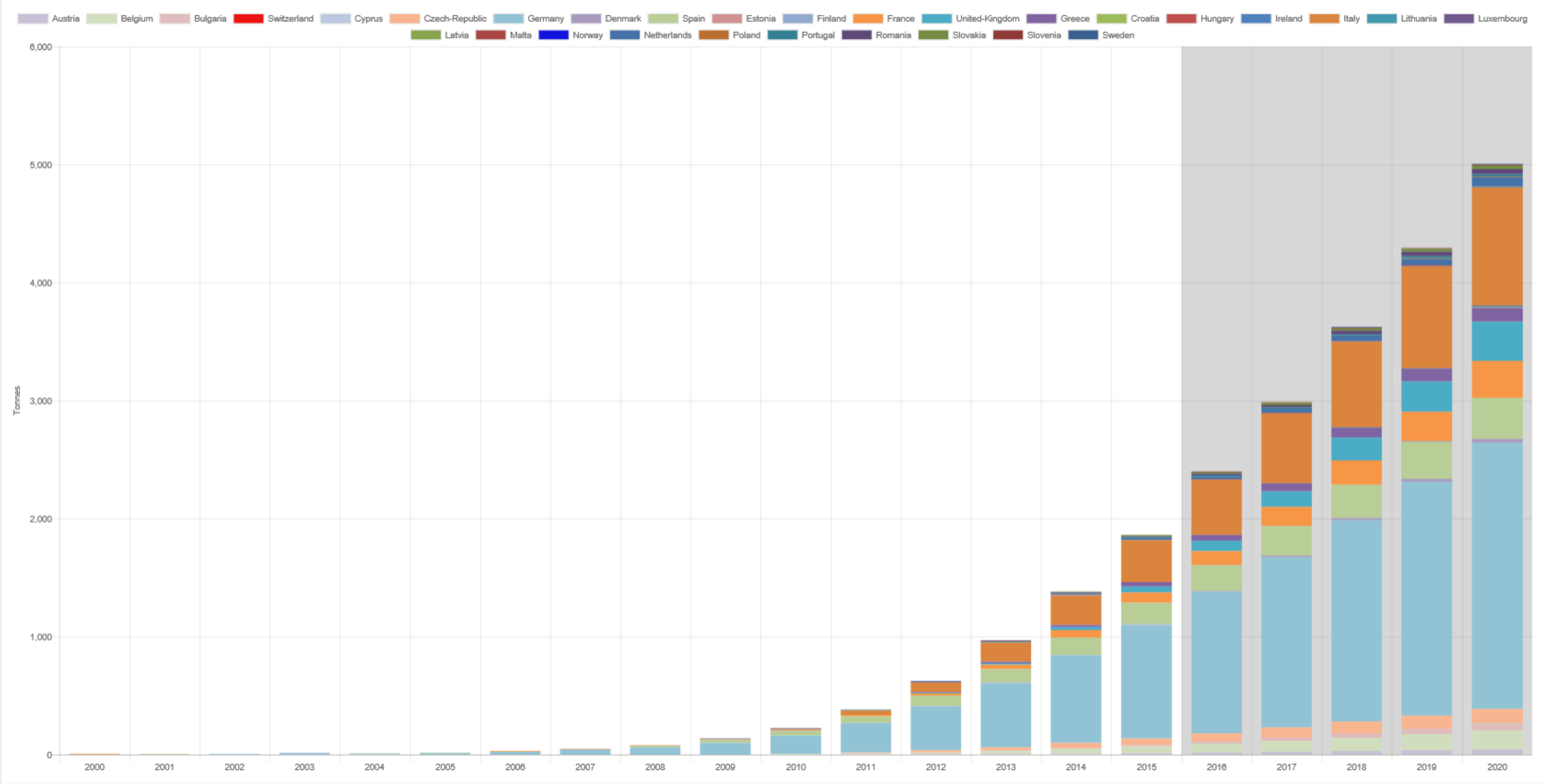


Figure 89:.Solar cell (Si based) waste generated per EU country in tonnes (Huisman et al., 2017)[261]



[261] *http://www.urbanmineplatform.eu/composition/eee/components*

3.4 Subtask 3.4 – Local infrastructure (barriers and opportunities)

General objective of subtask 3.4:

This section includes an assessment of the following aspects:

- Energy: reliability, availability and nature
- Installers, e.g. availability, level of know-how/ training
- Physical environment, e.g. possibilities for product sharing

3.4.1 Barriers

3.4.1.1 High upfront-cost for PV systems, access to and the cost of capital

The main barrier is often the high upfront cost relative to the long-term revenue combined with the cost for capital to invest in a PV project. It can also explain why investors sometimes prefer low price low lifetime products over high price high quality products or ultimately they do not want to invest in PV but prefer more rewarding other options. The consequence of this might be that for ground mounted systems, in which components can be easily replaced, the quality matters less than the price per KWh in comparison to roof mounted systems due to their more expensive repair and/or dismantling costs. It can also explain why residential PV are sometimes more popular compared to grid scale.

It is important to understand the common practice for investors to calculate the Levelized Cost of Energy (LCOE) for PV systems[262]. The "Levelized Cost of Energy" (LCOE) which is the price at which electricity must be generated from a specific source to break even over the lifetime of the project. It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel and cost of capital. The cost of capital takes also interest and inflation into account (see Task 2), the same approach as Life Cycle Cost calculations will be done in Task 5 according to the MEErP.

Inflation and interest rates change frequently over time and depend on the Central European Bank policy that is regularly reviewed[263]. Looking, for example, to the prevailing market conditions in 2016 inflation in the Eurozone was 1,1 %[264] and the MFI (Monetary Financial Institutions) interest rates on new euro-denominated loans to the euro area for non-financial corporations for loans of longer than ten years with an initial rate fixation was 1,84 %[265]. These are usually risk free loan conditions. Utilities and industry however might take into account their own risk premium and use their Weighted Average Cost of Capital (WACC) as a discount rate. The rationale is that companies raise money from a number of sources (debts, stocks, etc.) each with their own expectation on return. The more complex the company's capital structure, the more laborious it is to calculate the WACC.

The European Commission has recently developed a better regulation toolbox[266], of which Chapter 8 tool #58 discusses discount rate assumptions. The recommended social discount rate herein is 4%. This 4% rate is intended to be applied in real terms and is therefore applied to costs and benefits expressed in constant prices. It can, however, be adjusted for inflation such that if one were dealing with nominal prices, and inflation were to be, say, 3% per annum then a 7% nominal social discount rate would be used.

The JRC LCOE PV map study[262] was based on a 5% cost of capital, which is somewhat above what a private investor could currently expect from an investment of comparable duration in government bonds. The results for a reference residential system are illustrated in Figure 90 and as can be seen the major cost herein is capital. Figure 90 also shows that residential users sometimes have to invest in VAT at the time of purchase long before seeing the return. This Figure 90 shows the relative importance of capital cost and therefore also access to low interest loans, several banks already offer low interest

262 https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/cost-maps-unsubsidised-photovoltaic-electricity

263 https://www.ecb.europa.eu/stats/policy_and_exchange_rates/key_ecb_interest_rates/html/index.en.html

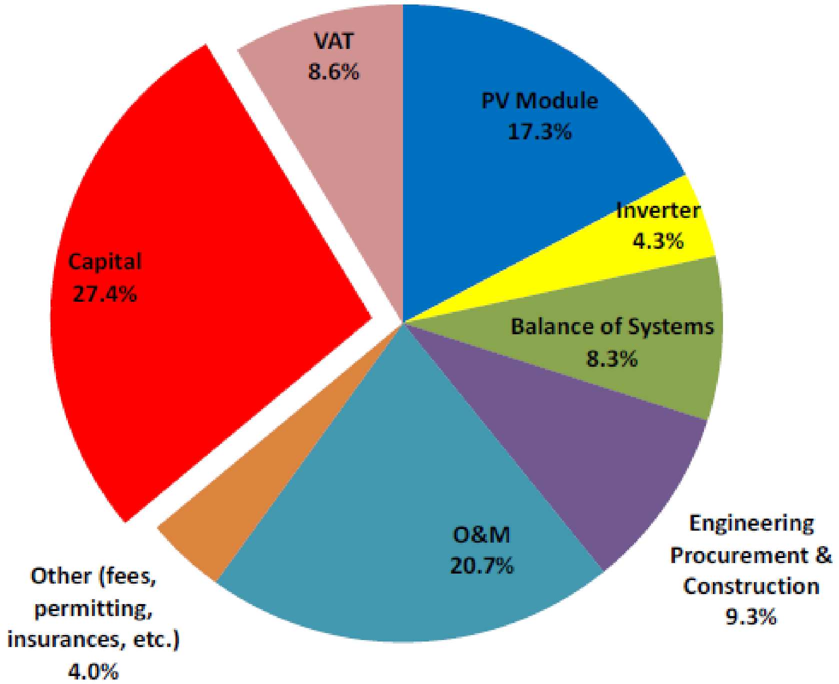
264 http://ec.europa.eu/eurostat/statistics-explained/index.php/Inflation_in_the_euro_area

265 https://www.ecb.europa.eu/stats/financial_markets_and_interest_rates/bank_interest_rates/mfi_interest_rates/html/index.en.html

266 http://ec.europa.eu/smart-regulation/guidelines/docs/br_toolbox_en.pdf

loans for VV systems[267, 268]. Also some countries therefore reduces the VAT for small residential photovoltaic installations to compensate this VAT capital investment barrier[269].

Figure 90. LCOE cost breakdown for a residential system costing 1 400 EUR/kWp +20%. VAT, 2% operation, maintenance and repair (O&M) cost, an annual generation of 1 000 kWh/kWp/y, financial lifetime of 20 years and 5% discount rate (T Huld et al., 2014[254])



3.4.1.2 Uncertainties in support policies

According to (IEA PVPS, 2017b[132]), PV development has been powered by the deployment of support policies, aiming at reducing the gap between PV's cost of electricity and the price of conventional electricity sources over the last ten years. This report says that about only 1% of the world PV market was driven by pure self-consumption or the sole competitiveness of PV installations in 2016. It also means 99% of the global PV market depends either on support schemes or adequate regulatory frameworks. Given the long lifetime for PV systems a stable and long-term support policy framework must be available to convince investors.

Most support schemes rely on FiTs, an overview of support schemes is in Figure 91. Net-metering allows consumers who generate their own electricity to use that electricity anytime, the balance is made per year or the meter turns back. Therefore net-metering is a kind of indirect support scheme because the grid costs and taxes should not be paid on all transported and sold or purchased energy (see Figure 94). Other support schemes rely often on Power Purchase Agreements (PPA) which are much combined with competitive auctions.

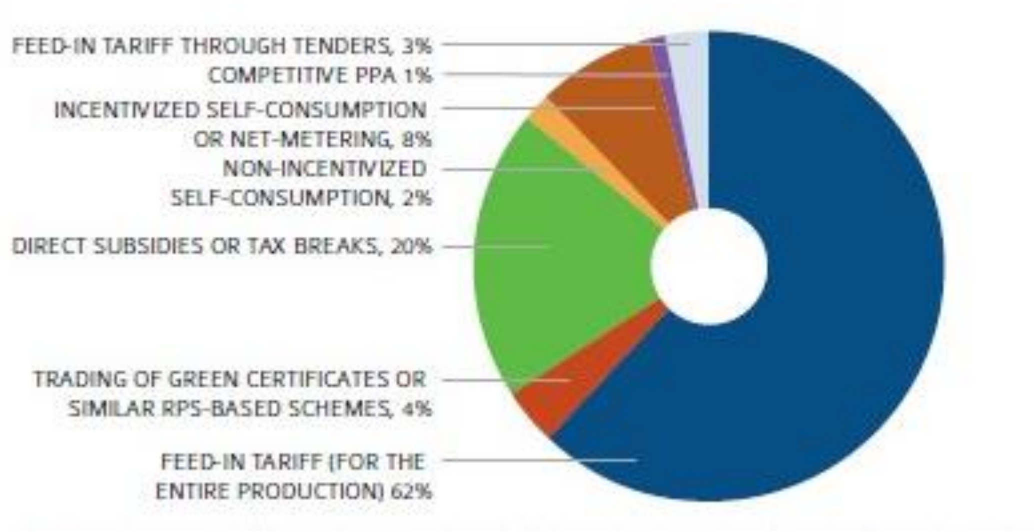
In many countries the debate on the financing of support schemes is ongoing creating uncertainty for investors.

[267] *https://www.finanzierung-photovoltaik.info/solarkredit.html#dkb*

[268] *https://www.vlaanderen.be/nl/bouwen-wonen-en-energie/lenen/energielening*

[269] *http://www.photovoltaique.info/Fiscalite#TauxdeTVA*

Figure 91. Historical market incentives and enablers for PV (IEA PVPS, 2017b[132])



3.4.1.3 Uncertainties in future energy prices

Apart from the support scheme (see 3.4.1.2) part of the return on investment will come from the value of the solar produced electricity per KWh. *For details on electricity market prices, the* market trends and the typical cost of PV systems please *consult Task 2* on photovoltaic system markets. The purpose of the section hereafter is not to analyse the electricity market into the details but only to illustrate the prospects and uncertainties that potential PV system owners will face.

When looking to the market value of electricity it is important to discriminate the wholesale market price from the retail price, for more details see Task 2. For PV system owners the wholesale market price is representative for the electricity sold to the grid and the retail price for self-consumed electricity.

The wholesale electricity market prices vary around 0,04 euro/kWh (Figure 92), it has so little value that projects are uneconomic and did not produce a return on investment (p.10, (Dunlop & Roesch, 2016)[270]).

Nevertheless, retail prices can be significantly much higher compared to wholesale market price which is illustrated in Figure 93 and therefore they can provide an important driver for investing in PV systems and in particular for self-consumption, for details consult Task 2 or Eurostat[271]. As illustrated in Figure 94 electricity prices can be very different per Member State and/or Region and consequently the driver to procure a PV system for self-sufficiency. Paradoxically enough these country differences are partially due to 'other taxes' which are often related to green levies to subsidize PV systems.

[270] Dunlop, S., & Roesch, A. (2016). D4.4 EU-wide Solar PV Buiness Models. Guidelines for implementation, (646554).

[271] http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics

Figure 92. Annual wholesale electricity prices in the EU between 2008 and 2015 of EU Member States (Ecofys, 2016[272])

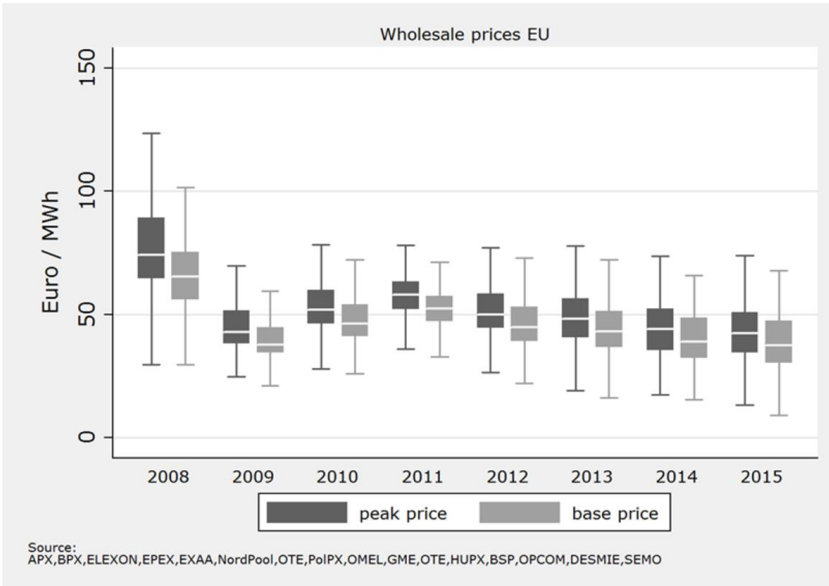
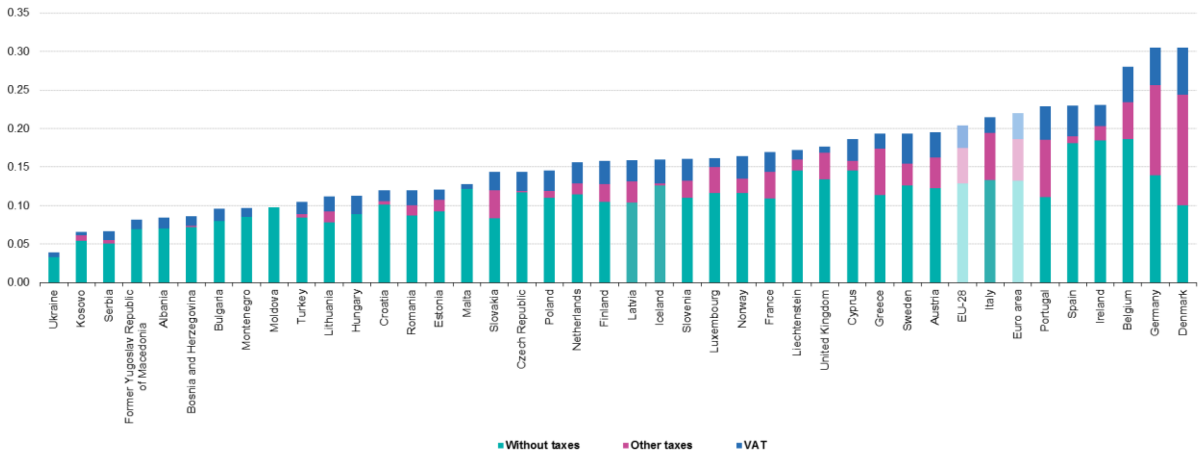


Figure 93. Electricity prices for household consumers, first half 2017 (EUR per kWh) (source/ Eurostat)



*This designation is without prejudice to positions on status, and is in line with UNSCR 1244 and the ICJ Opinion on the Kosovo Declaration of Independence.

Source: Eurostat (online data code: nrg_pc_204)

Future projections on electricity price are given in 'EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050' elaborated by the European Commission, which are summarized in Figure 94. In order to understand the uncertainty it is worth considering the future projections on electricity price The most commonly accepted source for this is the 'EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050' elaborated by the European Commission, see Figure 94. These complex electricity cost scenarios assume a continued uptake of renewables. Over time, the structure of costs slightly changes; capital intensive investments of RES such as photovoltaics and increasing grid costs bring a decrease of the share of variable cost components and a corresponding increase in the capital cost components.

The expected increase in grid costs are related to smart grids[273] and in particular the transition towards distributed RES, as discussed in subsequent section 3.4.1.5. More specifically, capital costs and fixed costs increase significantly. Higher shares of RES in power generation with similar fuel prices imply a reduction of the fuel cost component. Smaller components of the cost increase are national taxes and ETS allowance expenditures. In addition, there are the arithmetic effects of successful

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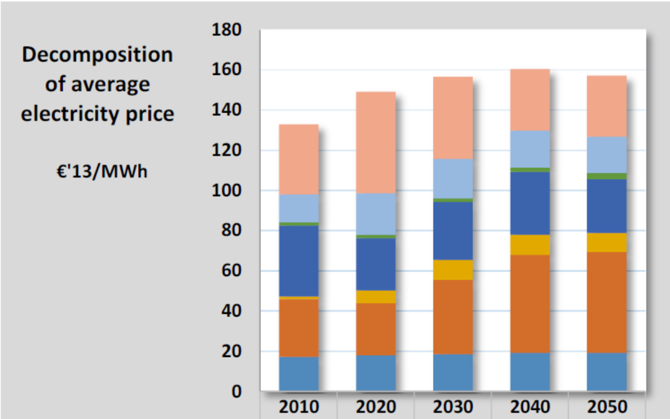
272 *Ecofys. (2016). Prices and Costs of EU Energy.*

273 *https://ec.europa.eu/energy/en/topics/markets-and-consumers/smart-grids-and-meters*

energy efficiency policies, which through curtailing electricity demand reduce the denominator for sharing out the electricity costs while the numerator is less affected due to the high share of fixed costs in electricity generation and supply.

As a consequence another barrier to investing in solar is simply the fact that electricity sold on the wholesale market has so little value that projects are uneconomic and do not produce a return on investment (p.10, (Dunlop & Roesch, 2016)[270]).

Figure 94. Components of average retail electricity price in EU (€ per MWh) historical and forecast values (source:EC (2016[274]))



	2010	2020	2030	2040	2050
Annual capital cost	35	51	41	30	30
Fixed costs	14	21	20	19	18
Variable costs	2	2	2	2	3
Fuel costs	35	26	29	31	27
Tax on fuels and ETS payments	1	6	10	10	9
Grid costs	29	26	37	49	50
Excise tax and VAT on electricity	17	18	19	19	19
Average price of electricity (after tax)	133	150	158	162	159

3.4.1.4 Uncertainties in forecasting the operational revenue

Forecasting the operational revenue of a photovoltaic system over its long lifetime (>20 years) might be the most important one given the interest of potential owners (see 3.0.1). In principle this is related to forecasting the yield of a PV system discussed in section 3.1.4

3.4.1.5 Potential technical barriers related to grid integration

The European Technology paper issued a white paper on this topic[275]. In a nutshell the main potential limitations for the distribution grid are related to:

- Grid congestion and therefore overvoltage issues
- Harmonics and malfunctioning of inverters
- Reverse power flows and transformer overloading

High shares of PV might in future also create system wide issues, related to the energy balance and ancillary services that are the responsibility of the transmission system operators[276].

[274] *https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf*

[275] *http://www.etip-pv.eu/fileadmin/Documents/FactSheets/English2015/EU_PVTP-Grid_Integration_white_paper_low.pdf*

[276] *https://www.entsoe.eu/about-entso-e/market/balancing-and-ancillary-services-markets/Pages/default.aspx*

Most of these technical barriers on grid integration are directly related to the requirements of the grid code, for example most European countries follow the German requirements VDE VDE-AR N 4105 on 'Power generation systems connected to the low-voltage distribution network' with the 'Technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks'[277]. Note that before 2016 the electrical grid codes was not harmonized and that this European harmonization is only recently initiated by the Commission Regulation (EU) 2016/631 that establishes a European network code on requirements for grid connection of generators. For a more detailed list on product requirements, European Regulations and Standards please see task 1.

Note that the white paper[278] also put forward mitigation techniques and therefore this barrier is also an opportunity for future PV grid inverters, see 3.4.2.4.

3.4.1.6 Market access and metering schemes for small producers

The way countries deal with the monitoring of energy locally generated from PV panels is not the same. For example, while in Belgium the most common situation in the residential sector is net metering (energy meter running backwards) and the residential prosumer receiving at the end of the billing period a corrected bill which includes the net excess generation, in other countries such as Germany there are two separate energy meters, being the second meter used for measuring the power generated by the PV panels and injected in the grid. In this case, the local utility provider pays the prosumer for the energy injected on the grid based on a price previously agreed. It may happen that the price for injecting energy on the grid was extremely subsidized and therefore very high.

3.4.1.7 Ownership of the roof and/or façade for BIPV/BAP, type of roof and building permits

The concept of prosumers and BIPV/BAPV is explained in section 3.0.2.4. There are also potential prosumers that do not own the roof or have only co-ownership, which therefore forms an important barrier for investment. The related section 3.0.2.4 on prosumers also gives examples of new business models and legislation to overcome this barrier.

Not all roofs are suitable to install PV panels taking into account the wind resistance and roof loading[279]. Especially flat roofs are often unable to withstand the additional wind load created by the PV panels and their counterweight or fixation. For flat roofs, the fixation of the support structure must also be done carefully in order to avoid water leakage. Therefore, from a constructional point of view attic roofs are in general more suitable compared to flat roofs.

3.4.1.8 Lack of knowledge or skilled subcontractors

The deployment, repair and maintenance of PV systems requires highly-qualified technicians (Tsoutsos et al., 2013[280]) which should demonstrate some form of certification attesting their qualification.

In this context, certification schemes can be used. However, across Europe these schemes may vary or might even be inexistent in some countries, even though training for PV installers exists might exist (PVTRIN, 2013[208]). Still, different eligibility requirements and qualifications may exist for the training courses. To avoid these situations and assure uniformity among the different Member States, the EU Directive (2009/28/EC) sought to lay down uniform requirements for accreditation and mutual recognition.

A training and certification scheme, for technicians responsible for installation and maintenance of small PV systems, compliant with 2009/28/EC RES Directive (Article 14, Annex IV) was proposed in (PVTRIN, 2013[208]).This training scheme was initially implemented in Greece, Bulgaria, Croatia, Cyprus, Romania and Cyprus. It involved key stakeholder groups to transfer the market's experience and needs and surveys were conducted in order to identify important aspects, namely "*to record the attitudes, perceptions and considerations of the PV industry/market actors regarding the training, certification and skills of PV installers and to record their opinion for the market growth, the adequacy of the existing workforce and the quality of current installations*". In one of those surveys installers skills were evaluated and *safety rules, integration in buildings and proper maintenance* were rated as inadequate raising important concerns (Figure 95).

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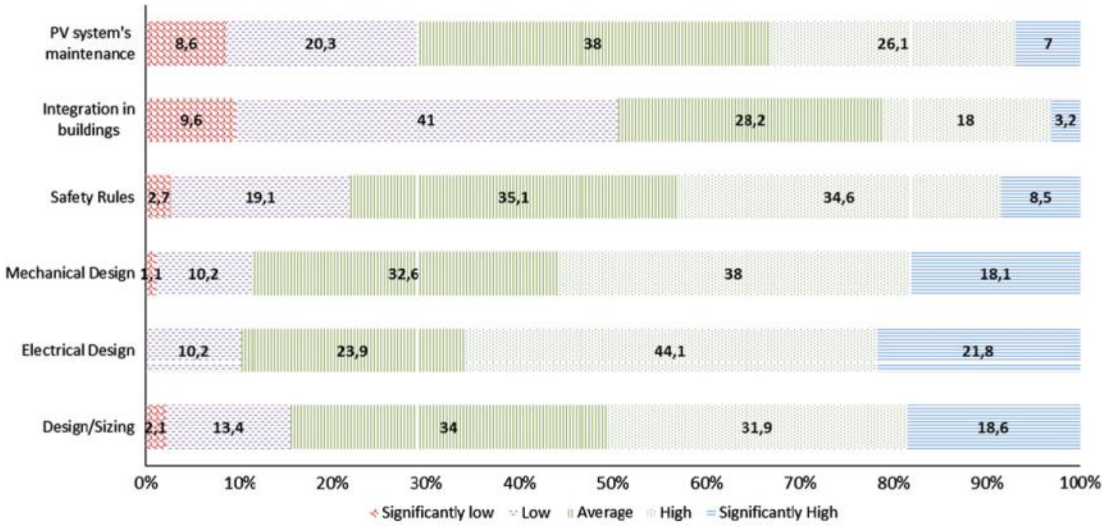
[277] *https://www.entsoe.eu/Documents/al/Germany/170623%20E-VDE-AR-N%204105%20zur%20Konsultation.pdf*

[278] *http://ec.europa.eu/eurostat/statistics-explained/index.php/Inflation_in_the_euro_area*

[279] *http://iawe.org/Proceedings/8APCWE/Daisuke%20Somekawa.pdf*

[280] *Tsoutsos, T., Tournaki, S., Gkouskos, Z., Masson, G., Holden, J., Huidobro, A., … Charalambous, A. (2013). Training and certification of PV installers in Europe. A transnational need for PV industry's competitive growth. Energy Policy, 55, 593–601. https://doi.org/10.1016/j.enpol.2012.12.048*

Figure 95. Rating of installers' skills according to the PVTRIN survey responders (Tsoutsos et al., 2013)



According to (PVTRIN, 2013[208]), installers following this training and certification scheme receive:

- "Appropriate, acknowledged training courses;
- Practical training materials and tools (handbooks, checklists and tips, e-learning platform;
- practical guides, lists of useful resources);
- Advancement and continuous updating of their knowledge and technical skills;
- Employability; recognition and professional competitive advantage due to their certification;
- according acknowledged quality standards;
- Mobility; the certification provides the "passport" to the EU job market".

This type of scheme certification will thus contribute to increase the knowledge and skills of installers and subcontractors.

It is worth noting that recently the IEA PVPS has also issued a guideline to introduce quality Renewable Energy Technician training (IEA-PVPS, 2017[281]).

3.4.2 Opportunities

3.4.2.1 Opportunities for batteries and demand response management to increase self-consumption

As it was mentioned in section 3.2.3, and mainly in the residential sector, there is a mismatch between PV production and the typical demand which opens up the way to energy storage. Also, as discussed in the previous section 3.4.1.5 high penetration rates in low voltage distribution grids can result in grid congestion or overvoltage.

Next to the existing solutions this can create opportunities for batteries and Demand Response Management (DRM). As far as it is relevant and within the scope of this study the technology can be discussed in Task 4. From a technical perspective various solutions exist depending on if and how the battery is integrated with the inverter, three possible topologies exist (BVES & BSW Solar, 2017[282]):

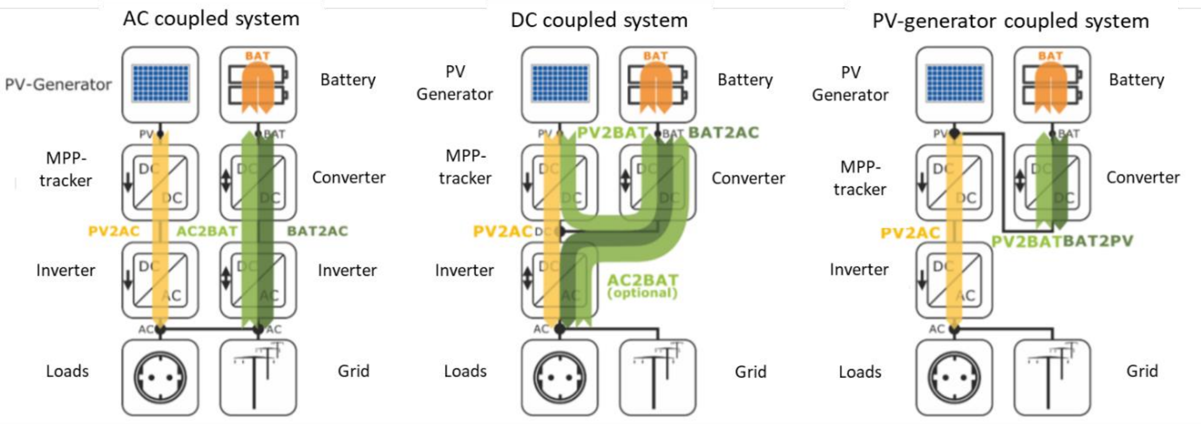
- AC coupled battery systems, i.e. an AC integrated battery/PV system.
- Batteries directly coupled to the PV modules, i.e. PV modules integrated with batteries.
- Batteries coupled to the internal DC bus of the inverter after the MPPT DC/DC converter, i.e. PV inverter with DC bus integrated battery.

281 *IEA-PVPS, R. (2017). Guideline to Introducing Quality Renewable Energy Technician Training Programs Guideline to Introducing Quality Renewable Energy.*

282 *BVES, & BSW Solar. (2017). Effizienzleitfaden für PV-Speichersysteme.*

The last system with batteries coupled to the internal DC bus of the inverter offers efficiency gains, see Figure 96.

Figure 96. Illustrative example of PV systems with batteries (BVES & BSW Solar, 2017[282])



An alternative future solution might be Demand Response Management (DRM) in to support the Smart Grid[283,284] which provides electrical load flexibility to cope with fluctuations in renewable energy supply. For appliances or plug loads, including domestic how water storage tanks, heat pumps and EV charging another Ecodesign preparatory study is already ongoing[285]. Hence, these issues can be left outside the scope of this study.

Concerning batteries, the principal is to use batteries to store the excess of local PV production and use that energy at a later time of the day when there is demand and no local energy is being generated (Labastida, 2017[286]). Nevertheless, residential batteries have not completely reached economic profitability in most of the current grid-connected situations (Pena-Bello, Burer, Patel, & Parra, 2017[287]) which is a major disadvantage concerning the use of that option to maximize self-consumption from PV. Indeed, as illustrated in section 3.2.3 that in the European climate it is not evident to cover the local load due to high variations in load profile in combination production variations due to clouds and seasonal differences.

Still in this storage need context, E.ON recently began offering a new product which allows solar power producers to "*store an unlimited amount of the energy they produce on a virtual electricity account and then draw on it anytime they like*" [288].At the initial phase this product, called SOlarCloud, will be firstly introduced on the German market.

3.4.2.2 Opportunities for communities to increase self-generation

An opportunity exists at the neighbourhood level to share local electricity production and consumption, through collective self-consumption models using a local grid loop. Even if a recent announcement in France made by the Energy regulator indicated that this electricity would be subject to taxes (and so not competitive with the electricity price), this could be developed in the future based on the usage of smart meters, or virtual meters.

[283] https://www.cencenelec.eu/standards/Sectors/SustainableEnergy/SmartGrids/Pages/default.aspx

[284] http://smartgridstandardsmap.com/

[285] http://www.eco-smartappliances.eu/Pages/welcome.aspx

[286] *Labastida, R. R. (2017). The Battle for the End Consumer: Residential PV and Battery Business Model Innovations in Germany. Retrieved from https://www.navigantresearch.com/blog/the-battle-for-the-end-consumer-residential-pv-and-battery-business-model-innovations-in-germany*

[287] *Pena-Bello, A., Burer, M., Patel, M. K., & Parra, D. (2017). Optimizing PV and grid charging in combined applications to improve the profitability of residential batteries. Journal of Energy Storage, 13, 58–72. https://doi.org/10.1016/j.est.2017.06.002*

[288] *https://www.eon.com/en/about-us/media/press-release/2017/eon-announces-a-new-initiative-in-digital-energy-products.html ; https://www.eon.com/en/about-us/media/press-release/2018/eon-brings-innovation-to-the-energy-market-storing-solar-power-without-batteries.html*

3.4.2.3 Upward trend in retail electricity prices and self-sufficiency

Section 3.4.1.3 explained the impact from of electricity prices on users, the expected upward trend of retail prices in some countries for some type of consumers will also create an investment opportunity in PV systems in particular to cover self-consumption.

3.4.2.4 Opportunities for inverters to provide grid ancillary services

Many of the barriers mentioned in section 3.4.1.5 on grid integration can be solved with control functions implemented in PV inverters. Task 4 will give more technical information. The European Technology & Innovation Platform PV issued a white paper on this topic[289].

3.4.2.5 Opportunities for public authorities to support residential installations

London tender example

3.5 Summary findings and conclusions

In this section the initial findings and conclusions that can be drawn from the Task 3 analysis of user behaviour and system aspects are presented. Alongside these findings, key points for discussion with stakeholders, together with requests for information and case studies, are also presented so that they can be addressed during the first stakeholder meeting and associated written consultation period.

3.5.1 Photovoltaic users, procurers and their requirements

3.5.1.1 The stakeholders involved in PV system ownership and use

A range of potential stakeholders are involved in PV system use whose influence over the decisions and processes involved in installation is an important first factor to consider. The interaction between the system owner or end-user, the designer or installer and other 'primary' stakeholders, such as the electricity distribution utility, is particularly important because of financial or regulatory requirements.

In order to understand the motivation and requirements of owners or end-users the possible ownership structures for a PV systems have been reviewed, together with the possible contractual routes used for the design, financing and installation. Based on a combination of the analysis made in Task 2 and in this Task 3, four broad types of ownership have been identified:

- Ownership by energy producers only: This type of ownership is increasingly becoming limited to larger systems that are able to win bidding processes for electricity price subsidies in each Member State. Self-consumption is forfeited for the security and revenue from an electricity price support contract..
- Independent power producers (IPP): These are entities without affiliation to a transmission, distribution or generation utility and who are responsible for developing, building and operating solar PV plants. An IPP may also serve as an investment vehicle.
- Third party ownership by Energy Service Companies (ESCo): A version of an IPP in which the land or building on which the solar PV system is installed may be owned by another party, with whom a lease or access rights are negotiated.
- Ownership by 'prosumers': Users that are both producers and consumers of electricity, usually at the same location or potentially as part of a community of collective self-consumers with systems installed at different locations on the same portion of the public distribution network.

The dual role of system owners as both producers and consumers of electricity is becoming increasingly important because of a reduction in subsidies. These so-called prosumers tend to be owners of smaller scale systems, typically less than 10-20 kW or in accordance with Member State electricity market legislation, whereas the first three types of ownership tend to encompass a range of public and private 'commercial' scale systems of >10 kW up to MW size.

A range of other public and private stakeholders are involved in, and may influence PV system design, installation and use. The influence and power of these stakeholders over the decisions and processes can play an important role. They will primarily include,

[289] *http://www.etip-pv.eu/fileadmin/Documents/FactSheets/English2015/EU_PVTP-Grid_Integration_white_paper_low.pdf*

- Central and regional government: Although their role is diminishing, government subsidies are still an important support mechanism for system owners and users, both at the point of making an investment and during a systems service life.
- Municipalities: Building permitting requirements will increasingly require Nearly Zero Energy performance, which in turn increase the focus on BAPV and BIPV as a solution.
- Banks and investors: Project finance or equity investment will come with associated due diligence requirements that may encompass system and component-level certification and quality assurance.
- Electricity distribution utilities: The local utility will impose financial and regulatory requirements on the system owner or end-user and their design and installation contractors.

Each of these stakeholders will impose specific technical requirements in order to receive finance, subsidies, permits and grid connections.

3.5.1.2 Consumer requirements for PV systems

The findings from a major consumer market testing exercise carried out for the CLEAR project in 2014 and from a more recent study for DG Justice in 2017, they both emphasise the importance to domestic consumers of financial savings relative to their current electricity source. Other factors to take into consideration include the capital and running costs, the payback time and the aesthetics upon installation on their property. The potential to reduce their environmental impact also registered as an important, but secondary, driver.

The priority placed by consumers on the savings potential means that an important factor at the design stage for a PV installation is the estimation of a systems annual AC energy yield. Making this estimation entails as a minimum an understanding of a system's Performance Ratio, as defined in IEC 61724-1, and the annual solar irradiation for the location.

The design of PV systems for the residential PV market is generally carried out using automated simulation tools and pre-defined packages of modules and inverters. This forms part of the quotation process for installers and retailers. Consumer expectations can also bring into the design process other considerations such as aesthetics (e.g. the appearance of modules or the visual effect on a roofline) or longer term maintenance such as access for cleaning and repair/replacement.

Consumer organisations across the EU provide advice on the installation of PV systems, as well the purchase of modules and inverters. Some of this advice is backed up by their own in-house performance testing and auditing of products according to varying and sometimes non-standard methods and metrics. Their priorities and focus e.g. the Belgian *Test Achats* and UK *Which?* audit PV manufacturers factory quality procedures and checks production samples. In contrast, the Spanish *OCU* field tests PV module and inverter kits which are then rated based on their performance in comparison to manufacturers claims.

3.5.1.3 Public procurement criteria and requirements for PV systems

Public authorities across the EU are increasingly looking at the potential to install solar PV systems on a range of buildings and sites. Calls for tender for installations may include four main types of criteria:

- Selection Criteria (SC): These criteria refer to the suitability and capability of the tenderer.
- Technical Specifications (TS): These criteria constitute minimum compliance requirements that must be met by all tenderers..
- Award Criteria (AC): At the award stage, the contracting authority evaluates the quality of the tenders and awards points that will have a weighting together with the price bid.
- Contract Performance Clauses (CPC): These clauses are used to specify how a contract must be executed and they may be linked to penalties or bonuses in order to ensure compliance.

Initial evidence from a search of tenders published in *OJEU* suggest that some public authorities are awarding points or establishing performance clauses on the basis of AC output power, warranty length, failure response services and the availability of spare parts. Monitoring of performance upon grid connection had also been specified.

The tender process itself and the potential to set criteria will be influenced by the type of contractual arrangement. Examples include:

- The purchase of PV equipment that is then installed by their own direct works company,
- The contracting of a designer, installer or turnkey contractor for PV systems, or

- To confer access rights to roofs or sites to an energy services company or renewable energy investment funds, who will then finance and install the PV systems.

There is some evidence that the third party financing PV installations on the basis of Power Purchase Agreements (PPAs) is emerging as another type of contractual arrangement. This option is being used where subsidies are no longer readily available.

Photovoltaic users, procurers and their requirements

Stakeholder consultation points

3.1 Of the consumer motivations and requirements identified which do you consider the most important to take into account in our PV system and component modelling?
3.2 Of the performance aspects addressed by EU consumer organisation which do you consider the most important to take into account in our PV system and component modelling?
3.3 Are you aware of any studies or information sources on the types of PV contracting used by public authorities?
3.4 In the case that you have participated in a call for tenders for a public authority relative to solar photovoltaics, what were the technical criteria?

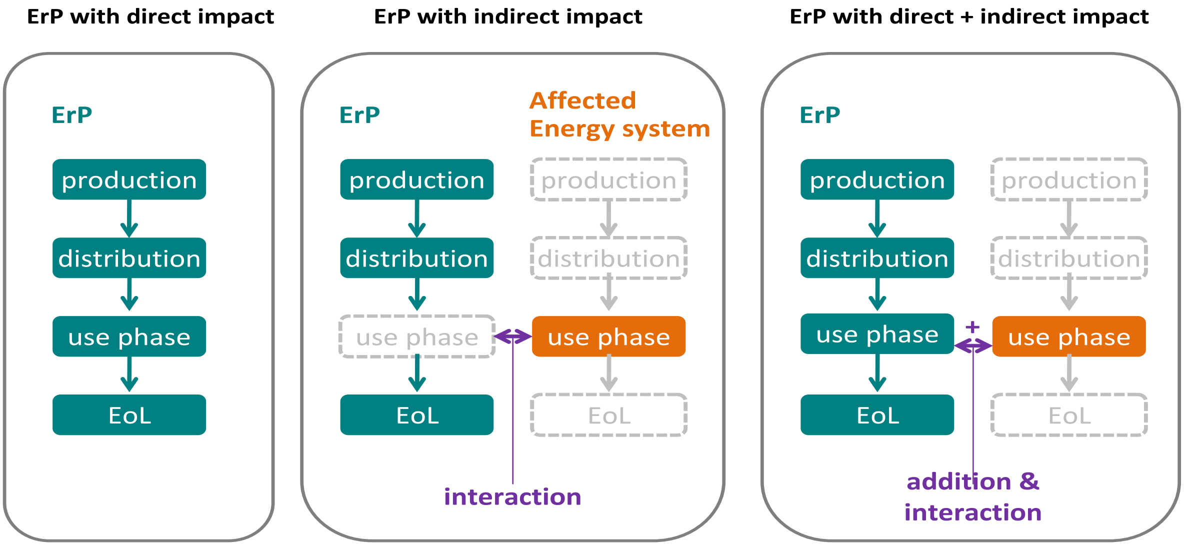
Requests for information and case studies

- Further examples of consumer organisations that carry out testing and audits of PV systems and components
- Further examples of public authority calls for tender and the associated technical specifications for solar PV installations are requested.
- Further examples of the inclusion of Green Public Procurement criteria in calls for tender for solar PV installations are requested.

3.5.2 System aspects in the use phase of solar photovoltaics

The Preparatory study follows the MEErP method, which establishes the concepts of analysing the direct and indirect impacts of an Energy related Product (ErP) on associated energy systems. Direct impacts are defined as those related to energy consumption in the use phase and indirect impacts as being related to an 'affected energy system' (see Figure 97). Both of these impacts require interpretation in order to apply them to solar photovoltaic systems and components, because the MEErP method was not developed with energy generating products in mind.

Figure 97. Illustration of possible system boundaries for direct and indirect impacts (Source: MEErP, 2011)



3.5.2.1 Direct impacts on energy production

Given that solar PV is an energy generating product it is proposed to consider direct impacts in negative terms i.e. those parameters that may constrain or reduce the amount of electricity generated during the use phase, or which may be considered as direct losses from a system during the use phase. In this way, a relation can be made to system design and specification decisions which can have a direct impact on the performance of a module, inverter or system.

The following direct impacts have therefore been identified and proposed as being taken into account in the modelling of base cases and scenarios in subsequent tasks:

- Performance Ratio (PR), which is the quotient of the system's final yield Yf to its reference yield Yr, and indicates the overall effect of losses
- Derate Factors (DRx) to disaggregate the Performance Ratio:
    - DRcapture for capture losses
    - DR_{BOS} for Balance of System losses
- In plane irradiation(Hi) [kWh/m²] over the specified time period

For the purposes of this study the reference standard for the Performance Ratio is proposed as IEC 61724-1:2017. A detailed proposal of the Derate factors to be taken into consideration in the modelling of a PV system during the use phase has been made in Table 52.

In line with the MEErP method four different approaches to the definition and modelling have been interpreted and applied to a PV system as the 'product' have been considered:

- Strict product approach
- Extended product approach
- Technical system approach
- Functional approach

The findings from an initial scoping of these four approaches are briefly summarised in Table 63. This scoping is supported by a review of current system design, yield estimation, operation, monitoring and maintenance practices in the market. Assumptions derived from these real-life practices, which may be requested and/or required by consumers and system owners in different market segments, will play an important role in the later modelling under Tasks 5 and 6. The functional approach to the choice of building technical systems is considered to fall outside the scope of this study.

Table 63. Scoping of the system boundary and approach to direct impact modelling

MEErP approach	Description of the approach	Technical implications
Strict product approach	In the strict product approach, the system boundary only contains the PV installation with its components. The operating conditions are nominal as defined in traditional standards.	• Modelling of a PV systems performance shall be carried out under Standard Test Conditions (STC) as defined in IEC 61853-1 • Standardised methods of estimating a PV modules efficiency and yield under STC, as well as the conversion and MPPT efficiency of the selected inverter according to a standard load profile, shall be used.
Extended product approach	In the extended product approach, the influence of real-life deviations from the testing standard are introduced, such as the use of local weather data for a chosen location.	• Weather data that is representative for the location of the PV system shall be used to estimate the final system yield in comparison to a reference yield. • A reference source of solar radiation data, as well as ambient temperature and wind speed data for the location is required. This shall have an hourly time interval, and represent a Typical Meteorological Year (TMY) based on a 20-30 year time series. • For the purposes of modelling base cases 3-4 representative EU locations and climatic conditions shall be selected. • The use of representative climate data will enable more accurate modelling of module capture losses due to the temperature, spectral mismatch, reflection and degradation – each of which has a derate factor.
Technical system approach	When viewed from the technical system perspective, the PV system is embedded in the surrounding building system or site, and therefore there is scope for interactions between the supply and demand for electricity.	• Factors related to the urban siting of the PV system and its integration into the built environment shall be described. • These factors include shading, soiling from various sources, and losses from low voltage cabling within metered premises. • Grid related curtailment and system failures will inform assumptions about potential downtime. System failures could include catastrophic module or inverter failures, necessitating a probabilistic assessment of reliability about failure rates. • A knowledge of operational, monitoring and maintenance practices shall be used to make assumptions about how derate factors may be managed, e.g. maintenance to clean module soiling, fault identification to prioritise repairs or replacements.
Functional approach	In the functional system approach, only the basic functions of a photovoltaic system, i.e. producing renewable energy and reducing CO_2 emissions, are the focus, and other building technical systems that can satisfy these basic functions are reviewed as well.	• For BAPV and BIPV, solar PV shall be compared with different building technical systems that may be used to deliver either: – a specific level of reduction in primary energy use and CO_2 emissions, or – to supply a specific proportion of a buildings energy from renewables. – To substitute the consumption on-site of a specific grade of energy e.g. heat for domestic hot water,

3.5.2.2 Indirect impacts on energy systems

Solar photovoltaic electricity generation will displace or substitute centralised, non-renewable electricity generation, thereby indirectly reducing environmental impacts. Other indirect impacts could include a reduction in transmission and distribution losses from local on-site production and, attempts to increase self-consumption. Three main types of indirect impacts have therefore been identified and are proposed to be taken into account in the modelling of base cases and scenarios in subsequent tasks. These three impacts are briefly summarised in Table 64.

Table 64. Scoping of the system boundary and approach to indirect impact modelling

Indirect impact	**Description**	**Technical implications**
Substitution effect of grid electricity	Avoided environmental impacts due to the substitution of non-renewable electricity with photovoltaic energy.	• Modelling of the substitution of the average EU impact resulting from the generation of 1 kWh of electricity • For a more accurate modelling the hourly or half hourly grid mix for a specific Member State should be used
Transmission and distribution grid losses	Transmissions and distribution losses associated with the grid transport of electricity. Ancillary grid support in order to curtail generation and adjust the grid frequency in order to manage asynchronous generation.	• Modelling of the solar PV electricity generation under low, medium and high grid penetration scenarios because of the variance in anticipated grid losses. • Consideration of the potential role of inverters which provide grid ancillary services e.g. reactive power to avoid congestion and frequency mismatches.
Demand side management and self-consumption	Demand side management in order to reshape load profiles so that there is better load matching with the supply. PV system integrated or grid level storage in order to load match within a 12-24 hour period of time	• Consideration of demand response at building level as a means of maximising self-consumption and minimising grid losses. • Measures to maximise self-consumption could comprise smart monitoring systems, the use of optimisers, smart appliances and battery storage.

System aspects in the use phase of solar photovoltaics

Stakeholder consultation points

3.5 Should the direct and indirect impacts be interpreted in any different way?
3.6 Should the scope of the direct impacts and the proposed derate factors be modified in anyway? *(see table 5, page 24)*
3.7 Do you agree with the product approaches as proposed to be addressed within the modelling of PV systems and components? *(see Table 63)*
3.8 Do you agree that a comparison of solar PV with other building technical systems that can deliver renewable energy of primary energy reductions, referred to as the 'functional approach', can be left out of the scope?
3.9 Should the scope of the indirect impacts be modified in anyway? *(see Table 64)*
3.10 For the purpose of PV system modelling 3-4 climate zones shall be defined and a location selected for each – which zones and locations would be the most representative? *(see table 6, page 29)*

3.5.3 End of life behaviour

An initial analysis has been made of actual user requirements regarding end of life aspects for PV systems. However due to the long lifetime of PV modules (>20 years) and inverters (>10 years), reliable and representative data for these tasks is not yet readily available. The limited evidence found today on user requirements, choices and behaviour might therefore be anecdotal and not yet representative for 2030 and beyond.

3.5.3.1 Recycling and disposal practices and the collection rate

The dismantling of photovoltaic systems and modules is typically carried out by a trained professional. Due to the long lifetime end-of-life of PV modules (>20 years) and inverters, and the relatively low overall deployment of the technology in the EU, only limited dismantling, recycling and disposal have taken place so far. In the framework of WEEE Directive, EU countries are setting up PV module recycling take back schemes such as PV CYCLE.

Data and estimates for Europe that are provided for each Member State have been compiled in the Commission's new WEEE calculator tool. It estimates that 2500 tonnes of solar module waste (Si based) was generated in 2016 in the EU. Estimates are only available till 2020 and suggest that 5000 tonnes of solar module waste (Si-based) will arise in 2020.

3.5.3.2 Module and inverter technical lifetime, degradation and failure mechanisms

The following key aspects of a solar PV system technical lifetime have been analysed in order to derive initial assumptions which can be used for modelling purposes. These largely focus on mechanisms that can lead to a decrease in yield or performance, or else a complete loss of function that cannot in all cases be recovered by repair or replacement:

- *Name plate module lifetime and degradation rates:* An annual degradation rate (power loss) of 0.5 – 0.6% in performance appears to be achievable in the short term, which would allow a module to still provide 80% of its initial yield after at least 25-30 years.
- *Life expectancy as a function of failure rate:* For modules and inverters this is taken to represent the theoretical technical lifetime of these components, as a catastrophic failure would mean that the module or inverter stops functioning and/or cannot be installed or operated safely.
  - *Module technical lifetime*: Major causes of failure are linked to the junction box and cabling, glass breakage and cell and interconnection damage. Failures can also occur during shipment, installation and operation. The means of protection against mechanical stress during transport is an important factor. A damage rate of 5% per annum has been identified. Other potential performance testing aspects are referenced in the main body of the report.
  - *Inverter technical lifetime*: Inverters have shorter lifetimes (5-20 years) and are comparable to other electronic products. The very limited number of independent reviews of inverter failure rates suggest 1%-15% yearly failure rate. These are related to their electronic component reliability, and mainly include the DC bus capacitors, IGBT power module solder joint lifetime, the main DC contactor (if any) and cooling fans (if any). The potential downtime is important to consider, with reports citing an average of 20 days/year downtime for string inverters and 3 days/year for central inverters. In this context the focus has been on Design for Serviceability (DFS) to reduce the "Mean Time To Repair".
- *Additional system components failure*: In a PV system the clamps, railings, cabling, and increasingly trackers should be considered. Trackers in particular may be subject to failure due to their mechanical nature.

3.5.3.3 Repair, refurbishment and second hand use of PV systems

When considering lifetime it is also important to look at the potential for repair and refurbishment, possibly leading to extension of the first service life or a second-hand service life. Upon maturity of the PV industry, in some EU Member States with a large PV deployment (such as Germany) several companies are now offering services for the repair and re-powering of PV modules. The following type of damage can typically be repaired:

- faulty bypass diodes and connectors,
- punctured backsheets,
- damaged frames.

The 'healing' of PV modules affected by Potential Induced Degradation (PID) is also offered by some companies. The most common failures that cannot be repaired are cited as being linked to damaged cell connections, delamination of the encapsulant and glass breakage to cite. Most repair companies provide a 2 year warranty on their repair work. Beyond repair or replacement of the damaged PV modules, adjusting the PV system design and eventually re-cabling of the PV string is necessary for optimal performance.

In general, inverter repair in the field appears to be less common, with faulty inverters mostly replaced. In order not to invalidate the (relatively expensive) inverter warranty only the inverter providers or a company commissioned by them is allowed to intervene for repair.

End of life behaviour

Stakeholder consultation points

3.11 Does the analysis of technical lifetime, degradation and failure reflect current feedback from the field?

3.12 Does the analysis of technical lifetime, degradation and failure reflect current assumptions used in business cases?

3.13 Are there any other aspects of performance that should also be addressed? If yes, please cite your supporting evidence.

3.14 To what extent are these repair practices and services available 1) in other Member States, 2) available to consumer PV system owners?

Requests for information and case studies

- Further examples of repair, remanufacturing and repowering practices and companies are requested.

4 Task 4: Technical analysis including end-of-life

4.0 General introduction

To allow policymakers, which often do not have a technical background, to understand the processes involved in the functional performance of the products, a brief and simple technological description of the products is made in this task. This technological analysis is conducted for technologies that are already on the market and that will become the basis for the base cases, but also for the identification of the Best Available Technologies (BAT) and state-of-the-art of the Best Not-yet Available Technologies (BNAT). This analysis concerns the product level, the component level and improvement potentials.

The aim of this task is also to collect a comprehensive data set of whole life data to undertake the analysis of the life cycle environmental impact and economics in the following tasks of this preparatory study.

Taking assumptions and lifetime definitions from Tasks 2 and 3 as a starting point, the following sections include an examination of factors that influence the technical lifetime of standard and potential BAT products, their performance, costs, end of life treatments, etc.. It focuses on the following main aspects:

- Performance

- Reliability and durability of product design

- Product end of life and circularity routes

- Resource use and hazardous substances

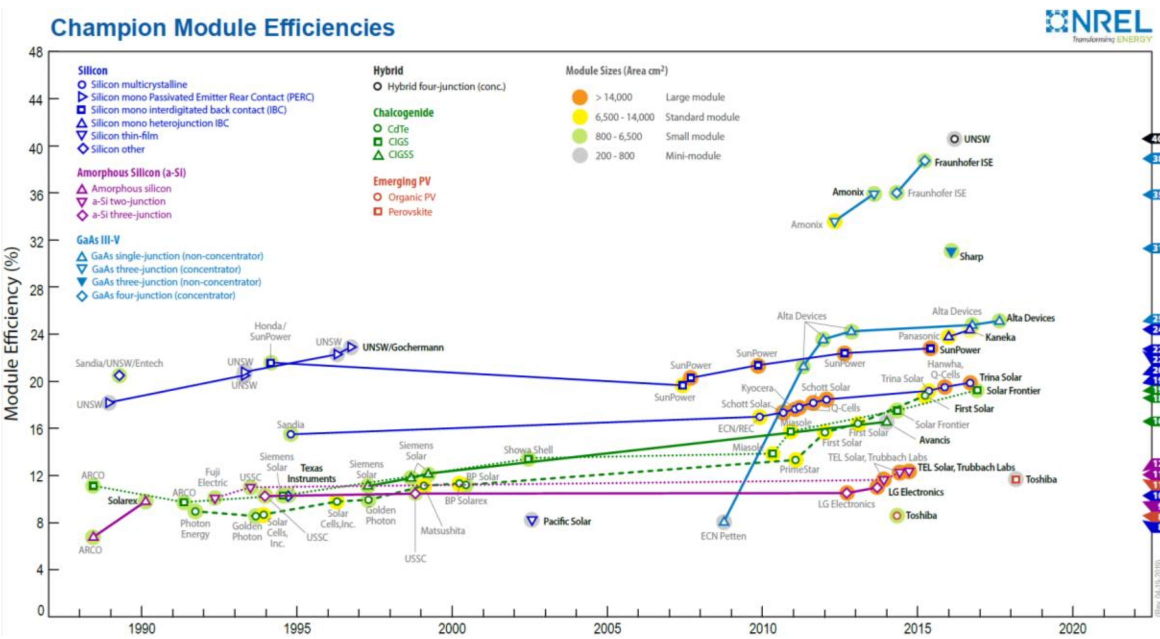
4.1 Technical product description of PV module, inverter and system solutions

Aim and background:

In this task a comprehensive technical analysis of the performance and design options of the products present in the market will be carried out.

There is an array of different photovoltaic module technologies, which have been the subject of intense research and development for the past decades, as it is depicted in Figure 98, where the evolution of record module efficiencies can be seen.

Figure 98. Record module efficiencies by NREL National Renewable Energy laboratories, April 2019.



Besides the base cases technologies, which should represent the average product entering the market today, product designs that may represent BAT and BNAT will also be assessed in terms of environmental improvement potential. The

assessment of those product designs provides the input for the identification of the possible design options and assessment of their improvement potentials in Task 6. The data and assumptions for the base cases will serve as an input for Task 5.

The overall aim of Task 4 is to identify the following products:

- **Base Case (BC) represents** the average product on the market in terms of resources efficiency, emissions and functional performance.
- The **Best Available Technology** point (BAT) represents the best commercially available product with the lowest resources use and/or emissions.
- The **Best Not yet Available Technology** point (BNAT) represents an experimentally proven technology that is not yet brought to market, e.g. it is still at the stage of field-tests or official approval.

The assessment of the BAT and BNAT should take place on purely technical grounds, i.e. the product with the lowest environmental impact, but it should be clear that in terms of functional performance, quality and durability it should be a product that is at least equivalent to the Base Case. This is an important condition, because there is evidence that in the past new products longevity has not been as durable, or their quality comparable with other products on the market for certain aspects of their performance. This last point is also relevant to the EU Ecolabel where criteria on fitness for use have had to be introduced for various products.

The BNAT point allows for future innovation and product-differentiation after the introduction of measures. The MEERP guidance also notes that in other preparatory studies analysts have tended to restrict the scope to technologies that were technically proven, where there is some idea of the costs and that are already at the stage of having conducted at least product field tests with pilot-series. This supposes at least 5-10 years of R&D work. From that stage onwards, considering that production and marketing development still has to start, it will be at least some 3 to 5 years before these products are actually on the market. It may be that for the solar PV product group the lead-time for R&D and then to bring products to market is much shorter.

The MEERP guidance also notes that:

- BNAT technologies could be accelerated to market by incentive programs once they have been evaluated as such in the Ecodesign preparatory study.
- the BNAT-level can be an indicator for future new energy classes i.e. A class must remain empty for BNAT.

4.1.1 Crystalline silicon PV wafer and cells technologies

4.1.1.1 Strict product scope of PV wafer technologies: performance

4.1.1.1.1 Wafer preparation

The complete value chain of silicon-based photovoltaic modules starts with the production of individual silicon wafers[1]. These individual silicon wafers are then processed into individual silicon solar cells, which are assembled together into modules typically consisting of 60 or 72 solar cells. The first step to produce a silicon PV module is therefore to produce a wafer, which is a silicon substrate of very high electronic material quality that has a typical thickness of around 180 micro-meter and a typical surface area of 15.6x15.6 cm^2.

Silicon wafer-based PV technologies have dominated the PV market since the beginning with a market share of around 95% of the global PV module production in 2017 [2]. Silicon wafer production is a long and energy-intensive sequence [3].

Metallurgical-grade silicon (MG-Si) requires high purity silicon in the form of quartz. There are various definitions of High Purity Quartz (HPQ) relative to the total and elemental contamination. The ultimate purity of the silica depending on the extent of which contaminants such as aluminium, titanium and lithium can be removed. Naturally-occurring ultra-pure SiO_2 (greater than 99.997%) which is suitable for production of high-purity fillers, silicon metal and use in solar cells and semi-conductors is geologically rare and commands a significant premium over the price of lower grader material[290].

At first, silica is reduced in an arc furnace to produce metallurgical-grade silicon (MG-Si), which contains high levels of impurities. Thus, MG-Si is dissolved in hydrogen chloride and the resulting chlorosilanes are distilled to produce high-purity silane gas, most commonly trichlorosilane (TCS). TCS is used in the Siemens process to produce polysilicon rods, which are broken into chunks and used as feedstock for the subsequent ingot production processes. Fluidized bed reactor (FBR)

[290] *http://www.verdantminerals.com.au/projects/dingo-hole-silica-project-nt/silica-high-purity-quartz-information*

technology, as an alternative to the Siemens process, did previously receive attention, owing to its lower energy usage [4], but it has now fallen out of favor.

For the sawing of the wafers, Diamond Wafer Sawing (DWS) is an alternative to slurry-based wafering (which still represents 50% of the market for multi-Si). It reduces kerf loss by 30%, and so directly reduces material and energy consumption[291].

Multi-crystalline Silicon wafer preparation

Two main types of ingot growth techniques are used for PV wafers, namely direct solidification (DS) and the Czochralski (Cz) process. Direct solidification is a casting method whereby polysilicon feedstock is melted and solidified in a large crucible to produce a large multi-crystalline silicon (mc-Si) ingot. Today's typical Gen 6 multi-c ingot is produced using 800 kg silicon charge and can be cut into 6x6 bricks [5]. The bricks are eventually sawed into individual wafers. During the sawing process, a significant amount of silicon is lost, which comprises the kerf loss. Typically thickness of mc-Si wafers today is ~180 µm. P-type mc-Si wafers constitute about 62% of the market share in 2017 [6]. Mc-Si wafers contain different crystallographic silicon grain orientations and hence grain boundaries which will limit the resulting energy conversion efficiency of solar cells made from this material.

Given the inferior quality of mc-Si compared to mono-crystalline, owing to the large number of structural defects, grain boundaries and impurities, various efforts to improve the electrical quality of mc-Si wafers have been undertaken. High-performance (HP) mc-Si wafers, which have a more uniform distribution of smaller grains and lower dislocation cluster density compared to traditional mc-Si wafers, exhibit higher bulk minority carrier lifetime and have been a huge success in recent years [5]–[7]. As such, the 2017 market share for HP mc-Si is around 40% compared to 20% for traditional mc-Si [6]. The market share of the highest quality of mc-Si referred to as mono-like Si wafers, which consist of large grains (predominantly (100) grains) is negligible today, and is not expected to increase in the coming years.

Mono-crystalline wafer preparation

In the Cz process, a single crystal of silicon (without any grain boundaries) is pulled out of a polysilicon melt using a small seed crystal to form a large cylindrical boule of mono-crystalline silicon with a typical body diameter of around 205-215 mm. The boule is then cropped and squared before being sawed into individual wafers. The off-cuts of the ingot are recycled by adding them back to the melt. Typical thickness of mono-Si wafers is ~180 µm, which is expected to decrease faster than mc-Si wafer thickness, in the coming years. Wafer sizes are expected to gradually increase from M0 (200mm diameter with 156.0mm side length) to M2 (diameter for 8.2-inch silicon wafer is 210 mm, and edge length is increased by 0.75 mm to 156.75 mm) which on module level can lead to more efficient area usage. Today the M2 format is the standard, in addition to M4 (211mm diameter with 161.7mm side length). Mono-c Si wafers take up about 38% of the market share and are mainly dominated by p-type Si, with only about 4% attributed to n-type Si for higher efficiency [6].

Alternative to traditional wafer preparation: kerfless wafers

Since silicon is an expensive material, accounting for ~40% of the costs at module level, **there is a strong drive to reduce wafer thickness and kerf** (due to the sawing) **silicon material losses**. With the present wafering technologies and the PV value chain described above, it is challenging to achieve sub-100 µm silicon wafer thickness[292] and to eliminate kerf loss. To this end, a wide variety of alternative and disruptive technologies have been under development. The set of technologies that produce silicon wafers or foils (<70 µm) with negligible or no kerf at all is collectively called kerfless or kerf-free wafering techniques, most of which rely on the detachment of thin Si active layers from the top of a substrate or ingot, a process that is termed lift-off.

Two of the lift-off techniques that are currently at advanced stages of development and that are being considered for commercialisation are (1) stress-induced lift-off, and (2) porous silicon-based lift-off of epitaxially-grown silicon. Stress-induced lift-off involves stress-induced spalling of thin layers of silicon from the surface of an ingot or a thick substrate using a stressor layer and a thermal cycle, without kerf loss. Until recently Siltectra has been involved in the development of this technology, aspiring to its potential commercialization. Though, in view of Silectra's recent acquisition by Infineon Technologies, it is yet to be verified – to our knowledge – whether there is any mid-term (BNAT) feasibility on commercialization of cold split for PV Si Wafers [8]. Porous silicon-based lift-off of epitaxial Si is another disruptive technology which not only tries to reduce or eliminate kerf loss but also to short-cut the extensive PV value chain by getting rid of the Siemens process as well as the ingot growth processes (casting or Cz pulling) [9]. This technology is currently

[291] *International Technology Roadmap for Photovoltaic, ITRPV, 2017: http://www.itrpv.net/.cm4all/uproc.php/0/ITRPV%20Ninth%20Edition%202018_1.pdf?cdp=a&_=16224ec6558*

[292] *The challenge is not so much to produce thin wafers, but to handle them and not to lose efficiency in the cell as there is less material to absorb the light.*

being commercialised by NexWafe [10]. The parent substrate is re-used several times to produce an epitaxial wafer per cycle.

4.1.1.1.2 Silicon material

Silicon recycling in wafer production

Silicon material that is recycled from the silicon kerf losses during production, or from end-of-life PV modules, or from yield losses during cell and module processing (broken wafers), can be re-used after purification in the ingot production of either multi-crystalline or mono-crystalline silicon. In this way, new ingots can be grown that consist partially of recycled silicon and partially of "new" silicon. This research topic is under investigation and its impact on cell performance and reliability is difficult to predict.

Silicon recycling from the end of life of PV modules, methods and value

Recycling of silicon at the end of life is in theory possible and several patents and methods are known[11][12]. Nevertheless, today Silicon recycling is not done because it isn't economically viable [13]; the rationale for this is the low value of Metallurgical Grade Silicon (MG-Si), which was about 0,8 €/kg (2015). This price is relatively stable as MG-Si is mostly used in the ferro-industry and is dominated (about 40 %) by the cost of electricity for manufacturing [14]. The market value of ultra-pure photovoltaic grade polysilicon was in 2015 around 18 €/kg [13] but today(10/2018) the price even dropped below 10 €/kg[293].

As shown in the literature, the silicon metal recycled from PV module waste could likely only replace metallurgical grade silicon at the stage before the production of solar grade polysilicon, i.e. the conversion of metallurgical grade silicon into hyper pure polysilicon which is the feedstock for solar wafers. Hyper pure polysilicon from quartzite would still be required and cannot be fully substituted by recycled silicon. This is because of the dopants and impurities that are likely to be present in a PV module silicon waste stream. As a consequence, the silicon scrap value in a module has to be compared at its best with metallurgical grade silicon (≈1 euro/kg), which is relatively cheap in comparison with solar grade polysilicon (≈15 euro/kg).

Silicon recycling therefore will likely not have a significant impact on reducing the need for crucibles in the polysilicon purification process, which relies on consumption of ultra-pure quartz (SiO2) mineral. More information on module recycling is in section 4.1.1.2 and 4.2.

Silicon metal or ultrapure quartz mineral for crucibles as a Critical Raw Material

Despite that silicon is next to oxygen the most abundant atom present on earth[15], 'silicon metal 'itself was considered as critical raw material for a circular economy[16]. Therefore it is discussed in more detail in this section. Given that silicon metal is available in large quantities for use in steel and aluminium alloys[15]; it is not obvious to consider this a critical raw material(CRM). However, note that the U.S. Geological Survey (USGS) does not survey the ultra-high-purity silicon industry for production and related data as they have only information in their report about these grades from foreign trade statistics and published sources [15].

As was noted in Task 1, silicon metal has now been identified in Europe as CRM. Little information is disclosed on the rational to consider silicon metal as CRM, it only refers to the fact that it is the base from which the ultra-pure Silicon used for photovoltaic cell manufacturing is ultimately derived. Quartz (SiO_2) with a low level of impurities is a good starting point for PV manufacturing and mining today is focused at these resources. Looking into more detail in the previous described manufacturing steps, another potential more critical issue is the dependency or resource depletion of ultra-pure silicon used for crucibles [17], they are needed in the purification processes described before. So far, little information is given or disclosed by manufacturers on this resource consumption and origin of their materials[18]. As a conclusion, the mining capacity and consumption of ultrapure quartz mineral[294] to manufacture could be considered as critical.

4.1.1.2 Strict product scope of PV cell technologies: performance

The next step in the silicon PV value chain is to process individual silicon wafers into individual solar cells. Whereas the silicon wafers are just substrates, the silicon solar cells are working electronic devices that contain a p-n junction, metal contacts, surface passivation layers and an anti-reflection coating. In the last decades a large variety of crystalline silicon

[293] *Daqo announces 6.8$/kg cots in 2020, Siemens technology. https://www.pv-tech.org/news/daqo-targeting-polysilicon-production-costs-of-us6.80-per-kilogram-in-2020*

[294] *https://www.sibelco.com/markets/renewable-energy/*

(c-Si) solar cell concepts have been developed by universities, R&D institutes, and manufacturing companies with the primary goal to improve energy conversion efficiency without significantly increasing processing costs. The following paragraphs give a brief overview of standard single-junction c-Si solar cell concepts most relevant to industry.

Aluminium back-surface field (Al-BSF) technology

The vast majority (~90%) of c-Si solar cells manufactured today are based on two-sides contacted solar cells [6]. Among these cells, the so-called aluminium back-surface field (Al-BSF) technology has been the dominant technology due to its simple cell design and relatively good resulting cell performance. Best reported large area (244.3 cm^2) **Al-BSF energy conversion** results on monocrystalline c-Si are around **20.8%**. Al-BSF solar cells are limited by two main loss mechanisms occurring at the blanket rear Al contact: (1) recombination of photo-generated charge carriers, (2) parasitic absorption of infrared light.

Passivated emitter and (totally diffused) rear cell (PERC/T) technology

To overcome these loss limitations from recombination and infrared absorption, the so-called "**passivated emitter and rear cell" (PERC)** was introduced in 1989 by UNSW but it took until 2014 for manufacturers to start adding significant production capacity of industrial PERC cells [19], [20]. The key feature of PERC concepts is that the rear side is passivated by dielectrics, typically a stack of Al2O3/SiNx, and subsequently patterned to formal local contacts. Today's best manufacturers are reporting **average PERC efficiencies** in production of around **22.0%**.

An alternative high-efficiency concept to PERC is the so-called "passivated emitter, rear totally diffused" (PERT) concept. In this concept, the rear side is totally diffused prior to dielectric passivation and subsequent metallization. The main benefit of PERT concepts is that lateral resistive losses to the rear side local contacts are reduced which relaxes bulk conductivity requirements. PERT concepts are being evaluated on both p-type and n-type c-Si. However, a major limitation of PERT is the extra processing complexity versus PERC. For this reason, research is on-going in PERT concepts to either simplify the junction formation sequence and/or the metallization sequence. In both PERC and PERT concepts, recombination losses are significant, particularly at the metal contacts, which limit the achievable open-circuit voltages (Voc).

Silicon heterojunction

Silicon heterojunction (SHJ) cells overcome this issue (typical Voc values are 730-750 mV) by making use of a thin stack of intrinsic and doped hydrogenated amorphous (a-Si:H) to simultaneously passivate the c-Si surface and extraction for photo-generated carriers [21]. For two-side contacted SHJ, record efficiencies up to 25.1% have been demonstrated on large area n-type Cz and equipment manufacturers are now demonstrating **average efficiencies above 23%** in pilot-production.

Back-contact cell technologies

Compared to two-sides contacted solar cells, back-contact solar cells have both contact polarities on the rear side which significantly reduces optical losses at the illuminated front side both from cell metallization and cell-to-cell interconnection. Various back-contact cell designs have been developed with the main ones being interdigitated back contact (IBC), metal wrap through (MWT), and emitter wrap through (EWT) [22]. In IBC solar cells, all metallization grids are placed at the rear side which completely eliminates front side shading losses and improves aesthetics. Current commercially available IBC based modules manufactured by Sunpower achieved an efficiency of 24%.

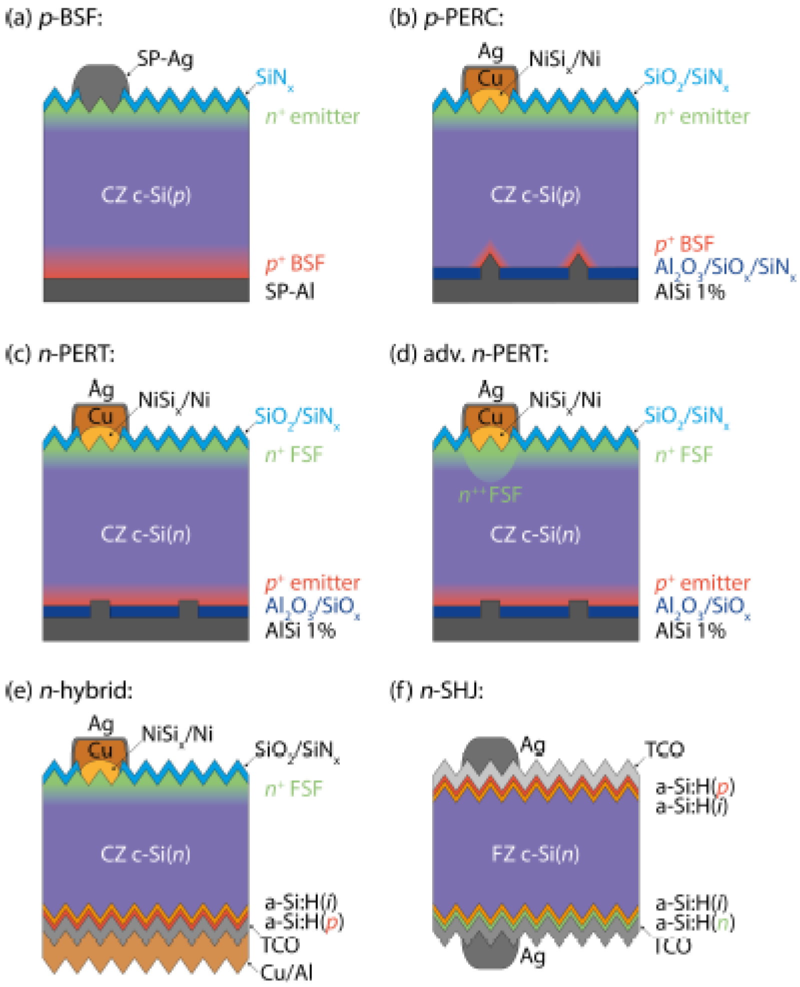
The benefits of IBC solar cells (no shading losses, improved aesthetics) and SHJ solar cells (excellent Voc) can be combined in so-called **IBC-SHJ which has culminated into the world-record 26.7% efficiency for c-Si solar cells set by Kaneka** [21]. Further process simplifications are however required to commercialize IBC-SHJ cells. First success in simplification has been recently reported by Meyer Burger with cells reaching 25% efficiency from industrial process flow. Due to the temperature sensitivity of amorphous silicon, an interesting alternative is to use doped polysilicon layers for contact passivation [23].

Bifacial technologies

Finally, a promising approach to further improve the performance of c-Si solar cells is to make solar cells bifacial so that both sides capture incident and diffuse sunlight [24]. **Most high-efficiency cell concepts such as PERC, PERT, SHJ, IBC, IBC-SHJ can be made bifacial** simply by using metallization grids at the rear side instead of blanket metal layers. This enables the reduction of the cell metallization and simultaneously increases the cell and module performance. Integration of these cells into PV module requires either glass-glass packaging or the use of transparent backsheet at the rear.

An overview of various cells architectures is displayed in Figure 99.

Figure 99: Overview of various cells architectures: (a) Al-BSF, (b) PERC, (c,d) PERT, (e) SHJ, (f) bifacial SHJ [25]



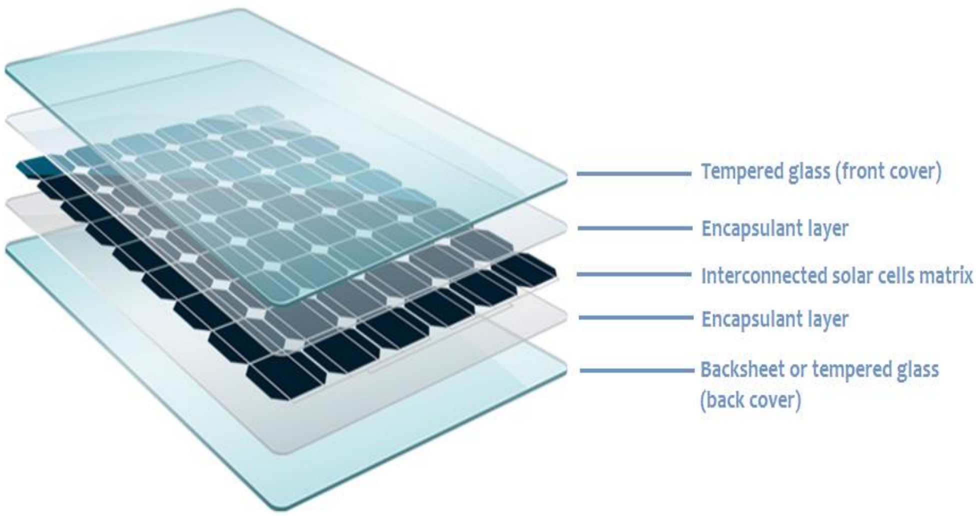
4.1.2 Crystalline silicon module technologies and materials

4.1.2.1 Crystalline silicon module technologies and materials

4.1.2.2 Strict product scope

The term photovoltaic (PV) module refers to an assembly of typically 6x10 or 6x12 series-connected solar cells, packaged into a protective multi-layered structure, which comprises 5 main components (Figure 100): a front cover (tempered glass), the electrical circuit (the interconnected solar cells matrix) in an envelope of two encapsulant layers (front/back) and a back cover (backsheet or tempered glass). Externally, metal frames consisting of racking components, and brackets are used to better support the module structure.

Figure 100: Typical structural layers in a c-Si PV module

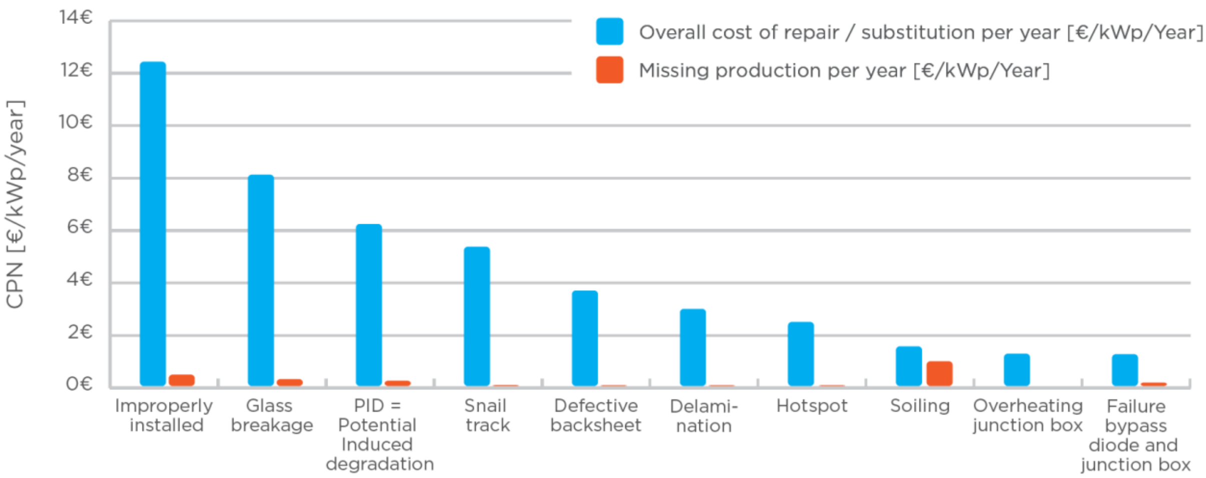


Each module is rated by its DC power output under standard test conditions (STC), which – for standard applications - typically ranges from 200 up to 435 W; while typical electrical efficiencies of commercially available PV modules are found in the 16-22% range. Electrical cables (i.e. positive and negative terminals), linked to a so-called junction box (situated on the back side of each PV module), are used to connect multiple modules either in series or in parallel to achieve respectively higher voltage or current outputs, at a PV system level.

PV modules are intended to operate outdoors – thus, being exposed to diverse field (environmental) conditions – for operational lifetimes that often exceed 20 or 25 years. Therefore, superior performance and long-term reliability are pivotal drivers of R&D in materials and technology for PV modules and components (i.e. interconnections, backsheet, encapsulant and glass).

The following section deals in turn with interconnections, the backsheet, encapsulant, front glass, the junction box and bypass diode. For some of these components the possibility of repair/replacement is discussed depending on their significance according to potential performance losses. As can be seen in Figure 101, the cost of module repair is in general relatively high when compared with the output losses. The reason may lie in the fact that the substitution of the defective module is the preferred procedure to repair, because the action of repairing modules could void the module manufacturer's warranty, but comes at a higher cost.

Figure 101. Costs during operation and maintenance (CPN), repair costs ($CPN_{failure\_fix}$) and performance losses ($CPN_{never\_detected}$) for top 10 risks for PV modules of all system sizes. Source: Solar bankability, 2017



Interconnection

Today, the most common PV module fabrication technology involves stringing of 2-side-contacted photovoltaic cells. The generated electrical current is collected through distributed metal fingers across the cell into typically two or more busbars. **By soldering tin lead ($Sn_{62}Pb_{36}Ag_2$)** coated copper ribbons to these busbars, **cells are electrically connected** in series to form cell strings. The exact silver content can change however the remaining composition of the alloy is little altered to remain close that eutectic formulation required for reliability. The size of these ribbons is a compromise between shadowing on the illuminated surface of the cells and resistive losses. The individual cell strings are connected with string connection ribbons and laminated into a module. The exact size of the ribbons is adapted by the manufacturer for every module product.

Soldering ribbons can be applied through different processes: hot bar, laser, hot air, infrared and induction. During the process the solder alloy temperature must be raised above the melting temperature of the solder alloy (>185°C) to create a solder joint between the cell and ribbons. This is implemented through gradual heating stages in industrial tabber and stringers to minimise thermal stress on the cell and improve the production yield.

For both improving electrical performance and reducing optical losses, a trend towards an **increasing amount of busbars** is materializing [26]. Indeed, for the same amount of material, a lower resistive loss can be obtained by decreasing the finger losses or alternatively for the same loss, **less material is needed**. In terms of optics, more narrow ribbons will result in a reduced reflection out of the module and thus enhance sunlight recovery, yielding a higher current.

Increasing the number of busbars on the cell and interconnection ribbons on the module overall leads to slight increase of the solder use, and hence the Pb content of PV module. We estimate the change from 2 busbar cells to 5 busbar cells leads to ~5-10% increase in the volume of Pb/module.

Culminating this trend are **multi-wire interconnection technologies**, with the additional advantage that busbars are no longer needed on the cells and the conductivity of the fingers can be strongly reduced, decreasing the cost of the silver metallisation on cell level. Apart from the electrical and optical benefits, also the aesthetics are improved, yielding a darker (cf. reduced optical losses) and more uniform module surface.

Two such **multi-wire interconnection technologies** are introduced on the market. One approach effectively mimics the standard technology by soldering SnPbAg coated ribbons on finger solder pads, replacing the busbar[27]. High performance and reliability have been demonstrated with this approach and is already in volume production by LG [28], reaching 340 Wp and 20% efficiency. A second approach applies a contact foil directly onto the metallized cell followed by a lamination process; this is the so-called Smart Wire Connection Technology (SWCT) [29]. The contact foil integrates low-temperature-solder-coated copper wires (with In or In-free formulations) on an optically transparent supporting film (PET) with an adhesive layer. The exact solder coating formulation and process to apply the solder coating is currently little known.

Next to multi-wire, **electro-conductive backsheets** have entered the market as a busbar-less cell interconnection option for standard BSF and future cell types. Amongst others, Sunport Power currently has a production capacity of 1GW in China, Energyra starting a 150MW line in NL and Silfab 300MW in the US. Due to full back-contacting of cells and reduced resistive losses, the cell-to-module (CTM) loss is eliminated. To enable back-contacting of cells, the front-side metalization is guided through holes (vias) in the cell to the backside (Metal Wrap Through technology). For IBC cells this is not needed as both contacts are already positioned at the back-side.

Lead-free soldering and ECAs

Low temperature and lead-free solder alloys have the following compositions: $In_{(52-42)}Sn_{(52-42)}Ag_{(0-2)}$ or $Sn_{(50-60)}Bi_{(38-48)}Ag_{(0-2)}$ with melting temperatures of 118-145°C and 139°C, respectively. During the lamination the wires of the contact foil are soldered directly to the metal fingers of the cell. In their latest version, Meyer Burger has demonstrated 60-cell modules with HJT cells reaching 335 Wp, based on In-free soldering and UV-transparent encapsulation (white tiger foils) [30]. They also publish good reliability results up to 2-3x IEC testing for damp heat and thermal cycling, for both glass-glass and glass-backsheet modules. Although their commercialization could be gradually starting up , the 10th edition of the ITRPV (2019) only shows a very limited uptake of lead-free soldering in 2018/19 (~10%) and forecasts that share only to grow to 25% by 2025

Similar low-temperature solder coatings can be also used in combination with standard ribbon interconnection technologies relying on tabber and stringer for the soldering.

Implementation of Pb-free soldering for the interconnection of various types of solder cells is under investigation by numerous players. Although, Meyer Burger and several other players reported that their Pb-free technology can pass IEC certification proving the reliability of solder joints, the material and process development required to reach these targets is challenging. The low temperature solder alloy intrinsically have higher diffusivity and form brittle intermetallic alloys [31].

Their low solder temperature compared to SnPbAg can also mean that they will not meet the requirements of certain high temperature applications of PV modules (e.g. BIPV).

In short, our current insights on low temperature and lead-free solder alloys is limited and their potential to reach extended PV module lifetime (and which conditions) up to 25-30 years has to be further proven. The use of Sn or its alloys: Sn(Ag, Cu, Zn) with melting temperature above >200°C is difficult to combine with current PV cell types and PV module assembly processes. The trends to evolve to more advanced cell structures (with high temperature sensitivity) and/or thinner wafers will make the integration of Sn based alloys in the module process even more difficult.

More challenging solar cell processing due to thinner wafers and emerging new cell designs that cannot resist to high T process have raised the need for an evolution in electrical interconnect materials [32]. The use of **electrical conductive adhesives (ECA)** in heterojunction and certain thin-film technologies is implemented for ribbon soldering. Furthermore the emerging shingled PV modules and back-contact cells connected with conductive backsheet interconnect technology often rely on ECAs. Conductive adhesives are generally based on a polymeric matrix, which is filled with conductive metal particle (Ag most commonly). During manufacture, storage and processing the adhesives are liquid and can be applied with appropriate dispensing systems or printing technique. A thermal (or in some cases UV cure) step is indispensable to ensure good glueing and electrical conduction. The temperature treatment remains <150°C in most cases hence considerably lower the soldering process temperature.

This interconnection section describes the solutions for two-side contacted (mono- and bifacial modules). For back-contact cells a number of different approaches exist which are often developed jointly with the cells technology. A detailed review of the technologies and materials is available here [33].

Backsheet

The PV backsheet is designed both to perform as an electrical insulator and to protect the inner “active” components (i.e. solar cells and interconnections) from external stresses including UV radiation, daily and seasonal thermal cycles, operating temperatures up to 90°C or higher, as well as mechanical loads (due to snow and wind). PV backsheets typically follow a three-layer structure, comprising a core layer and two protective layers. Most core layers are based on polyester (i.e. PET) which alone offers a suitable and cost-efficient solution for electrical insulation and against moisture ingression. The core layer is sandwiched with the two protective layers (on the cell and air side respectively) which mainly protect the core from UV induced degradation and hydrolytic degradation.

On the basis of the material used in the latter, module **backsheets** can be classified in two groups; **fluoropolymers and non-fluoropolymers**. For products from the former group, either one or both of the protective layers are fluorine based; made up either by polyvinyl fluoride i.e. PVF (Tedlar® [34]) or by polyvinylidene fluoride, i.e. PVDF (Kynar® [35]). In a different approach [36], a so-called fluorine skin is used facing to the cell side of the backsheet and Kynar/PVDF film for the air side, thus providing sufficient UV protection, while avoiding the use of expensive fluoropolymer films on the cell side. On other hand, fluorine coating based alternatives [37], [38] are suggesting significant cost-efficiency, due to 50% lower consumption of fluorine, and reliability scores similar to the fluoropolymer film based products.

In the non-fluoropolymer segment, technological advances in polyester chemistry and film production engineering have enabled the development and commercialization of PET or polyethylene-based films [39], [40] or coatings [41] with enhanced UV stability, claimed with comparable protective attributes as fluoropolymer-based products [42]. Compared to fluoropolymer based products, backsheets with PET or polyethylene protective layers **come with about 20 to 30% lower price, however their long-term reliability in the field is not yet proven**, particularly in terms of UV stability and adhesion quality under harsh environmental conditions.

Apart from the above classification, another alternative [43] is a co-extrudedbacksheet. It employs a polyolefin (PO) film based core layer, with polyamide and polyethylene as protective layers at the air and cell side respectively. Material-wise, such solution may appear a “premium” and rather costly product. However, the co-extrusion technology, results in a faster lamination process, reduction in acetic acid as well as in mitigating potential induced degradation[295]. Instead of laminating pre-manufactured films with adhesives, these backsheets are produced in a single pass. This eliminates the need for pre-manufacturing of films, as well as solvent based adhesives. Furthermore, the thermoplastic character of the co-extruded backsheets makes them 100% recyclable and the polyolefin based core layer is more durable, having greater hydrolytic stability and crack resistance compared to the PET films used today. The more durable core layer also allows for elimination of the use of fluoropolymers in the outer layers. Today about 10 companies supply/develop co-extruded backsheets, all PO core layer based[296].

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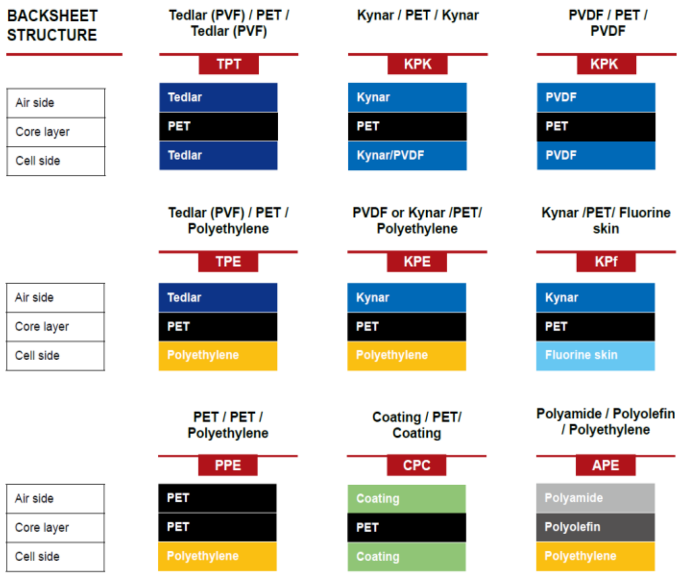
[295] *Kempe, M. Encapsulant materials for PV modules, chapter 10.2 in “Photovolaic Solar Energy”, Reinders et al. Wiley (2017)*

[296] *http://taiyangnews.info/reports/market-survey-on-solar-backsheets-2018/*

Focusing then on certain application-driven features transparent [38] and colored backsheets can offer an advantageous lightweight alternative for bifacial PV and BIPV applications respectively, compared to today's prominent though heavy glass-glass PV module designs. Moreover, backsheets with highly reflective layers [44] - towards improved light management – are being developed. Figure 102 shows the different PV backsheet configurations available today.

Figure 102: The different PV backsheet configurations available today.(Source: S.K. Chunduri and M. Schmela, "Market Survey on Solar Backsheets 2018", Public Report TaiyangNews)



Encapsulants

Next to PV backsheets, encapsulants play an equally significant role in preventing water ingress and/or dirt infiltration into the PV module structure, serving thus as an indispensable sealing layer for the solar cells. In addition, encapsulant layers on either side of the solar cell matrix, also act as shock- and vibration-protective shields. As such, in order to optimize PV module's performance and reliability, PV encapsulants should carry certain properties:

- Low light absorption and excellent transmission in the relevant spectral band (350–1200nm for c-Si technology), along with an adapted refractive index to minimize interface reflectance;
- High thermal conductivity, to minimize the operating temperature of the module, thus increasing its energy yield;
- Electrical insulation, against unacceptably high leakage currents;
- Durability against real-field environmental stressors, i.e. UV irradiation, humidity, thermal cycling, mechanical loads;
- Strong and uniform adhesive bonding towards the other module components;
- Cost-efficiency in terms of material, manufacturability and processing.

Selecting the appropriate encapsulating material is an important aspect in PV module design. In principle, encapsulant types be classified into two categories[297] [45]: i) non cross-linking thermoplastics or thermoplastic elastomers (TPE) and ii) elastomerics (forming covalent bonds between the polymer chains). Ethylene vinyl acetate (EVA) and two-component silicone and urethane (TPU) materials must be subjected to a crosslinking process which can be induced by high temperature levels or UV irradiation or via a chemical reaction.

Thermoplastic elastomers (TPE), polyvinyl butyral (PVB), thermoplastic silicone elastomers (TPSE) and ionomers, as well as modified polyolefines (PO), melt during the module manufacturing process without forming chemical bonds between the polymer chains (cross-linking). EVA particularly has been the exclusive PV encapsulant material for nearly 3 decades, thus being widely field-proven – with a solid record of long-term reliability – and a low-cost option as well. On the other hand, EVA's susceptibility to certain degradation mechanisms and the recent emergence of thin film and high efficiency solar cell technologies as well as new PV applications, has highlighted the need of introducing new PV encapsulant materials, e.g. the ionomers, the thermoplastics or the silicones.

[297] *C. Peike et al. (2013), "Overview of PV module encapsulation materials", Photovoltaics International.*

Of the alternative encapsulants, TPSE are highly impermeable to water and have good UV resistance, light transmission and electrical insulation properties[298]. Besides, since the cross-linking is performed via hydrogen bonds, TPSE-based PV modules offer better recyclability compared to the EVA-based ones[299]. Moreover, thermoplastic PO (TPO) encapsulants are interesting candidates for PV modules, in terms of cost-efficiency, having also high electrical resistivity and resistance against hydrolysis; whereas, they also present no degradation related to acetic acid formation, which is a common degradation mechanism in EVA-based modules. However, compared to EVA, TPO presents significantly higher water permeation.

In thin film glass-glass and building integrated PV (BIPV) applications, PVB emerges as a competitive alternative to EVA, featuring superior UV stability and better adhesion to glass. Last but not least, ionomer-based encapsulants were also introduced as highly competitive alternatives to EVA, particularly in terms of rigidity and durability against mechanical stresses, reduced lamination cycle time, as well as high electrical resistivity and resistivity against moisture ingression[300].

Front glass

In the PV module packaging the glass is the third critical element, which both determines its performance, durability and safety. The front glass in PV modules is tempered low-iron containing extra clear glass of 3.2 mm in general. Recently the use of antireflective coating has become wide-spread. Anti-reflective glass can enhance the PV module performance by 2-3% as measured in standard testing conditions [46]. The durability of this treatment, especially in harsh environmental conditions is under validation. In most European climate the quality suppliers warrant 10 years of lifetime for this treatment.

An initial screening suggests that repellent properties are combined with Anti Reflective coatings. Chemistries which have been used as AR coatings are mostly based on silicon dioxide and may include zinc oxide and titanium dioxide. The latter two substances lend the coating anti-soiling properties.

Anti-soiling and self-cleaning properties are under development and validation, they claim to improve the energy yield approx.1%/year. However this strongly depends both on the local soiling rate and PV system installation. The weight of 1 m^2 front glass [47] with 3.2 mm thickness is 8 kg and therefore it contributes the most to the weight of a commercial module (>50 %). Further weight reduction is possible with front glass thicknesses up to 2.8 mm being available.

Junction box and bypass diode

The junction box is an enclosure which contains and protects the cell strings of the PV module and their connection to the module's external terminals. Junction boxes are typically fixed on the backside of modules, using silicon adhesive. Inside a PV junction box, 4 connectors are wired together, comprising the output interface of the PV module; which, in turn, allows an easy and electrically safe connection of each PV module to the PV array, through cables with electrical connectors (typically MC4/MC5). An important technical specification of PV junction boxes is the so-called IP (i.e. "Ingress Protection") rating as defined by the EN 60529. For instance, a completely water tight junction box carries IP 67. However, IP 65 is still a common rating among standard PV junction boxes.

The principle function of PV junction boxes is to ensure that the generated DC current flows at the correct direction. This function is carried out by one or more (typically three) bypass diodes, which indeed protect solar cells of each sub-module (cell string) from becoming reverse-biased and overheated (hot spots), when shadowing or other electrical mismatches occur. Schottky diodes is the most common type used as bypass diodes in PV modules. Such diodes are highly susceptible to static high voltage discharges and mechanical stress. Thus, careful treatment, avoiding any ungrounded contact should be ensured. Yet, under real-field conditions, i.e. throughout PV modules' operational lifetime, several bypass diode failures [48][49]may still occur as a result of single or combined factors (e.g. lightning strikes, repeated activation and thermo-mechanical stress cycles due to shading, etc), which eventually result in a module power output loss by at least one third (assuming 3 bypass diodes per module).

Bypass diode failures evolve and often go undetected, especially in the case of large-scale PV plants with inverter-level monitoring, as they relate neither to visible (physical) degradation nor to significant drop in the system's DC current and overall power. However, bypass diodes failures can be related to increased temperature, resulting in inhomogeneous that, in turn, can be easily and timely detected with the use of standard infrared (IR) imaging equipment. Moreover, with the recent advance of drone technology, aerial IR inspections are efficiently applied to PV plants to detect and identify modules with

[298] Wiesmayer et al. Impact of Permeation Properties and Backsheet-Encapsulant Interactions on the Reliability of PV Modules, Renewable Energy 2012(1–4),DOI: 10.5402/2012/459731

[299] Peike et al. Overview of PV module encapsulation materials, Photovoltaics International Volume 19, 2013. https://www.pv-tech.org/technical-papers/overview-of-pv-module-encapsulation-materials

[300] Assessment of Photovoltaic Module Failures in the Field, Report IEA-PVPS T13-09:2017

bypass failures that require repair and/or replacement (decommissioning)[50][51] . The repair or refurbishment of most modules affected by bypass diode failure is technically feasible, by simply dismantling them and replacing the failed diode in their junction box[301] . However, access to the diodes maybe prevented by the junction box sealing or casing design and some diodes are now soldered potentially preventing easy repairing/replacement.

An alternative solution to mitigate the aforementioned risks of electrical mismatches (e.g. due to shading) in a PV module, is also offered by recently introduced "smart" PV modules[302]; which come with built-in intelligent cell optimizers (Maxim integrated), at cell-string level, that minimize the power output losses and the risks of hot spot formation, without the need of bypass diodes. Yet, module-level monitoring is technically non-feasible in such cell string-level optimization, in contrast to the case of module DC optimizer or microinverters.

Other junction box failures that are commonly observed in the field may include poor fixing/adhesion on the PV backsheet, open or badly closed boxes due to manufacturing defects, moisture ingression with follow-up corrosion of the connections and internal arcing or short-circuit due to erroneous wiring. In general, a quality PV junction box is certified for reliable long-term safety and sufficient heat dissipation in operating conditions.

4.1.2.3 Extended product scope: energy generation potential and reliability under non Standard Test Conditions (STC)

As mentioned, PV modules are rated (and sold) on the basis of their output power at STC; besides, their electrical efficiency is often perceived as a conclusive indicator of their quality. However, from a PV installation and financing perspective, the energy produced in the course of a PV module's operational lifetime is a key determinant for the return of investment (ROI). As a result, PV stakeholders are shifting from a (rather misleading) module power-based rating, to a more accurate and specific rating based on the module's expected energy yield, commonly referred as "**energy rating**" of a PV module.

With an extended product scope, PV modules are rated, classified and optimally selected according to their site- or climate-specific energy yield. In this direction, the recent IEC 61853 series establish those requirements that are taken into account when evaluating PV module performance based on power (W), energy (Wh) and performance ratio (PR, %). Energy Yield and Performance ratio have also been discussed in detail in Task 3. In brief, PV module energy rating consists of 3 basic sets of data:

- module characteristics at STC, i.e. power, irradiance dependence, temperature coefficients and spectral response;
- reference weather data (at least irradiance and temperature) for specific climates and configurations (tilt, azimuth, etc.) (see Task 3) and
- output data from detailed energy simulation(s) for the rated module(s) (see Task 3).

The lifetime for modules is for the purpose of this study defined as the time a module is used until the requirements of the user to provide a minimum of 80% of the initial rated power output is not fulfilled due to a degradation in performance and/or a product failure (see Task 1 report).

Given the current knowledge and state-of-the-art, energy yield predictions and module energy rating come with considerable uncertainties and limitations [52]. The latter are typically related to the influence of module's reflection and thermal response; but, most importantly, to the impact of long-term reliability, i.e. to the evolution of different degradation mechanisms and failure modes in PV modules and their components.

A significant number of research groups aspire today to establish accurate lifetime energy yield predictions for PV modules operating in the field, by means of simulation models. In overall, the current state-of-art modelling approaches can be divided into three main classes: finite element (FEM)[303], circuit-based and parametric modelling approaches. Table 1 below shows the strengths and the weaknesses of each class. Most tools for PV energy yield simulation are based on black box models, calibrated with semi-empirical parameters [53]–[59]. In principle, these tools still neglect the degradation of PV modules over time or, in the best case, assume steady-state losses (i.e. gradual or linear degradation), without any correlation to degradation rates or failure modes. Hence, the impact of different climate- and site- specific parameters (e.g. environmental stressors) is neglected, due to time granularity and/or due to specific non-realistic assumptions, e.g. uniform module temperature. One example of a model is the one developed recently by IMEC, being based on bottom-up physics models [60]–[63].

[301] http://www.rinovasol.com/about.html

[302] https://jinkosolar.com/product_355.html

[303] Finite element modelling (FEM) is a numerical method for solving problems of engineering and mathematical physics. Thermal behaviour of modules is modelled considering

Table 65. Comparison of different state-of-art approaches for PV energy yield modelling.

	FEM modelling	***Circuit-based***	***Parametric***
Extrapolation	+	-	--
Temporal variations	+/-	+	+
Non-uniform irradiance	+	+	-
Fast	-	+	++
Versatile	-	+/-	--
Physics – based	++	+/-	-
Accurate	++	+/-	+/-

However, if energy yield predictions and energy rating of PV modules are intended to give PV end-users (that are often non-experts) a clear and reliable indication of a PV module's long-term performance, then they must also include thorough insights into the impact of lifetime reliability issues of PV modules. Through the years, research community and industry gained significant experience in understanding and minimizing reliability issues related to "infant mortality" of PV modules [64]. There are a number of opportunities to minimise failures during the production process related to :

- Incorrect cell soldering
- Undersize bypass diode
- Visually detected hotspots
- Incorrect flash test
- Arcing in a module

Rigorous and extensive "design qualification" and "type approval" tests exist to control quality, as per relevant established IEC, ASTM and UL standards [65]–[68]. However, the existing framework of qualification testing provides neither actual lifetime expectancy of a PV module nor any correlation to the influence of degradation and failures on its lifetime energy yield.

Over the last five years, active research [69]–[75] and collaborative programs [76]–[80] shed light on identifying the most commonly experienced degradation rates, reliability issues and dominant failure modes of PV modules: module optical degradation (delamination, encapsulant discoloration), packaging materials failure (fractured glass/frame, backsheet delamination and/or loss of adhesion, bypass diode and junction box failures), electrical mismatches (cell cracks, snail trails, broken interconnections) and electrochemical degradation (potential induced degradation (PID), corrosion).

Independent of the climatic and site conditions where a PV module operates, some failure modes stand out in terms of resulting power losses on module and/or system level. However, these failures are difficult to be properly assessed by PV operators and asset owners because there is still very little information on when, how often and how severely such reliability issues will occur in real-world PV installations, under combined stress factors (e.g. heat, moisture, UV radiation) and site constraints (e.g. shading, soiling).

"PVlife", a reliability predictive tool developed by Mikofski et al. [81], [82], remains today at the forefront of PV reliability research, and claims to be able to determine long-term, temperature induced failures. However, it is adapted to PV modules that feature a particular type of commercial solar cells – the back contact products of US manufacturer Sunpower, as reviewed in section 4.1.1.2 - which differ significantly from those in common PV modules. Besides, it is an entirely proprietary model, hence cannot be considered as accessible state-of-the-art.

4.1.2.4 Recycling of PV modules

Market context

This section deals with the material content and possibilities to recycle crystalline PV modules in a circular economy perspective. End-of-life (EoL) management of PV modules in the EU Member States is regulated by the Waste Electric and Electronic Equipment Directive since its revision of 2012 (2012/19/EU). The transposition period for the different Member States concluded in February 2014 setting collection, reuse and recycling targets.

Collection, recycling and the financing of the future waste management is often coordinated by Producer Responsibility Organizations (PRO), such as PV CYCLE [83]. Small-quantity, household PV waste is collected by take-back infrastructures, being either certified collection points (such as in France and the UK) or municipality collection sites (such as partly in the Netherlands and Germany). For large quantities at professional sites or solar farms, tailor-made pick-ups can be arranged for on-site collection. CENELEC has developed a supplementary standard specific to PV module collection and treatment to assist treatment operators (EN 50625-4).

According to International Energy Agency (IEA) and International Renewable Energy Agency (IRENA) by 2030, the projected waste PV modules will amount to 1.7 – 8 million tonnes and 60 – 80 million tonnes by 2050 as per in 2016 for the low and high scenarios of PV deployment figures by IEA. Moreover, the EU WEEE directive requires 85% by mass of waste PV modules shall be recovered and 80% shall be prepared for re-use and recycled [86]. Currently, the dedicated recycling of both crystalline-Si PV modules and non-silicon modules is not feasible at a commercial scale with some limited exceptions. However, to improve the process efficiency, recovery and recycling rates, cost effectiveness, and environmental performance capabilities of these methods, several approaches have to be developed.

In the next 10-15 years, up to 80% of the PV module "waste" stream estimated by IRENA will consist of products with premature failures [84], such as production defects or damage from transportation and installation, instead of products reaching EoL. Therefore it has been estimated that about two thirds of these PV modules may be possible to repair or refurbish. Consequently, about 50% of the PV module "waste" can be diverted from the recycling path. In reality, the ratio will be even higher since decommissioned functional PV modules currently also enter the "waste" stream. Approaches are proposed to develop a global end-of-life treatment for PV modules where modules are sorted (with automatic recognition) and diverted between refurbishment and recycling paths.

Nevertheless, re-use, repair and refurbish remain rather informal in the PV industry today. These activities are currently performed by independent private companies, without any support from the original manufacturers. There are currently limited regulations or standards on the testing, certification and labelling of refurbished PV modules. The repaired/refurbished PV modules are often rebranded and sold largely to less developed electrified markets. A small portion is sold on European markets via e.g. online second-hand platforms. Since it is still an informal sector operating at small-scale and geographically specific (e.g. Germany), almost no data is available. More information is already available in the Task 3 report.There are several ongoing research initiatives in the area of PV eco-design, such as CABRISS[304] and Eco-Solar[305], aim at reducing resource consumption in PV production, increasing material/value recovery in PV recycling, and using recycled raw materials in new PV Modules. The most advanced achievement regarding design-for-circularity so far is the NICE glass/glass module technology developed by APOLLON SOLAR[306]. The module has no encapsulation material, no soldering and no lamination requirement. Therefore components can be recovered for further recycling or re-use.

Within recycling operations the PV modules are separated by module technology (silicon-based or non-silicon based) and sent for recycling[13]. PV module collections from small installations (e.g. residential installations or households) can pose a significant challenge due to their mixed brands and technologies in small quantities.

Recycling PV modules: technologies

Recycling technologies can be classified into bulk recycling (recovery of high mass fraction materials such as glass, aluminium and copper) or high-value recycling (recovery of both semi-conductor and trace metals)[307].

Currently the most common approach in PV module recycling in a bulk recycling using a crushing and grinding process after the removal of the junction box and the frame. With this method over 90% of the cSi PV modules by weight can be recycled[85][13]. A PV module is mostly glass and aluminium in weight and consists only a small amount of more valuable metals such as copper, silicon and silver. The market price of recycled glass cullets, often used for new glass products and glass insulation or glass foam applications, is at about €50 per ton at best and is subject to volatility. The raw materials (mainly glass cullet and scrap aluminum) recovered from PV module recycling amounts to less than €1 per module[308] As a result, PV recycling is a net cost to the value chain and strongly relies on subsidy from Extended Producer Responsibility

[304] CABRISS is a joint initiative of 16 European companies and research institutes and received approval by the EU's Horizon 2020

[305] Eco-solar is a joint initiative of 10 European companies and research institutes and received approval by the EU's Horizon 2020

[306] N.I.C.E.™ (New Industrial Cell Encapsulation), from https://www.apollonsolar.com/

[307] P. Sinha, S. Raju, K. Drozdiak, A. Wade, Life cycle management and recycling of PV systems, PV Tech, 2017

[308] Based on market price of scrap glass and aluminum

(EPR) schemes and directives. From crystalline PV modules the silicon itself is not recycled[13] with this approach for reasons mentioned in section 4.1.1.

Several alternative recycling approaches are under development that may allow for more sophisticated dismantling and segregation of the materials in a module. For example, the delamination of the glass from the cells has required the development of novel approaches to implement a high-value recycling. In the last few years, technology development and patents from different players are focused on the improvement of this step in particular[309,310]. After the removal of the junction box and framing, the delamination step using mechanical, thermal, chemical treatment and even more frequently a combination of them method are possible.

Optimized **thermal delamination** enables the intact recuperation of the Si wafer, which provides the highest value in recycling. However, this approach is expensive in low volumes and furthermore the incineration of fluorinated backsheet materials requires adequate safety measures.

Several **mechanical approaches** are investigated where either the cells are cut, scribing on the glass or non-glass is made, or a crushing/grinding process is applied. The first two approaches are more interesting where the low-Fe containing glass is kept intact and hence can be re-used in PV modules. Major disadvantage of the various mechanicals approaches that recuperation of full wafer is currently not possible. It is important to mention that in combination with chemical processing, the recovery of metal and Si pieces is possible. Low-cost and low energy consumption of this approach has made it the current technique of choice for several players on the market.

Chemical processes using selective etching enable the highest value recycling, but come at the expense of considerable chemical use and treatment costs. The most promising recycling approaches use a combination of these different techniques. In an example study the combined mechanical and chemical recycling enabled next wafer recycling the recovery of Cu and Ag (see the table below for the improvement in recycling rate).

Figure 103: Comparison of the efficiency of different recycling approaches (Dufluou et al.[311])

	Baseline scenario		Thermal and chemical scenario		Delamination scenario	
Material fraction	kg recov. /Tonne PV waste	% recov. (kg recov./ kg input)	kg recov. /Tonne PV waste	% recov. (kg recov./ kg input)	kg recov. /Tonne PV waste	% recov. (kg recov./ kg input)
Glass	532.94	89.6%	583.23	98%	583.23	98%
Aluminium	130.45	78.1%	144.10	86%	144.10	86%
Steel	80.14	92.7%	84.77	98%	84.77	98%
Copper	13.49	34.7%	33.06	85%	36.95	95%
Silver			0.917	74%	1.18	95%

In February 2016, PV CYCLE announced a new record in silicon-based PV module recycling, achieving a 96% recycling rate. Enabling the recycling of silicon flakes – a combination of EVA laminate, silicon-based semiconductors and metals – in a way which is both economical and environmentally sound, the advanced process is currently being applied at one of PV CYCLE's Europe-based recycling partners for silicon-PV [87].

4.1.2.5 Summary and reference data on the performance and cost of the products and technologies described

PV modules are based on a range of cells technologies which are evolving rapidly in order to improve efficiency and yield as well as with a focus on long-term performance and reliability. Following on from the reference year 2016, in which Aluminium back surface field technology can be seen based on its market share to be a suitable base case, it can also be seen that a number of competing cell structures have subsequently been commercialised and could be candidates for BAT.

[309] *G. Heath et al, IEA End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies, 2018*

[310] *K. Komoto et al., End-of-life management of photovoltaic panels: Trends in PV module recycling technologies. 2018.*

[311] *. R. Duflou et al, Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery, CIRP Annals, Volume 67, Issue 1, 2018, Pages 29-32*

These comprise: PERC family, heterojunction, back contact and bifacial technologies. One alternative that is not yet in the market are epitaxially grown silicon cells that could be considered as a potential candidate for BNAT. Another alternative under R&D is a heterojunction cell based on silicon and perovskite thin film, this is discussed further in the next section.

Beyond the cell technology a number of developments can be identified that relate to the module design and components such as improved and reduced silver/lead content interconnections, the UV protection provided by the backsheet, highly impermeable and UV resistant encapsulants, anti-soiling and self-cleaning front glass, and easily repairable junction boxes and bypass diode.

Current PV modules on the market are not designed for circularity (meaning easy disassembly, repair, refurbishment and recycling). They are not usually designed to be "re-opened" and the only way for recycling to take place is through destructive processes such as shredding. Such irreversible design severely limits not only the potential for repair/refurbishment, but also the recovery of valuable materials. There are only currently limited examples of module design to support ease of disassembly or dismantling for recycling.

In summary based on the previous sections, Table 66 displays possible combinations of design improvements at cell level and module level. The cell technology is proposed as starting point for making the combinations because it is fundamental to achieving performance improvements in yield.

Table 66 Base case and design options for the improvement of crystalline PV modules

	Base case (2016)	cell-PERX	cell – SHJ	Additional cell-designs	
				cell- Bifacial	cell- Back-contact
Cell technology	BSF	PERC, , PERT, PERL	SHJ	PERC, PERt or IBC (mostly)	IBC, MWT, IBC-HJ
Module efficiency	14.7% (PEF)	18.65% (72 cells) 19.6% (60 cells)	19.7%	+10-20% compared to monofacial modules	25%
Cells per module	60	60-72	96	60-72	60
Performance degradation rate (% per year)	0.7%	0.5%	1%[1]	0.5%	0.32%[2]
Failure rate modules (%/year)	0.005-0.2%[3]	TBD	TBD	TBD	TBD
Power Temperature Coefficient (%/°C)	- 0.40	-0.37	–0.258	-0.37	–0.29
Module power density (Wp/m²)	~ 155-160 (60 cells)	191.5 (72 cells) 195.8 (60 cells)	197.1	210 (72 cells assuming 10% gain) 215,4 (60 cells assuming 10% gain)	211.6
Silicon (g/m²)	0.638	0.595	0.38315	0.595	-
Compatible with epitaxial wafer	Yes but not yet available.				
Compatible with Pb-free metallisation	Yes. Just being commercialised		Yes and available		Yes. Just being commercialised
Compatible with reduced Ag metallisation	Yes		-		
Compatible with F-free backsheet	Yes		Yes	No yet.	Yes
Cost (EUR/Wp)	0.48	+0.1[4]	+0.2[65] ?	+0.14[5]	+0.02[5]

Notes

1. Jordan et al., Progress in Photovoltaics, 2016.

2. Mikofski et al., Integrated Model for Predicting PV Performance Degradation over 25+ Years, Sunpower White paper.

3. Kurtz S. NREL, reliability and durability of PV modules in Photovoltaic Solar Energy: from fundamentals and applications, John Wiley and Sons, 2017.

4. IMEC professionals judgement.

5 Judgement of imec PV experts, in view of the PV module price index (https://www.pv-magazine.com/features/investors/module-price-index/), based on pvXchange (https://www.pvxchange.com).

4.1.3 Thin-film module technologies and materials

4.1.3.1 Strict product scope: performance

Technology and performance

At present, it is understood that given the market economics it is not possible to make a viable business case for products with module efficiencies below 12%. As a consequence, thin film silicon (either in the form of a-Si, microcrystalline Si, tandem of triple junctions) is rapidly declining in the market, despite the multi-billion investments in upscaled mass production facilities led by Applied Materials and Oerlikon at the turn of the decade. Also dye sensitized solar cells (DSSC) and organic photovoltaics (OPV) so far failed to take this 12% hurdle, and up to this date no substantial scale production was achieved. The two thin film technologies that are able to commercially deliver high performance and yield are CIGS and CdTe.

At this moment, there are only two thin film PV producers on a GW/year scale: First Solar (US) with CdTe on glass (17-18% efficiency), and Calyxo (13% to 15.4). Solar Frontier (J) with CIS (ca. 15%-15.4% module) and CIGS on glass (11-17 % efficiency) with CIGS on glass. Both of these products have improved temperature coefficients and spectral response when compared to mainstream crystalline technologies which under certain conditions can improve the yield. Both are in the process of restructuring their production, aimed at short term cost reductions of 20-40%. Of the latter two technologies, First Solar has managed to achieve through successive generations of cell improvements the highest commercialized product efficiencies. The declared module efficiency of the latest series 6 is up to 18%[312].

At some distance to these market leaders, over a dozen producers can be identified with individual manufacturing capacities up to hundreds of MWp/year. However, it should be noted that thin film PV is a declared part of the Chinese PV roadmap, and companies like CNBM, Hanergy and Shanghai Electric are leading a larger group of emerging thin film investors. CNBM alone expressed a 15 GWp ambition based on CIGS and CdTe for the coming years, and started up production on several 100MW scale in the last quarter of 2017. Hanergy has a few companies in their portfolio (MiaSolé, Solibro and Global solar) providing flexible CIGS with high module efficiencies. These products (CIGS on stainless steel foil) are well designed for integration in BIPV products.

GaAs and III-V multijunction devices in general do not yet contribute substantially to earth bound PV electricity production, but have a dominant and proven market position for space applications. Thin film production based on III-V may be brought to larger scale through lift-off techniques enabling re-use of expensive substrates for epitaxial growth. Notable example of such an attempt is the development of a roll to roll lift-off process by Hanergy owned by Alta Devices (US). Another route for more substantial earth-bound application of III-V utilizes their high conversion efficiency under concentrated sunlight conditions, by incorporating them in low cost solar concentrator devices.

Perovskite based thin film PV is not yet in production, but this technology has made remarkable progress in the past few years. Because of its potential of very low cost production, and its suitable bandgap for tandem formation with crystalline silicon, it could be (or pave the way for) a significant and disruptive technology PV energy generation.

For perovskite solar cells, a distinction is to be made for a future with or without lead content. A potential disadvantage of perovskite PV modules is that they currently contain a small amount of lead: approximately 0,5 g/m². This is less than the amount of lead in the junction boxes currently also used for crystalline PV. But because lead could end up in the environment if a solar module were to become damaged and there was water ingress into the module, the extent of the resulting harm and how it could be reduced should be further investigated. Tin, and also the less harmful bismuth are under investigation as a lead replacement. Perovskites could potentially match the functionality of CIGS which currently is virtually unlimited in its applicability to all types of use, on rigid glass as well as on flexible foil.

Regarding the perovskite/Si tandem, recently the start-up Oxford PV has gained a lot of attention by their results showing that the tandem configuration has the potential to outperform single junction Si PV with efficiencies over 22%. They have acquired a production facility in Germany targeting tandem pilot production by 2019-2020.

Thin film technologies are claimed to offer significant improvements in material efficiency when compared to wafer based crystalline technologies. This is because it requires inherently less material and because the production processes are based on vapour deposition on a substrate rather than on the cutting of silicon ingots, which incurs material losses. However, these efficiency gains must be balanced against lower cell efficiencies because of the heterogeneous cell structure. These cell types could have environmental and/or resource efficiency benefits and therefore are an improvement option to explore

[312] *First Solar Series 6 Datasheet, available at: http://www.firstsolar.com/en-EMEA/-/media/First-Solar/Technical-Documents/Series-6-Datasheets/Series-6-Datasheet.ashx*

later in Task 6. The environmental benefits of these cell types can be understood better with reference to the findings of the LCA review in Task 5.

Recycling of Thin film PV modules

Thin-film CIGS and CdTe modules are comprised of 89% and 97% of glass, respectively which enables a higher recycling rate. Their recycling can be conducted through bulk or high-value recycling. For example, the US-based producer of CdTe modules, First solar, provides a circular management of their PV modules. Their recycling process is operational at industrial scale since 15 years and achieves high recovery rates: it is reported that up to 90% of the semiconductor material can be reused in new modules and 90% of the glass can be reused in new glass products [88].

4.1.3.2 Extended product scope: energy generation potential and reliability under non Standard Test Conditions (STC)

Some other advantages claimed for thin film PV, sometimes for specific applications are the following:

- Lower temperature coefficient

Every PV module shows a decreasing efficiency with increasing operating temperature, described by the (negative) temperature coefficient. In general, all thin film PV technologies have lower temperature coefficients than crystalline silicon. This gives them an advantage in applications with higher average operating temperatures.

Depending on average operating temperatures over the year, this leads to higher electrical energy output in kWh/Wp when comparing thin film and crystalline PV with the same nameplate efficiencies under standard conditions (25^0 C). First Solar claims up to 3% higher output with respect to Si when averaged over the lifetime period.

- Reduced shading loss

A general consequence of monolithic integration of thin film modules, is that they are more tolerant to partial shading than strings of Si cells. Shading of one single cell reduces (stepwise) the total current of an entire string, while monolithically integrated thin film modules only show gradual decrease of total current when increasing parts of the module are shadowed (as long as none of the cell lines is fully covered).

This effect has been shown to lead to notable advantages in PV application on ground and on roofs. For First Solar (focused on utility scale PV on ground) it is an essential element in their strategic choice to reduce BOS costs by going to more densely packed fields of larger size modules.

- Spectral response advantage

There is now more substantial evidence form the field of an advantage of thin film over crystalline silicon in terms of the spectral response under different illumination and weather conditions, averaged over a year of operation.[313,314,315,316] Under specific climate conditions or module orientations this leads to power outputs which are higher than would be expected under standard certification conditions, as a consequence of response to varying spectral light compositions and angles of incidence (direct/diffuse lighting). Manufacturer First Solar has indicated that based on the use of a commercial software a relative advantage in kWh/Wp energy yield when compared to performance under standard test conditions of 0,5% to 7,5 % for important parts of the world.

- Climate conditions/ relative advantage in kWh/Wp energy yield

To market the thin film CdTe product around the globe, First Solar combined these annual yield advantages as a function of climate conditions in a world map.

[313] *Dirnberger, Daniela, Gina Blackburn, Björn Müller, und Christian Reise. Solar Energy Materials and Solar Cells 132 (Januar 2015): 431–42. https://doi.org/10.1016/j.solmat.2014.09.034.*

[314] *Schweiger, Markus, Werner Herrmann, Andreas Gerber, und Uwe Rau. „. IET Renewable Power Generation 11, Nr. 5 (12. April 2017): 558–65. https://doi.org/10.1049/iet-rpg.2016.0682.*

[315] *Alonso-Abella, M., F. Chenlo, G. Nofuentes, und M. Torres-Ramírez. Energy 67 (April 2014): 435–43.*

[316] *DeLong, Nicholas, und Geoffrey Rich. Conference Paper. 40iest PVSC, 2015.*

4.1.3.3 Summary and reference data on the performance and cost of the products and technologies described

There are two main technologies that could be considered as BAT because they provide a yield comparable in some cases with silicon based PV technologies. The highest declared yield for a commercially available technology is provided by CdTe cell type. Claims from manufacturers that the material efficiency of the thin film production process outweigh the lower yield compared to the best performer crystalline cell are to be analysed further in Task 5.

On the other hand, perovskite technology either on its own or in tandem with crystalline silicon cells has the potential to provide material efficiency and high yield that could be considered as BNAT since it is not yet being commercialised.

In summary based on the previous section, Table 67 displays possible combinations of design improvements for thin film PV modules.

4.1.4 Inverter technologies

4.1.4.1 Introduction to grid coupled photovoltaic inverter technology with standard performance

Photovoltaic inverters are all power conversion equipment (PCE) for use in photovoltaic (PV) to convert electrical power of a PV module to AC. If separated devices are required to do this conversion, the inverter is defined as the sum of the required devices. Examples include PV-string inverters with included MPP-Trackers, the combination of a DC optimizer plus the inverter in systems where both are necessary, micro inverters, etc.

Inverter performance and energy efficiency

The basic function of a solar power inverter is to convert the variable direct current (DC) output of a photovoltaic (PV) solar module into a utility frequency alternating current (AC).

The Euro Efficiency is an averaged operating efficiency over a yearly power distribution corresponding to middle-Europe climate. This was proposed by the Joint Research Center (JRC/Ispra), based on the Ispra climate (Italy), and is now referenced on almost any inverter datasheet. The value of this weighted efficiency is obtained by assigning a percentage of time the inverter resides in a given operating range.

Euro Eff = 0.03 x Eff5% + 0.06 x Eff10% + 0.13 x Eff20% + 0.1 x Eff30% + 0.48 x Eff50% + 0.2 x Eff100%.

The inverters have special functions adapted for use with photovoltaic arrays, for example a maximum power point tracking (MPPT) and an anti-islanding protection function.

The aim of the **maximum power point tracking (MPPT)** function is to obtain the maximum possible power from the PV array. The yield from solar cells has a complex weather dependent relationship between the solar irradiation and temperature. Therefore, the converter needs a real time MPPT control system to obtain the maximum yield out of the cells. Optimisation of MPPT trackers is still an area of research and can make a difference depending on the algorithm such as Perturb & Observe method or incremental resistance method. The **MPPT efficiency** can be quantified according to a standard (see Task 1).

Table 67. Design options for the improvement of thin film PV modules

	CdTe	CIGS	BNAT	
			Perovskite	**Perovskite/Si tandem**
Cell technology	CdTe	CIGS	Perovskite	Perovskite/SHJ, PERx
Module efficiency	18.0% (PEF)	15.0%	>22%	>28%
Cells per module	Monolithic	Monolithic	Multijunction	60-72
Performance degradation rate (% per year)	1.0%	1.0%	-	-
Failure rate modules (%/year)	0.2%	0.2%	-	-
Power Temperature Coefficient (%/°C)	- 0.32	-0.36	-	-
Module power density (Wp/m²)	146-180	130-170	-	-
Silicon (g/m²)	-	-	-	Dependant on tandem
Scaling of module size		Passivation, reducing absorber thickness	Overall raising of MRL	Integration of perovskite processing on Si PV cell
Compatible with epitaxial wafer	Not applicable			Potentially
Compatible with Pb-free metallisation	Yes. Just being commercialised		Lead-free designs are still at R&D stage	
Compatible with F-free backsheet	Glass-glass	Glass-glass	-	
Cost (EUR/Wp)	<0.18	<0.22	<0.09	<0.35

Categories of Inverters

Depending on their rating (kVA) and application several **categories of inverters** are on the market as defined in Task 1 and 2, which technologies is discussed hereafter briefly.

One category of inverters that is mainly used in utility-scale power plants are **central inverters** (see Task 1). They have a rated capacity up to 4 MW and a euro efficiency that varies between 97.5% and 98.6% [1]. In architectures using central inverters, strings are parallel-connected in DC combined boxes; then the output of such combiner boxes are connected to the central inverter. Central inverters typically have one MPPT. The main disadvantage is that mismatch losses increase whenever the system is working under non-uniform conditions, such as partial shading along with higher installation cost and larger inverter footprint. Main advantages are simplicity in design and connection, and low O&M overhead [93].

Another category of inverters are **string inverters (see Task 1).** String inverters have a wide range of capacities, from few kW up to 166 kW-AC, that makes them suitable for all kind of applications: from residential to utility-scale. Single-phase string inverters have a capacity of up to 6 kW, thus they are mainly used in residential applications. Commercial and utility-scale PV systems use instead three-phase string inverters. String inverters deployment in utility-scale PV systems is becoming the new trend for certain applications. The continuous decrease of cost, together with the increase of voltage (up to 1500 V) during the last years drove such a change. The euro efficiency of string inverters typically varies between 95% and 98.2% [94]. String inverters usually have multiple input channels, each channel implementing an independent MPPT.

This reduces mismatch losses in comparison to central inverters. However, architectures based on the use of multiple string inverters are still more expensive. High-power string inverters (125 to 166 kW-AC) usually have a single MPPT tracker.

DC power optimizers and microinverters together known as **Module-level power electronic (MLPE) converters,** are mostly used in residential and commercial application. Whereas it is not deployed in utility-scale PV systems, they are a fast growing market segment in solar industry (see Task 2). **Performance improvement with MLPE is expected when one or more modules may be shaded or modules are subjected to different irradiation levels,** e.g. when modules are installed in different orientations, or there is shading from the environment (e.g. from a chimney, or a tree) or a module mismatch on PV system performance. The two main classes of MLPE are [95]:

1. **String/central inverters with module-level DC power optimizers**: small DC/DC converters are installed on every module to perform module-level MPPT. Then, outputs of power optimizers are connected, usually in series, to the string inverter. The largest manufacturer of such devices is SolarEdge that recently presented a new single-phase string inverter designed ad-hoc for such application [96]. The main advantage of such solutions are:
    - Module-level MPPT.
    - Safety requirements as rapid shutdown implemented per module.
    - Monitoring per module.
2. **Microinverters** represent an alternative to the use of power optimizers and string/central inverters. They perform both MPPT and DC-to-AC conversion per module therefore providing the same advantages in euro efficiency terms as an optimiser at module-level. The main advantages of microinverters are:
    - Independent functioning: if there are problems with one of the modules or one of the microinverters into the system, the other modules keep on working normally.
    - The use of microinverters implies that there are no points with high DC voltage in the system, thus enhancing safety.
    - Monitoring per module.

    The main disadvantage nowadays is represented by their high cost. The largest microinverter manufacturer nowadays is Enphase Energy. Enphase microinverters euro efficiency is declared at 97.5%[97]. They are designed for connection to a single module, thus they have a single input channel. A different approach has been followed by manufacturer AP systems, that produces microinverters that have multiple MPPT channels (2 or 4)[98], so that multiple modules can be connected independently at the various channels. The euro efficiency of AP systems microinverters ranges between 94% and 96%. The temperature resistance of MLPE is also a critical parameter to consider. As the modules are installed on roofs, considering the temperature resistance helps preventing degradation, reduced lifetime or adjusting the conditions of the guarantee. The operating temperature range of MLPE should be aligned with temperature observed on roofs (65°C-85°C).
3. **DC/DC Optimisers** are a slightly different concept than SolarEdge DC-DC MPPT optimizers plus fixed-voltage inverters. The MPPT is still done by the string inverter for the full string, and the optimizer adjusts the current of modules deviating from the main direction of the PV plant. These MLPE can be used with various inverters and need not be installed on every module of a PV installation - in contrast with installations based on microinverters.

As mentioned before the euro efficiency in standard conditions of these photovoltaic converters is high (>95 % peak). The achievement of a **higher inverter efficiency** today and the differentiation on the market is due to the availability of new power components in the field of semi-conductors and magnetics, as well as to different power topology designs depend on the following:

- 80% of losses takes place in switching of power semiconductor like IGBT and AC inductors [99].
- The number of levels in the converter topology causes a difference in efficiency
- Cooling methodology of these power semiconductor devices like air-flow

For designing PV inverters more than 50 topologies are known and/or on the market today [100]. Improving the efficiency at high load results in an oversizing of parts: more copper, semiconductors with more silicon and an increased cost. The efficiency improvement at no load levels is achievable with: a better design with smarter digital control, reduction of energy losses and reduction in auxiliary circuits" (internal power supply, fans, coils, etc.), improved bleeder resistor circuits, diode and transistor leakage currents and lower magnetic losses with improved magnetic materials for inductors and transformers. The purpose of a bleeder resistor is to discharge filter capacitors when the equipment is turned off for safety

reasons. For energy savings the bleeder resistor should be disconnected under normal operation, but this comes at the extra cost of a more complex circuit. The same might apply to inrush current protection circuits to protect the DC bus capacitors.

In general, PV inverters found today on the market are at the state of the art in energy efficiency and have most of these improvement options already to a high extent. This is probably due to the high value of PV generated electricity and the market awareness already for inverter efficiency. Despite this, there is still some differentiation in inverter efficiencies that can be found in the market. The most known and complete database of PV inverter efficiency is the **PHOTON** database[317]. Future inverters can still be expected to become more efficient due to new **wide bandgap semiconductors** (WBG), such as silicon carbide (SiC) and gallium nitride (GaN) used in MOSFETs[318] [101], [102]. Apart from being more efficient they will have a positive impact on the volume and weight of the cooling and housing.

In terms of power electronic converter technology, and bill of materials photovoltaic inverters, sources of failures and lifetime issues are considered to be similar to Uninterruptable Power Supplies (ENER Lot 27), LED or fluorescent lamp drivers (ENER Lot 19) and motor drives (ENER Lot 30).

Protection methods implemented in Inverters

The role of the **anti-islanding** protection function is to protect power system equipment, utility workers and allow to disable the PV inverter, in case, grid enters into island condition. In its absence and during a grid fault, the feeder continues to be energized if the load matches the PV generation making safety and reliability concerns [89]. Therefore, the anti-islanding protection will shut down the PV inverter within 2 seconds when a grid anomaly is detected such as a fault. It is an important function in grids with distributed generation, for photovoltaics mainly systems installed in the low voltage distribution system (230 VAC).

Another function sometimes added to inverters is a **frequency control** function. This function will limit the injected power in case of oversupply and grid unbalance. It depends on the local grid code and the size of installation to determine the requirement of this function. The response to frequency deviations of devices connected to the network can potentially have an adverse impact on the operation of the power system. In 2005-06, Germany introduced a requirement that all generating plants connected to the low voltage network, including PV, must switch off immediately if power system frequency increased to 50.2 Hz [90].

Similarly most inverters have a **grid overvoltage** control function, which limits the power injection at high grid voltages. The overvoltage control function is important in congested low voltage distribution grids. Therefore, if the voltage reaches to 1.10 per unit because of PV injection then the inverter will be disabled automatically. It has an impact on the performance ratio, see Task 3. This function is sometimes combined with a **reactive power injection** function. The reactive power injection function or Q on-demand can remediate grid over-voltages and help in reducing the burden on utility grids. However, it will decrease the operating efficiency of the inverter and therefore affect the performance ratio, see Task3.

Under standard conditions, inverter efficiency is defined at unity power factor or in other words without reactive power injection. If there is a requirement from the grid operator to foresee reactive power compensation, this can result in an inevitable need to either oversize the inverter in order to supply both peak active and reactive power or to decrease the efficiency.

Moreover, the input voltage and current range of the inverter should match with the expected output of the modules, which will impact the Performance Ratio (see Task 3). It is the role of the PV system designer to select the correct inverter and to avoid this loss of performance (see Task 3). A monitoring function can reveal such a mismatch between the input current and voltages and expected output.

The **earthing and the galvanic isolation** of PV system are other important aspects which relate to safety of a device and personnel, insulation safety requirements as well as protection against failures due to overvoltage induced by lightning [91]. There are mainly two different inverter connection technologies and therefore, protection (isolation) schemes. Therefore, according to the isolation there are two types of photovoltaic inverters that can be found in the market:

- **Inverters with transformers** provide galvanic isolation from the grid and operate at either low frequency (50 Hz) or high frequency. These are utilised with the grounded PV modules. Nonetheless, the transformers cause additional losses and especially decrease efficiency at low yield due to the no load losses of these transformers. These inverters with transformers have usually an Insulation Monitoring Device (IMD) incorporated that will shut down the inverter only in case of an insulation failure (e.g. water infiltration).

[317] https://www.photon.info/en/photon-databases

[318] Metal oxide semiconductor field effect transistor (MOSFET)

- **Transformer-less inverters** provide no galvanic isolation to the PV modules to the grid that means a failure in the dc side of modules will propagate to the ac side and therefore, trip its residual current detector (RCD). An important benefit of these inverters is their higher efficiency. A design challenge for the transformer-less inverters is to prevent the DC fault current from being supplied to the AC grid since they do not have electrical isolation between DC and AC circuits. This may raise some grounding and/or lightning protection concerns [92].

Apart from heat and humidity, the earthing concept and the voltage of the PV cells relative to earth potential can have an impact on Potential-induced degradation (PID).

There is a trade-off between efficiency and system reliability when choosing between an inverter with or without transformer. Therefore, **when considering inverter efficiency,** later on, **one has to compare both types of inverters**.

Lifetime and inverter failures

For inverters the **lifetime** is defined as the time span for which an inverter is considered to function as required, under defined conditions of use, until for the specific type of inverter an unacceptable level of failure is reached, the level of which is to be defined.

It is important to note that the system level lifetime prediction should be calculated accurately using both quantitative and qualitative lifetime modelling in order to give preciseness to the prediction. These three factors play an important role in predicting system lifetime:

- Junction temperature (solder fatigue due to uneven current distribution at solder joint)
- Gate oxide breakdown (Gate failure due to higher electric field across oxide)
- Body diode degradation (Diode failure due to high variation of voltage in time)

Field failure studies performed on different PV systems (residential, commercial and utility-scale ones) have shown that PV inverter failures represent the main reason for a PV system failure. The inverter is cited as being responsible by far for the largest percentage of service calls between 43% and 70%, which leads to higher maintenance costs and lost power production [103] . The inverter has also been reported to be the greatest factor leading to energy outages, responsible for up to 36% of the energy loss.

Inverters are composed of different components the failure of each can result in downtime and power loss of the inverter. Table 68 presents an overview of rates of failure of inverter components. According to field studies, the key components that have the higher rate of failure and likely lead to inverter replacement are PCBs, solid-state switching devices and capacitors [73][103]. Other components as AC contactors, fuses, fans also have high rate of failure. However, they mainly imply repair of the inverter rather than replacement.

Among all sources of failures, 55% of failures in PV inverters are reported to be thermally induced. This is because of the irregular thermal profiles and the mismatch of the thermal expansion coefficient leading to mechanical stress to bond wires and solder joints [108]. To overcome this, SiC MOSFET based power modules have been given attention in comparison to Si based inverter because of their better performance in high power applications, high temperature tolerance, lesser volume and high efficiency.

Another frequently occurring failure mode identified is related to control software or firmware. It is significant enough to be the first or second greatest cause of power loss events for inverters, and could be linked to some of the components failures identified in Figure 104 and Table 68.

One should be aware that during the last decade power electronics have progressed significantly and inverter designs have been upgraded. Therefore failure statistics found today for installed products are not necessarily representative for new products. Inverter failures do not necessarily imply inverter replacement. According to an IEA Task 13 report on financing[104] (p. 52), the life of an inverter is considered to be between 10-15 years. According to that report the technical lifetime of the PV system in general and the inverter follows a so-called bathtub failure profile with more 'early life' and 'wear out' failures in the beginning and the end.

Figure 104. Inverters components that fail, from PV System Reliability: An Operator's Perspective, Golnas and Voss, SunEdison

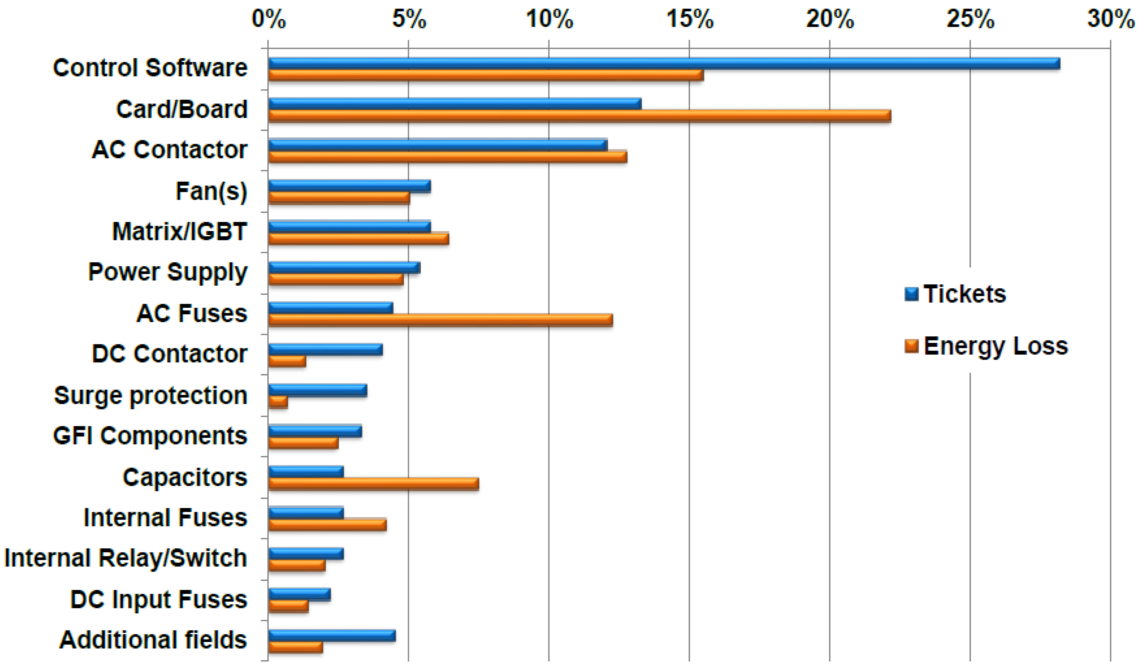


Table 68 Frequency of failure tickets and associated energy loss for each general failure area [105]

Inverter Failure Area	% of Tickets	% of kWh lost
No-Fault-Found Failures	28%	15%
Card/Board	13%	22%
AC Contactor	12%	13%
Fan(s)	6%	5%
Matrix/IGBT	6%	6%
Power Supply	5%	5%
AC Fuses	4%	12%
DC Contactor	4%	1%
Surge Protection	3%	1%
GFI Components	3%	2%
Capacitors	3%	7%
Internal Fuses	3%	4%
Internal Relay/Switch	3%	2%
DC Input Fuses	2%	1%
Other	5%	2%

One should be aware that during the last decade power electronics have progressed significantly and inverter designs have been upgraded. Therefore failure statistics found today for installed products are not necessarily representative for new products. Inverter failures do not necessarily imply inverter replacement. According to an IEA Task 13 report on financing [104] (p. 52), the life of an inverter is considered to be between 10-15 years. According to that report the technical lifetime of the PV system in general and the inverter follows a so-called bathtub failure profile with more 'early life' and 'wear out' failures in the beginning and the end.

PV inverter warranties depend on the technology and the rated power, as well as on the manufacturer. Standard warranty of string inverters is 10 years [106]. However, some manufacturers offer an extended warranty up to 15 or 20 years. Also,

there are still some manufacturers giving only a 5 year warranty, mainly on high-power inverters. The warranty of microinverters from APsystems is similar to the one of string inverters (10 years standard with optional 15-years extension). However, microinverters from Enphase have a 25 years warranty. This warranty for the hardware costs only may have a limited value, as the labour costs for the exchange on the roof may be largest costs. It has also to be noted that such micro-inverters have only been deployed in the field for a few years, thus there is no proof of such a long lifetime. Larger central inverters are modular and on site repair is a common practice, often forming part of a service contract (see Task 3).

Ensuring longer lifetime is also important because after 10-15 years from the date of installation it may be not possible to find an equivalent replacement having the same form, or fit, or functionality. As an example from the past, the typical rated voltage of utility-scale central inverters has changed from 600 V to 1500 V in ten years [107].

A longer lifetime can be achieved in different ways. Reducing the total number of components usually leads to increased reliability, given the less possible points of failure. Wide-bandgap technologies as Silicon Carbide (SiC), that can handle higher voltages compared to current semiconductor devices, might enable simpler inverter topologies. However, as already stated before, the lifetime of SiC transistors still needs to be proven, although some literature studying lifetime prediction for SiC-based inverters is becoming available recently.

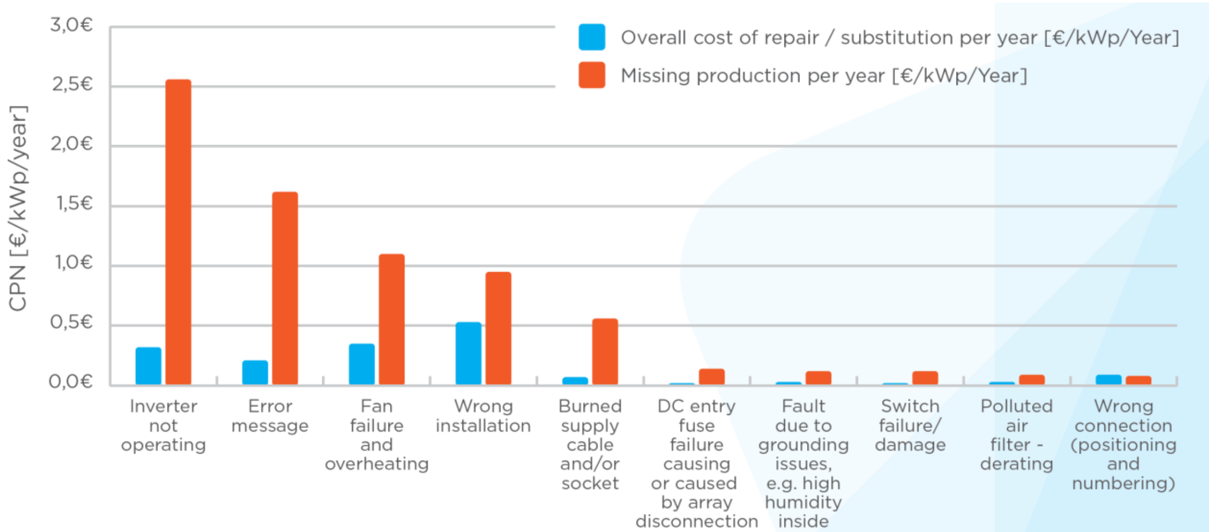
Proper selection of electrical components, both active and passive, is core to ensure longer lifetime. The rated current and voltage of each component must be selected according to worst-case analysis and taking into account both normal and abnormal operating conditions, e.g. higher operating temperature due to issues with the fans or dust entrance, as well as the interaction between the components within the inverter during operation. Ratings must be good enough to ensure the longest lifetime of each component.

PV inverter repairability

The availability of an inverter is a number based on the reliability and repairs, and there is an operating cost to secure a given availability of inverters. A higher repairability is desired to minimize unplanned or unexpected outages, and minimize repair and power restoration times. While it is economically impractical to attain inverters that never fail or need maintenance, or achieve 100% availability, the impact of inverter outages on the revenue streams of PV projects must be recognized in any case. These aspects motivate the use of reliability testing and quality standards utilizing quality management principle to reduce the unpredictability of operating costs for owners and operators. As it was identified in the previous section there are certain components of the inverter that favour repair rather than replacement. These are understood to include AC contactors, fuses, fans which can have a relatively high rate of failure.

For some of these components the possibility of repair/replacement may depend on their significance according to potential performance losses. As can be seen in Figure 105, the cost of inverter repair is in general relatively low when compared with the output losses (see also Figure 101 in which the situation is the reversed).

Figure 105. Costs during operation and maintenance (CPN), repair costs ($CPN_{failure\_fix}$) and performance losses ($CPN_{never\_detected}$) for top 10 risks for PV inverters of all system sizes. Source: Solar bankability, 2017.



Besides internal damage, which can often be lead back to component fatigue, lightning and overvoltage can be the cause of damage. If your inverter breaks down because of lightning or overvoltage, the insurance company usually answers for the damages. Within the warranty period, internal damage is born by the manufacturer. An inverter damage report will provide a clear indication on the cause of damage and damaged components. Besides internal damage, component fatigue, lightning and overvoltage can be other causes of damage. If the inverter breaks down because of lightning or overvoltage, the damage would usually be covered by an insurance company. Within the warranty period, claims relating to internal damage are born by the manufacturer[319].Besides internal damage, which can often be lead back to component fatigue, lightning and overvoltage can be the cause of damage. If your inverter breaks down because of lightning or overvoltage, the insurance company usually answers for the damages. Within the warranty period, internal damage is born by the manufacturer.

Recycling of inverters

This follows the same route and procedures as other power electronics that are in the scope of the WEEE Directive [111] and to our knowledge there are not currently any relevant exemptions for hazardous substances (ROHS Directive) to be mentioned here. The majority of the bill of materials of an inverter consists of the external housing made of sheet metal which could be steel or aluminium, aluminium heat sinks, and the internal structure. Commentators suggest that plastic housing may be used in the used in the future with polycarbonate cited, which may create challenges for recycling. Then, in terms of the electrical components, the inductors, circuit board and connectors contain metals of higher value. And it is these components could be the target for ease of dismantling for the purpose of recycling.

Monitoring function added in the inverter

Adding performance monitoring to the inverter is also an improvement option. Ideally, proper monitoring and diagnostics would support a decision for repair vs. replacement. The benefits were already discussed in Task 3 and will also be discussed in a later section on system performance.

4.1.4.2 Introduction to grid coupled inverters with combined battery storage function and prospect for future DC grid applications

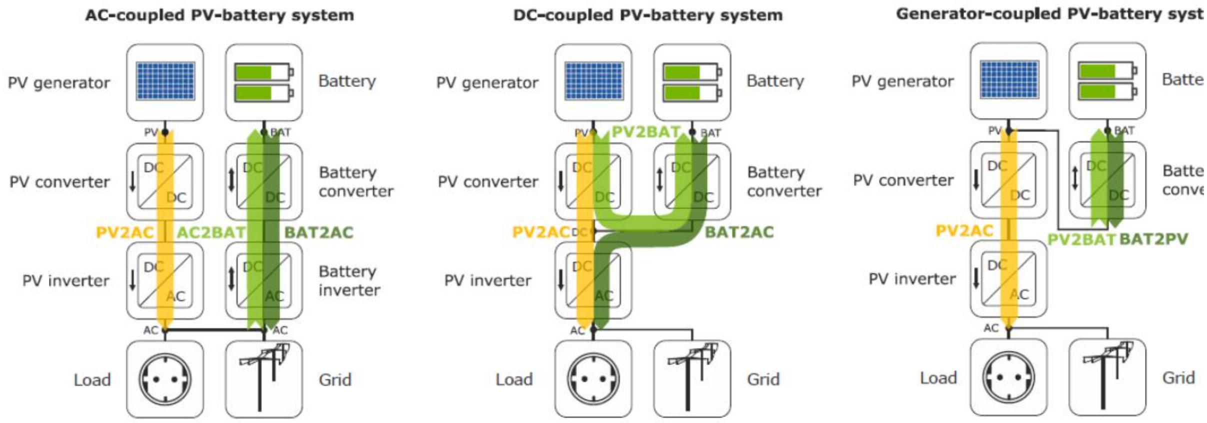
Battery energy storage is a collection of methods used to store electrical energy on a large scale within an electrical power grid[320]. Battery systems connected to large solid-state converters have been used to stabilize power distribution networks. Some grid batteries are co-located with renewable energy plants, either to smooth the power supplied by the intermittent wind or solar output, or to shift the power output into other hours of the day when the renewable plant cannot produce power directly. These hybrid systems (generation + storage) can either alleviate the pressure on the grid when connecting renewable sources or be used to contribute to greater self-consumption.

There are three principle configurations that can be used for connecting PV and battery systems – AC coupled, DC coupled and generator coupled (see Figure 106). In the below section AC coupled system is briefly analysed. The majority of residential PV systems installed in the EU are understood to have AC coupled configurations.

[319] https://www.secondsol.com/en/services/pv_wechselrichter_reparatur.htm

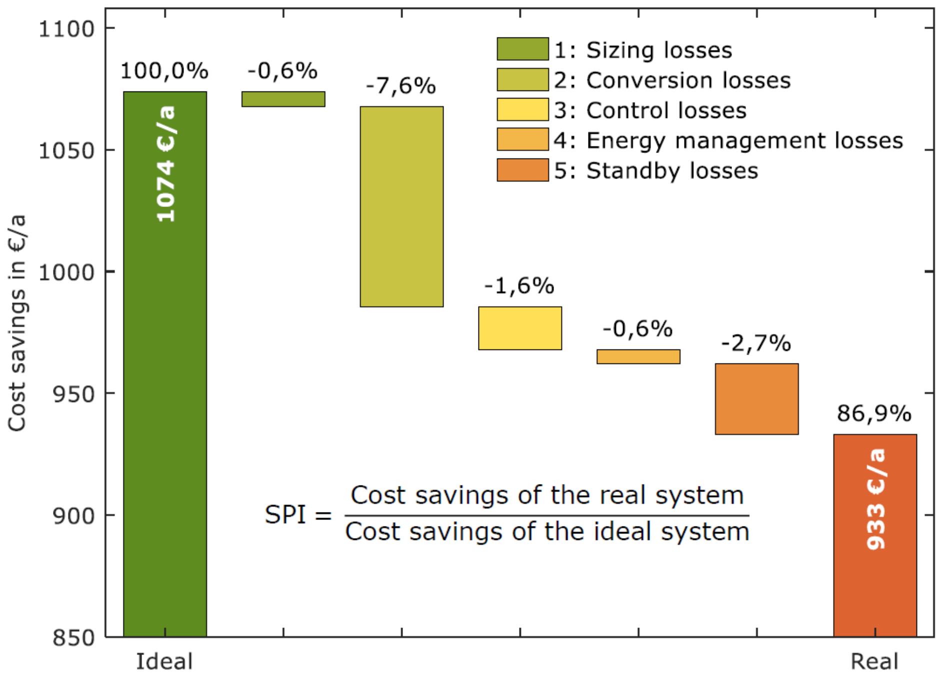
[320] I. Gyuk, P. Kulkarni, J. H. Sayer, J. D. Boyes, G. P. Corey, and G. H. Peek, "The United States of storage," IEEE Power Energy Mag., vol. 3, no. 2, pp. 31–39, 2005.

Figure 106. System topologies for connecting PV modules and batteries.



The Effibat project is working towards developing a standard for the comparison of the efficiency of battery systems. This standard will be based on a metric which will aggregate five types of losses that have been identified in what they call system performance index (see Figure 107). This index does not address the intrinsic performance and lifespan of the battery itself.

Figure 107. PV output 5 kWp, battery capacity 3,7 kWh, load demand 5 MWh/a, feed-in tariff 12 ct/kWh, retail price 28 ct/kWh



Batteries connected on the AC side of the inverter

It is possible to have battery storage connected with a charger/inverter or bidirectional converter to the AC grid. Those are referred as AC coupled battery systems, see Figure 106, i.e. an AC integrated battery/PV system. Those systems can be installed anywhere irrespective of a PV system or any other system being connected behind the meter in the AC grid. It is in principle not related to PV system but is an indirect consequence of its variable production and the potential mismatch with the local loads, see Task 3 for more details.

Batteries connected on the DC bus of the PV inverter

The efficiency of systems where PV is combined with storage is strongly dependent on how many AC/DC and DC/AC conversions are performed: the number of conversion stages should be minimized to increase efficiency. Thus, **the battery**

storage should be preferably implemented on the DC side, namely the inverter input, where PV strings are connected. The other option, meaning a connection on the AC side, would reduce the overall efficiency. However, it would represent the easiest solution for connection of batteries to already existing systems, since it allows for a direct connection of the battery controller/charger to the system output, namely the inverter output.

Several examples of inverters with combined battery storage can be already found on the market, like the Fronius Symo Hybrid 5.0-3-S [112]. In principle there is no negative impact from incorporating battery storage on the DC side of an inverter, however in some protection topologies a grid coupled inverter with transformer might be required, see previous section 4.1.4.1, and as mentioned there they have lower efficiency compared to transformer-less designs.

Note that batteries are part of another Ecodesign study: https://ecodesignbatteries.eu/

The option of a DC distribution grid

A relative new development but not available in the market yet is to connect the PV modules and the battery to a **DC distribution grid** incorporating also DC loads instead of AC. The concept of DC grid with its many advantages over AC like improvement in efficiency is capturing the industries and markets. It is able to garner relatively good support and momentum on this technology. Many loads or applications today are essentially DC-based, e.g. an inverter driven heat pumps, ICT, LED lighting, fire alarm etc. Thus, by deploying a DC distribution rather than conventional AC, a number of conversion steps can be eliminated and therefore, losses as well. This is a new development that requires new standardisations and at member state level early initiative are ongoing [113] TBC [114]. For example, this might require a standardized DC voltage that is accessible to other applications.

4.1.4.3 Summary of the technical improvement options and impact on Performance, Bill of Material and product price for inverters

In summary based on the previous section the following base cases (BC), and possible combinations of design improvements have been identified for inverters (see Table 69, Table 70 and Table 71). These comprise:

- The 'Base Case'(BC) as an average performing inverter wherein:
    - BC 1: is a 2.5 kW transformer-less single phase string inverter
    - BC 2: is a 20 kW transformer-less three phase string inverter
    - BC 3: is a large central inverter 1500 kW
- The following improvement options have been identified as potential candidates for BAT:
    - To change from average inverter efficiency to the best commercially available, referred as BC-EE options in Table 69, Table 70 and Table 71.
    - To extend the lifetime and to ensure ease of repair referred as BC- repair in Table 69, Table 70 (note: large central inverters are assumed to be repaired by default)
    - To add the monitoring function in BC 1 and 2, referred as BC- monitor in Table 69 and Table 70 (note: in large systems BC 3 this feature can be added at system level and not at the level of the inverter, a certain degree of remote monitoring of the inverter malfunctioning is assumed as a default feature).
    - To shift to module level converters in BC 1 which is referred as BC1- MLI
- The following improvement options not yet commercially available have been identified as potential BNAT:
    - To use Wide Band Gap materials to improve the inverter efficiency, which is BC- WBG in Table 69, Table 70 and Table 71.

Extending the lifetime of an inverter and ensuring it can be repaired are potentially important topics to reduce its environmental impact to be assessed in Tasks 5 and 6. This should be done with the following definitions:

- Technical lifetime of an inverter [years]: is the average time between the putting into service and the failure of an inverter in real conditions, which can also be modelled by the Mean Time Between Failure (MTBF).
- Failure rate inverter [%/y]: This is the linear average failure rate per year of an inverter relative to its technical lifetime (= 1/MTBFinv). The average data for Annual failure rate is based on Table 15 from Task 3.

Table 69. Base Case 1 single phase string inverters and improvement options

	BC1- 1 phase (BC1)	**BC1-EE (More efficient)**	**BC1- repair (repaired)**	**BC1- monitor**	**BC1- MLI (module level converter)**	**BC1- EE-WBG (wide band gap converter)**
Rating [kVA]	2.5	2.5	2.5	2.5	10x250	2.5
Topology	Transformer-less String 1phase	See BC1	See BC1	BC1 + monitoring	Transformer-less module level inverter	BC1 with WBG
Euro Efficiency η_{conv}[%]	96	98	96	-	97	99
$DR_{shading}$	0.96	0.96	0.96	0.96	0.99	0.96
Repaired components assumption	none	TBD	Components as identified	TBD	Components as identified	Components as identified
Impact on cooling BOM & housing	100 %	+5%	BC1	+5%	TBD	-30 %
Cost impact	100 %	+10-20%	100-200 euro/repair incident	100-200 euro/repair incident	+100 -200 %	TBD
Failure rate (%/yr)	10 %	10 %	10 %anticipated lower replacement rate	TBD	10 %	TBD
(1) Based on the assumption of the assumption that the lifetime is extended by replacing.						

Table 70. Base Case 2 three phase string inverters and improvement options

	BC2 -3 phase (BC1)	**BC2- EE** **(More efficient)**	**BC2- repair** **(repaired)**	**BC2- monitor**	**BC2- EE-WBG** **(wide band gap converter)**
Rating [kW]	20	20	20	20	20
Topology	Transformerless String 3-phase	See BC2	See BC2	BC2 + monitoring	BC2 with WBG
Euro Efficiency η_{conv}[%]	97%	98%	97%	97%	99%
Repaired components assumption	none	TBD	Components as identified	TBD	Components as identified
Impact on cooling BOM & housing	100%	+0%	TBD	+5%	-30%
Failure rate (%/yr)	Below 10%	Below 10%	Below 10%	Below 10%	Below 10%
Cost impact	100 %	+10-20 %	400-800 euro/repair incident	200-400 euro/repair incident	TBD

Table 71. Base Case 3 large central inverters and improvement options

	BC 3 (BC3)	**BC3- EE** **(More efficient)**	**BC3- EE-WBG** **(wide band gap converter)**
Typ. Rating[kW]	Central inverter TBD	See BC3	BC3 with WBG
Topology	Connected to LV transformer	See BC3	New
Euro Efficiency η_{conv}[%]	97%	98%	99%
Impact on volume	100%	105%	70%
Impact on cooling BOM & housing	100%	105%	70%
Cost impact	100 %	+10 -20 %	TBD
Failure rate of active components (%/yr)	Below 10 %	Below 10 %	Below 10 %

4.1.5 PV system level technologies and practices

The role of a good design, maintenance and monitoring is important in any PV system has already been discussed in detail in Task 3. Some specific aspects of these three points will be further analysed here.

The balance of system (BOS) encompasses all components of a photovoltaic system and this represents more than the previously discussed PV modules and inverters. The parts that can also have an impact on the performance and yield are the wiring and the monitoring system. They will be discussed hereafter in more detail.

Note that Building Integrated Photovoltaic (BIPV) systems will be discussed in a separate section 4.1.6.

4.1.5.1 Technology selection as a response to real climatic conditions

Different PV modules technologies show different effects of deviations from STC observed for irradiance, module temperature, spectral composition of irradiance and angle of incidence[321]. These factors have been described in Task 3 and will be analysed further in the system design options (Tasks 6 and 7 of this Preparatory study).

4.1.5.2 PV system design software

Current commercial PV plants and ever increasing utility scales PV plants require adapted software solution to design the physical layout, installation conditions and electrical architecture of the system. For larger systems, maximizing land usage i.e. installation of highest number of PV modules, has been the driving principle of the design. However, the clear paradigm shift towards optimization of PV plants to achieve the highest energy yield instead of the highest capacity installation requires the use of more advanced PV system design solutions.

From an investors perspective reference is also made to a probabilistic assessment of yield uncertainty. For example, software package PVSyst can identify the uncertainty at different percentiles (see Figure 108). Different components of the yield assessment have their own uncertainty range and mitigation measures can be used to reduce the uncertainty, e.g. the temperature model, the climatic variability, etc.

The deployment of new technologies to optimise performance such as bifacial PV modules and/or trackers, requires additional consideration of shading patterns/reflectivity. With the increasing share of renewables in the electrical grid, solutions proposing peak shaving or other specific requirements for the local grid are favoured in some cases.

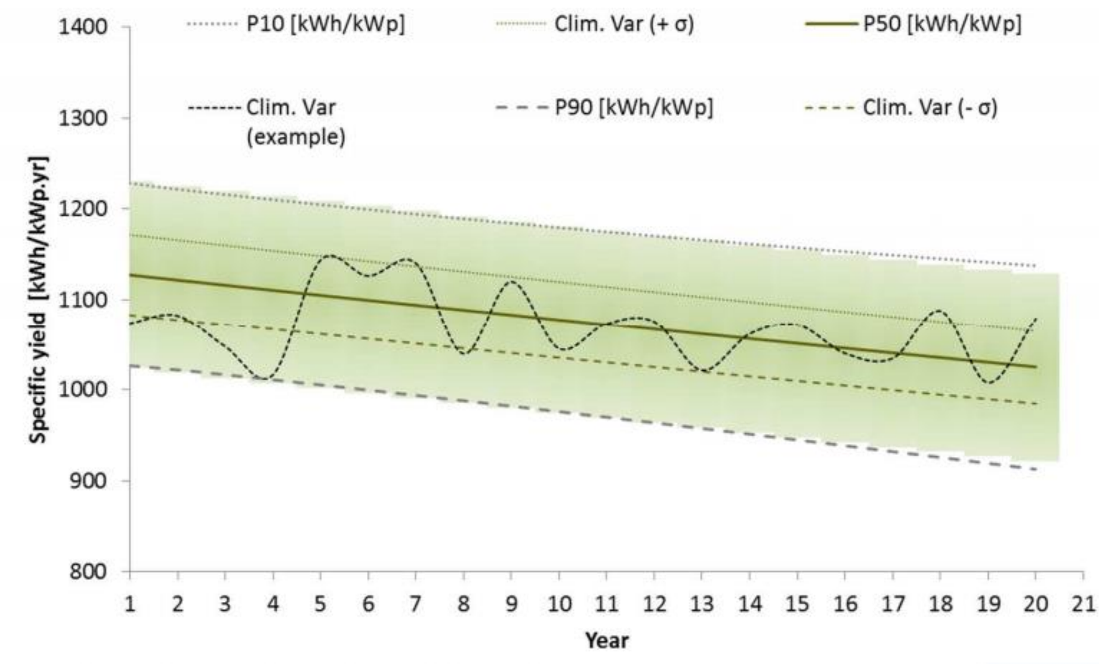
The energy yield of a bifacial system is more dependent on the mounting and conditions of the ground than for monofacial systems as they harvest light also on their rear side. Four different installations conditions can be distinguished: fixed tilt, vertical and one or double axis tracking. To define optimal installation conditions of bifacial systems the interlinked impact of system height, module orientation, row spacing and ground reflectivity (albedo) need to be considered. To minimize mismatch losses, optimal electrical layout of the bifacial PV system resolving the impact of varying rear-side shading conditions within one string and in between strings as well as the use additional module level power optimization must be also considered.

The types and form of the supporting structure of the modules for bifacial systems should be equally adapted to minimize back-side shading by using cable guides and enable safe clamping of frameless modules. In general frameless modules are preferred in bifacial systems over framed one due to important self-shading of the modules in the early morning and later afternoon when the sun is close the horizon.

[321] *Prog. Photovolt: Res. Appl. 2017; 25:218–232*

Prog Photovolt: Res Appl. 2018; 26:74–85.

Figure 108. Yearly expected mean specific yiled (P50) and its exceedance probabilities (P10 and P90) for each year of the economic life of the project. Source: Solar bankability [322]



PV plant failures

Photovoltaic (PV) plant failures have a significant influence on PV plant security, reliability, and energy balance. Energy losses produced by a PV plant are due to two large causes: failures and inefficiencies. During the operation of PV system, failures can be found in the PV array such as snail trail, hot spot, diode failure, EVA discoloration, glass breakage, delamination with breaks in the ribbons and solder bonds, light induced degradation, low irradiance losses, potential induced degradation, shading effect, soiling effect, sun tracking system misalignments, wiring losses, and mismatching effect in solar array [109].

Some of these possible failures and risk of production losses have been categorised and assigned to stages in the project life cycle of a PV system, see Figure 109.

The impact of energy loss due to inefficiencies or system derating factors are estimated to be between 22 to 28% that is higher than the energy loss due to failure, which is estimated to be lower than 1%. Monitoring on the DC side is not so critical, instead the focus should be on the inverter, transformer and the AC grid side. On the PV module side, the source of failures are module, DC wiring and junction box that accounts for a very small percentage of total failure rates. Furthermore, the PV plant is connected to the AC grid, presenting the possibility of curtailment of generation, shutdown and overvoltage, transformer failure, electrical setting protection failure and overheating due to overcurrent.

The main failure causes of PV inverters in terms of power electronics are either the power semiconductors or the capacitors. In the future, a priority should be to ensure that either the reliability of these two components is increased or the power electronics is empowered to make intelligent decisions about state of health of the inverter or these components [110] .

[322] *D3.1. Review and gap analysis of technical assumptions in PV electricity cost. Solar bankability, 2016*

Figure 109. Example of Risk Matrix for PV modules and inverters. Source: Solar bankability, 2017

A. MODULES	B. INVERTERS
Product testing / development	
• Failed insulation test • Incorrect cell soldering • Undersized bypass diode • Junction box adhesion • Etc.	• Inverter derating issue • Maximum power point tracker issue
PV plant planning / development	
• Soiling losses • Shadow diagram issue • Modules' mismatch • Uncertified modules • Etc.	• Inverter wrongly sized • Incorrect IP rating • Inverter cabinet inadequately ventilated • Inverter exposed to sunlight • Etc.
Transportation / installation	
• Module mishandling (Glass breakage) • Module mishandling (Cell breakage) • Module mishandling (Defective backsheet) • Etc.	• Inverter configuration incorrect • Missing contact protection • Inverter has no surge protection • Etc.
Operation / maintenance	
• Improperly installed • Hotspot • Delamination • Glass breakage • Snail trails • Etc.	• Fan failure and overheating • Theft or vandalism • Grounding fault • Firmware issue • Etc.
Decommissioning	
• No product recycling procedure defined or implemented	• Inverter size and weight issue

The modules themselves can incur damage during transportation and handling at the site where they will be deployed:

- Damaged wiring
- Glass breakage
- Cell breakage
- Backpane damage

PV module failures also depend upon the climatic condition where a defective bypass diode is highest in hot and dry climate. Similarly, cell cracks are higher in cold and snowy climate in comparison to moderate climate and hot climate [104].

4.1.5.3 PV system monitoring

High quality Operation and Maintenance (O&M) services, when well-managed, reduce the LCOE of PV plants and thus positively impact the return on investment over the entire lifecycle. Best operations and maintenance practices, and related training of the technical staff have been listed in Task 3. Complementary, this section focuses on current and emerging technical solutions for O&M.

<u>PV system yield monitoring</u>

There are two approaches in monitoring, a comparative approach (peer-to-peer monitoring) or performance metric monitoring when weather sensors are available. This latter approach is used for commercial and utility scale system. Its basis is the energy yield monitoring, typically on plant and/or string level, correlated with on site or satellite weather data input to detect under-performance. The monitoring of different parameters at plant level is required for the calculation of different key performance indicators (KPIs). This basic monitoring system provided irradiance, energy and performance ratio at plant level and, in case of malfunctioning, will trigger an alarm.

The most common key performance indicator is the performance ratio (PR) that normalizes the system output compared to measured insolation and DC system capacity at standard test conditions (STC) following IEC 61274. More advanced metric such a weather-corrected performance ratio or performance index have been proposed[323].

The Standard IEC 61724-1(2017) defines three classes of PV monitoring systems that are summarized in Table 72. For the smaller string inverters discussed in 4.1.4 it is possible to include part of a class C monitoring system in the inverter. A class C system requires the AC energy output, the in plane irradiance and the on-site ambient temperature to be recorded with 1 minute time interval. Irradiance and temperature do not need to be measured on site. Monitoring features that are not required by class C, but may also be useful and that can be easily incorporated in inverters are:

- Internet connection
- Power (PAC) and temperature read out of the inverter
- Logging of insulation errors detected RCD/IMD
- Logging of grid frequency, anti-islanding, over-voltage and undervoltage alarms
- Vpv/Ipv present voltage and current of the PV string
- Logging of daily maximum power (PAC) combined with monitoring the maximum string voltage (this can indicate a wrong sizing of the inverter voltage versus string and/or a failed PV module)
- Operating hours

It is also possible to add the monitoring system as a separate system components[324]. This is a more common practice in larger systems, for which it can be more useful, as it was discussed in section 4.1.4.1. Adding more features, more accuracy and sensors can finally result in a class A system which can be considered as a candidate for BAT for large central inverters.

Table 72 PV monitoring system classifications and suggested applications (source: IEC 61724-1:2017)

Typical applications	Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy
Basic system performance assessment	X	X	X
Documentation of a performance guarantee	X	X	
System losses analysis	X	X	
Electricity network interaction assessment	X		
Fault localization	X		
PV technology assessment	X		
Precise PV system degradation measurement	X		

More advanced monitoring platforms include lower granularity performance monitoring, numerous customised KPIs and fault analysis tools. For example string level monitoring (also critical for systems with different module orientations) and module-scale monitoring solutions are appearing on the market. Additionally tools for monitoring the health of the DC circuit by detecting alterations in the series resistance of the system exist, e.g. detecting cable corrosion which otherwise would be only detected upon catastrophic failure.

More advanced inverter monitoring solutions are proposed by numerous companies. Applying these solutions enable the early fault detection (before major power loss) and provide insights in the potential origin of the failure mode and its location. Several solution providers also make high-level recommendations to the site owner and guide technical operation and maintenance staff[325] . Besides production monitoring the PV plant owners often request a visual inspection tool to gather further information on the status of its PV plant, e.g. IR imaging based aerial inspection.

Monitoring solution providers often provide the owner with access to the database of the historic performance, logging of inverter faults, and previous interventions which provide an important foundation for valuation of PV plants. Most utility scale PV plants use a Supervisory Control and Data Acquisition (SCADA) system. The hardware backbone of such a system is

[323] *Joshua Stein; Mike Green; Novel strategies for PV system monitoring; PVtech Power; Vol 2., 2015*

[324] *https://shop.solar-log.com/en/equipment/?p=2*

[325] *3E,Health Scan*

a programmable logic controller (PLC) or a similar type of smart relay.. Alternatively the high-speed internet has enabled the development of web-based solutions either integrated with hardware solution or hardware diagnostic platforms.

Note that monitoring can support maintenance practices (see Task3) to extend the maintenance periods as longs as everything is reported normal. However it cannot replace them all (e.g. visual inspection, cleaning modules and sensors, general house-keeping such as pruning trees, tightening bolts, calibrating sensors, etc.). Among the O&M contracts surveyed reported in an IEA PVPS study[104], annual frequency was the most common time frame contracted for preventative maintenance frequency.

Field inspection for fault diagnosis

Infrared imaging

Recent research[326] and increasing feedback form the field experience,[327] has established infrared (IR) imaging as a very efficient and reliable tool for detailed inspection and advanced diagnostics of PV plants. Indeed, these efforts have demonstrated the applicability of IR imaging to detect different (electrical, optical, thermal) failures on PV system, module and cell level. They have also validated methodologies to diagnose and classify most of these failure modes from certain IR patterns (i.e. thermal signatures). Regular IR inspection could therefore be a candidate for BAT for commercial and utility scale PV plants.

As a result of broad deployment, IR-based diagnostics in the PV field has nowadays become streamlined and standardized, particularly through the work of technology collaboration platforms[328] and the release of IEC technical specifications[329]. Numerous pioneering service providers of aerial IR imaging for PV plants[330,331,332], are active in the EU.

Flash testing and electroluminescence on the field

The use of complementary characterization techniques such as flash testing and electroluminescence imaging on the field can provide valuable information about fault diagnosis. Companies offering these services are just emerging and exact standard on their application on the field are not yet available. We consider these techniques could potentially be candidate as BNAT in the field of O&M.

4.1.5.4 Additional system components

Solar Trackers

For ground mounted systems solar tracking structures can be installed and they can boost the annual output up to 50 %[1] Such structures orient the modules better to the sun depending on the season and/or time of the day. These structures can move around one or two axis and the impact on yield can easily be calculated per location[333] .

Single axis trackers follow the movement of the sun from east to west, potentially increasing yields by up to 25%, while two axis tracking solutions allow to consider the seasonal variations and can increase yield by 35%[334]. The current split market share of single axis vs. dual axis has been estimated as being 65% and 35%, respectively but it is changing dynamically with dual axis trackers loosing market share due to their complexity[335]. The exact energy yield gain depends on geographical location, types of trackers used, module temperature coefficients, since the module operating temperature increases with the light level and exposure time. Some studies have identified the potential for significant divergence

326 J.A. Tsanakas et al. (2016), Renew Sustain Energy Rev 62: 695–709.

327 P.B. Quater et al. (2014), IEEE J Photovoltaics 2014.

328 U. Jahn et al. (2018), Report IEA-PVPS T13-10:2018.

329 IEC/TS 62446-3:2017.

330 Heliolytics Inc. [http://www.heliolytics.com/]

331 Sitemark (f.k.a. DroneGrid) [https://www.sitemark.com/]

332 Above Surveying [http://www.abovesurveying.com/]

333 http://re.jrc.ec.europa.eu/pvgis.html.

334 PV Tracker System Net Gain Associated to the Local Climatic Conditions, C. Cabo Landeira, Á. López-Agüera, International Journal for Research in Applied Science & Engineering Technology Volume 6 Issue I, January 2018

335 GLOBE NEWSWIRE, 2017

between simulated and real yield gains from tracking systems, suggesting that careful attention is needed to the validation the results that simulation softwares can provide.

Tracking systems require more area to avoid row to row shading and therefore can be considered as an improvement option for large ground mounted systems with central inverter. During the system design the energy yield gain calculation should balance these elements with the increased installation and maintenance cost.

The tracker market is currently adapting to bifacial modules with adapted structural design to minimize rear shading and tailored tracking algorithms. To maximize light harvesting in bifacial systems the conditions of the sky and diffuse radiation must be considered by the tracker algorithm. Compared to monofacial tracking, unfocusing the tracker to favour backside production could be interesting in specific weather conditions[336],[337].

Of all the components of a system it is understood that trackers have the greatest potential for failure. The associated downtime and loss of efficiency has to be factored in the calculations.

Cabling

For photovoltaic installations wires with a sufficient Cross-sectional Area (CSA) are needed to avoid cable losses. This issue was already extensively examined in a separate Ecodesign study (Lot 8) on Power Cables [115]. The main recommendations of the study related to the application of the relevant standards relative to energy efficiency in electrical installations. In the case of PV installations, the following have been identified:

Maximum voltage drop prescribed by IEC 60364-7-712 - Low Voltage Electrical Installations - Part 7-712: It is recommended that under maximum load conditions the voltage drop from the most remote module in the array to the input terminals of the application circuit should not exceed 3 % of the PV array voltage at its maximum power point. This will impact cable sizing.

Economic cable sizing as defined in IEC 60287-3-2 - Electric cables - Calculation of the current rating - Part 3-2: Sections on operating conditions - Economic optimization of power cable size. This methodology is the one recommended by IEC 60364-8-1: Low-voltage electrical installations - Part 8-1: Energy efficiency.

Environmental Conductor Size Optimisation (ECSO) as defined in IEC CD 60125 Environmental considerations specific to insulated electrical power and control cables. Environmental and energy cost based Conductor Size Optimization (ECSO) is taking into account the cable's life phases' costs and reduction in power loss costs during use phase and related costs of CO_2 compared to the conventional sizing of highly loaded cables with significant energy losses. ECSO takes specifically into account:

- The initial cost of investment including manufacturing, transportation, installation and final disposal costs;
- Cost for CO_2 emission during manufacturing, transportation and installation and final disposal;
- Costs for Joule losses during anticipated lifetime;
- Costs for CO_2 emission during the anticipated lifetime.

Temperature correction factor. The following references are relevant:

- EN 50618 Electric Cables for photovoltaic systems. The electrical resistance of each conductor at 20°C shall be in accordance with the requirements of EN 60228 for a metal coated Class 5 conductor. Also, this standard provides the appropriate figures for the current carrying capacity of PV cables and the current rating conversion factors for different ambient temperatures. See attachment with TüVRheinland PV cable approval example according to EN 50618.
- IEC 60364-7-712 - Low Voltage Electrical Installations - Part 7-712: Requirements For Special Installations Or Locations - Solar Photovoltaic (PV) Power Supply Systems. A PV array's performance may be affected by many factors, including but not limited to temperature rise. Cables used within the PV array shall:

  Have a temperature rating according to the application, taking into account that PV modules frequently operate at temperatures of the order of 40ºC above ambient temperature and therefore cable insulation of wiring installed in contact or near PV modules shall be rated accordingly;

[336] *J. Guerrero, Both sides of the story, Pv Tech Power, vol 16, 2018*

[337] *Vokas et al., Single and dual axis PV energy production over Greece: Comparison between measured and predicted data, Energy Procedia, 2015*

The ambient temperature for cables subjected to direct heating from the underside of PV modules shall be considered to be at least 70ºC

These options could be of particular relevance to any potential Green Public Procurement (GPP) criteria for systems.

4.1.5.5 Dismantling PV systems at the end of life

PV systems and their components fall within the scope of the WEEE recycling, see section 4.2. Particular issues at system level that require consideration relate to the ability to dismantle and return the components for reuse or recycling.

While dismantling and returning PV components from larger systems installed in open field or on flat roofs may be considered more straightforward, this type of dismantling work can be more complex, cumbersome and relatively expensive for multiple smaller residential Building Attached PV (BAPV systems). This is in part due to the costs of gaining access to roofs.

Note that apart from dismantling at end of life also a building catching fire is a possible end of life scenario that could warrant further attention within the frame of this study.

For **smaller systems two relevant improvement options are to consider halogen free cables and backsheets**. This can be beneficial to avoid harmful halogen smoke during incineration at the end of life or when a building takes fire.

4.1.5.6 Summary of improvement options and impact on Performance, Bill of Material and product price

In summary based on the previous sections the following base cases (BC) and possible combinations of design improvements have been identified at the system level (see Table 73, Table 74 and Table 75). These comprise:

- The 'Base Case' (BC) as an average system wherein:
  - BC 1: is a 2.5 kW residential PV system
  - BC 2: is a 20 kW commercial PV system
  - BC 3: is a large central inverter 1.5MW
- The following improvement options have been identified as potential candidates for BAT:
  - To change from an 'average' designed system to the best available (see also Task 3), referred as BC-des.
  - To change from an 'average' monitored and designed system to the best available (Class C monitoring + options for BC1, Class B monitoring for BC 1, Class A for BC1), referred as BC-mon.
  - To change to a halogen solution in BC 1 (see also Task 3), referred as BC-F-free.
  - To add solar trackers to utility scale PV systems, referred to as 'BC-track'

4.1.6 BIPV module and system

4.1.6.1 Standard product scope: performance

The term building integrated photovoltaics (BIPV) refers to multifunctional building elements which use the sunlight to generate electricity, on the basis of solar cells technology. In other words, BIPV systems comprise photovoltaic components that also serve multiple building and architectural functions, similarly to conventional elements of the building envelope (i.e. façades and/or roofs). Thus, BIPV are defined both in functional terms (in line with the European Construction Product Regulation CPR n.305/2011) and in aesthetical terms, as an architectural concept [116]. Such required "multifunctionality" of BIPV relates to integral **performance properties**, i.e. thermal and electrical insulation, water and air tightness, acoustics (soundproofing), induced thermal comfort and ventilation, aesthetics and impact on visual comfort (daylighting/shading, colour, texture), energy economy and recyclability.

Two main BIPV segments can be identified, based on their application area: roofs and façades. Most BIPV technologies that are widely available in the market today come from the former segment. Solar tiles in particular (also including variations, such as shingles and slates) are the BIPV product with the leading share in the market (24%), followed by full roof solutions (15%). In terms of the PV technology used, crystalline silicon (c-Si) based solutions represent the most dominant, by far, product for roof BIPV applications, corresponding to 72% of the relevant market [117].

Table 73. System level improvement options for a residential PV system

	BC 1	**BC 1-des**	**BC 1-mon**	**BC 1- F free**
Type	Small residential Default installation	Small residential Optimised design and yield forecasting	Small residential Optimised monitoring and maintenance	Small residential halogen free cables
Predicted yield	100 %	+5 %	+5 %	+0%
PR	0.75	0.80	0.85	0.75
Cost	100 %	+5 %	+10%	TBD
Bill of Material	Standard	Standard	Standard	Halogen free cables

Table 74. System level improvement options for a medium size commercial PV system

	BC 2	**BC 2-des**	**BC 2-mon**
Type	Medium commercial Default installation	Medium commercial Optimised design and yield forecasting	Medium commercial Optimised monitoring and maintenance
Predicted yield	100 %	+5 %	+5 %
PR	0.75	0.80	0.85
Cost	0	+ 20 €/kW[1]	+4€/kW+10%[1]
Bill of Material	Standard	Halogen free cables	Halogen free cables
1. Best practice guidelines for PV cost calculations. Solar bankability, 2016			

Table 75. System level improvement options for a large utility scale system

	BC 3	**BC3-des**	**BC3-mon**	**BC3-track**
Type	Utility scale Default installation	Utility scale Optimised design and yield forecasting	Utility scale Optimised monitoring and maintenance	Utility scale With single axis trackers
Predicted yield	100 %	Already standard practice	Already standard practice	+25% (calculated, depends on location)
PR	0.75	0.80	0.85	0.75
Cost	0	+ 20 €/kW[1]	+4€/kW+10%[1]	TBD
1. Best practice guidelines for PV cost calculations. Solar bankability, 2016				

Figure 110. Examples of small-sized (upper right/left images) and large-sized (lower right/left images) BIPV solar tiles [25].

Focusing further on the most common roof BIPV product, solar tiles are in principle classified in terms of size (Figure 110) [118]:

- Small (≤0.5 m^2, typically 0.4×0.6 m^2); a few solar cells encapsulated in a PV laminate, within structures (composed of several materials, e.g. plastic, clay) resembling traditional construction products.
- Large (>0.5 m^2, typically 0.6×1.5 m^2); more complex systems/structures that include building elements and interconnections, 2-4 times wider than traditional tiles (or shingles or slates), mostly based on glass or foil. Such systems usually allow for full roof-filling. Typical weights: 13-20 kg/m^2.

In both groups of solar tiles, the electrical efficiency and power output per area are generally lower than in standard PV modules.

The leading BIPV roofing products in the market today come with power output in the range of 9 to 60 W per unit, for small-sized solar tile products; and in the range of 86 to 150 W, for large-sized ones [338]. Small solar tiles are considered advantageous for optimized roof filling and aesthetics, while larger tiles come with the potential of lower price per area unit. Solar tiles can be either glazed (glass sub/superstrate) or foil-based on i.e. polymer membranes or coatings [116]. Normalized power outputs for both size groups are rather varying, in the range of 80.1 up to 184.2 W/m^2. Besides, the electrical efficiency of such solar tiles ranges from 13.9% to 15.9%, values which are significantly lower – as aforementioned – when compared to standard PV modules.

In the façades segment, rain-screen ("cold") façades and skylight/solar glazing solutions are the most widespread products. Rain-screen façade systems typically consist of a load-bearing sub-frame, an air gap and a cladding panel. On the other hand, glazed PV laminates for skylight/solar glazing applications are made either by c-Si cells with adjusted spacing or by laser grooved thin films which provide filtered vision, encapsulated within glazed panes. Notably, 44% of commercially available BIPV façade solutions are based on thin films technology. The advantages of superior aesthetic appearance and lower cost per area unit are the main drivers for such a relatively large share of thin films among BIPV façades [118].

Depending on the unit size, rain-screen PV façade products have power output which ranges from 33 to 125 W for thin film based products; and from 40 to 310 W, for c-Si based ones[339]. In the skylight/solar glazing products group, available solutions in the market come with a power output from 44 to 55 W for thin film based skylights; and from 80 up to 380 W for c-Si based ones [340]. As in the case of solar tiles, normalised power outputs for both two BIPV façade types are in the range of 100 up to 186 W/m^2, while the electrical efficiency of such products varies from a relative low 11.2%-12.8% (for thin film based ones) up to 18% (for solutions based on standard glass-glass c-Si PV modules).

[338] *Solarcentury C21e series (UK), ZEP Zonneceldakpannen (Netherlands), SunTegra™ Solar Shingles & Tiles (USA), Sun Net Solcelletaktegl (Norway/Germany), Heda Solar PV module/tile (China), Romag Intecto Solar Roof Tiles (UK)*

[339] *Flisom AG, SF Gen1 (Switzerland), Hanergy Solibro CIGS (China), Scheuten Glas Optisol Skin (Netherlands), Solarwatt Vision (Germany)*

[340] *Asola Technologies GmbH VITRUM SunSecret (Germany), Ertex Solar VSG-EVO-Module (Austria), Galaxy Energy GmbH Galaxy Energy Indachsystem (Germany), Kaneka SEE-THROUGH (Belgium), Scheuten Glas Optisol Sky (Netherlands)*

4.1.6.2 Extended product scope: energy generation potential and reliability (incl. warranty/product claims)

BIPV reliability and performance considerations

In BIPV systems, the particularity of the full integration and operation of PV modules within the buildings' envelope lead to considerably higher operating temperatures. Various strategies are being investigated to reduce the PV temperature of BIPV façade/roof systems.

- *Metal fins/heat sink:* In this option, metal fins are attached on the back side of the PV modules, working as heat sinks to cool the modules. The effectiveness of this low-cost solution was investigated through an experimental pilot. This type of BIPV façade system was built and tested in Eurac[341]. Application of fins could be considered as a "passive-low cost" strategy to slightly improve the performance of a BIPV façade system.
- *Phase change materials (PCM):* Using PCMs for temperature regulation and temporary heat storage in photovoltaic/thermal systems (PVT) is an emerging technology that has attracted attention recently. The PCM absorbs heat and regulates peak temperature, which allows the PV module to operate at lower temperatures during peak solar conditions. Further, the waste heat stored in the PCM can be used for other applications.

Apart from PV degradation and failures due to high operating temperatures, mismatch losses due to shading and soiling can have substantially negative impact on the BIPV energy yield, especially for systems/buildings with certain architectural constraints and/or located in areas with adverse conditions (e.g. dust or snowfalls). Indeed, research activity has shown that mismatch losses are largely site-dependent [119]–[121], principally related to small-scale effects and location or building characteristics. Thus predicting, quantifying and mitigating losses due to soiling or shading remains a challenge. Standard PV financing models and simulation tools assume mismatch losses ≤2% of the annual energy yield. In principle, matching such a rate in BIPV installations, requires costly "smart" monitoring or distributed power electronics; and a range of other (often non-optimized, non-standardized) solutions for soiling and shading management and mitigation (e.g. manual or robotic cleaning). Indeed, module power electronics (DC optimizers or micro-inverters) are greatly beneficial boosting by up to 15% the energy yield of multi-string residential BIPV installations that are more prone to mismatch losses [122], [123].

BIPV standardization aspects

In the case that BIPV products form part of the building's envelope providing electrical energy, the requirements and test conditions from the building side following the EUROCODE come from CEN and ISO, while the electrical performance and safety rules come from CENELEC and IEC. The requirements for building construction materials and components are generically formulated, and hence tests are performed on specific test samples. The tests on PV modules are related to the very specific type and form of the modules, and changes in dimensions and components require subsequent retesting [342].

There was an attempt from ISO technical committee Glass in Building TC160 [120], to write a standard for glass/glass PV modules for building integration (draft ISO DIS 18178 Laminated solar PV glass). IEC TC82 started a new work item on proposals for PV building integration. In addition, at international level under the framework of the PVPS Technology Collaboration Programme of the International Energy Agency [120] there is also an active group working on PV building integration issues. Recently, these different approaches are bundled in the new Project Team PT 6309213, that is a collaboration based at IEC, open to members of ISO and the IEA PVPS. It was decided to take the European EN 50583:2016 BIPV Standard as a starting point for the future development of an international standard. The latter assigns application-specific requirements to PV modules – divided into the main categories; "containing-" and "not containing glass panes". It further differentiates between general requirements that have to be fulfilled by all products (electrical- and building-related requirements) and requirements that only have to be fulfilled depending on the constructional set-up (e.g. fire resistance classification acc. to EN 13501-1).

Dismantling and recycling BIPV systems at the end of life

PV systems and their components fall within the scope of the WEEE recycling, see 4.2. Particular issues at system level worth mentioning are related to the effort to dismantle and return the components for recycling. **Two relevant improvement options to consider are Pb-free and halogen-free modules**. This can be beneficial to avoid harmful halogen smoke if polymers are incinerated at the end of life or when a building catches fire. Also in BIPV the identification

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[341] EURAC, Bolzano (Italy) [http://www.eurac.edu/en/research/technologies/renewableenergy/researchfields/Pages/Photovoltaic-systems.aspx]

[342] At present the retesting guideline is a document from the international community of high quality test labs, CTL within the IECEE CBTL scheme agreed on, see https://www.iecee.org/committees/ctl/documents/ctl-documents.htm. An international IEC Guideline, is almost finished: IEC TS 62915 ED1: Photovoltaic (PV) modules - Retesting for type approval, design and safety qualification, expected in 2018.

and sorting of Pb and halogen containing polymers can be more complex compared to standard solutions and therefore these two improvement options can be relatively more important.

4.2 Lifecycle analysis available data sources to model production for lifecycle analysis

Aim:

This section includes a compilation of data sources for the bill of materials (BOM), that would be modelled according with the revised ecodesign methodology (MEErP) and complemented, where relevant and feasible, with information from the Product Environmental Footprint (PEF) results.

4.2.1 Selected data sources and BOM

4.2.1.1 Modules –

An updated bill of materials for multi-Si modules will be provided by the PV sector. Other possible sources of data are:

- Product Environmental Footprint screening study[343]: Data available for:
    - Cadmium-telluride PV technology
    - Copper-indium-selenium (CIS) PV technology
    - Micromorphous Si PV technology
    - Multicrystalline Si PV technology
    - Monocrystalline Si PV technology
    - Electric installation and mounting structure
- Ecoinvent[344]
- IEA PVPS task 12[345]

Base case Multi Si

Data from the PEF screening study[56].The BOM in Ecoreport format is available in task 5.

Recycling

- Life cycle inventory of recycling of photovoltaic modules is available in a publication from treeze Ltd. (Stolz et al., 2016[346]). This publication contains LCI data for the recycling of c-Si PV modules and the recycling of CdTe PV modules.

4.2.1.2 Inverters

- Life cycle inventory of inverters is available in a publication from treeze Ltd.: (Tschümperlin et al. 2016). This publication contains LCI data for the manufacture and disposal of solar inverters of 2.5 kW, 5 kW, 10 kW and 20 kW.
- Bill of materials of photovoltaic inverters, sources of failures and lifetime issues are similar to Uninterruptable Power Supplies (ENER Lot 27), LED or fluorescent lamp drivers (ENER Lot 19) and motor drives (ENER Lot 30).

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[343] *Wyss F., Frischknecht R., de Wild-Scholten M., Stolz P. 2015. PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots*

[344] *Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8>*

[345] *Frischknecht R., Itten R., Sinha P., de Wild-Scholten M., Zhang J., Fthenakis V., Kim H.C., Raugei M., Stucki M. 2015. Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, International Energy Agency (IEA) PVPS Task 12, Report T12-04:2015*

[346] Stolz P., Frischknecht R.. 2016. Life cycle assessment of photovoltaic module recycling. Available online: http://treeze.ch/fileadmin/user_upload/downloads/Publications/Case_Studies/Energy/174-LCA-Recycling-PV-Modules-v1.1.pdf

Base case String 1 phase – 2500 W

Data for the inverter have been taken from a publication from treeze (Tschümperlin et al. 2016).

The BOM in Ecoreport format is available in task 5.

Base case String 3 phase – 20 kW

Data for the inverter have been taken from a publication from treeze (Tschümperlin et al. 2016).

The BOM in Ecoreport format is available in task 5.

Base case Central inverter

Consists of several 20 kW inverters.

4.2.1.3 System level

At system level the modelling will be based on the module characteristics described in Table 76.

The previous data sources do not necessary use the same units that are used in the MEErP, which is in mass per PV module. Based on some physical properties the typical Bill of Material data for silicon and front glass can be calculated. For example, for a typical multi Si module with 60 cells, see

Table **77**.

Table 76. Module characteristics

	Multi Si	**Mono Si**	**CdTe**
Module Size (m^2/module)	1.6	1.6	0.72
Module weight (unframed) (kg/m^2)	11.2	11.7	17.1
Module conversion efficiency (%)	14.7	15.1	14.6
Wafer thickness (micrometer)	200	190	2.5
Cell size (mm^2)	156*156	156*156	-
technology	Average technology mix of front/back cell connection, diffusion and front collection grid	Average technology mix of front/back cell connection, diffusion and front collection grid	
Main data source	De Wild-Scholten (2014)	De Wild-Scholten (2014)	First Solar (2014)
Rated power (Wp/m^2)	147	151	145
Average annual yield (kWh/kW)	926.25	976	984.75
Degradation rate	0.7%	0.7%	1.0%
Failure rate	0.005-0.1%[1]	0.005-0.1%[1]	TBD
Module area per kWh produced (m^2) – 3 kWp installation	2.39E-04	2.34E-04	2.44E-04
1. Kurtz S. NREL, reliability and durability of PV modules in Photovoltaic Solar Energy: from fundamentals and applications, John Wiley and Sons, 2017			

According to the IEA PVPS report on recent tends [104], there is a predictive maintenance practice wherein an inverter replacement is usually planned just after year 10 of the PV system operation. Therefore the inverter will be replaced 2 times in 30 years in the life span (at year 10 and at year 20).

For larger central inverter systems we will assume that the housing cabinet, connectors, distribution boxes will be kept because they won't wear out and this simplifies the replacement work. For larger rated systems the data can be upscaled in proportion to the rated power (kVA).

Batteries recycling will be discussed in another Ecodesign study on rechargeable electrochemical batteries: https://ecodesignbatteries.eu/

Table 77. Extrapolated data from the PEF to a commercial PV module

PEF data	Multi Si - 3 kWp
Module Size (m^2/module)	1.6
Module weight (unframed) (kg/m^2)	11.2
Module conversion efficiency (%)	14.7
Wafer thickness (micrometer)	200
Cell size (mm^2)	156*156
link to commercial module	
Area of module(m^2)	1.6
Module power rating	235
Cells per module	60
Weight of cells (g/ m^2)	558.7
Max. scrap value of silicon metal in module(euro)	0.67
Weight of Silicon on module(kg/module)	0.67
Silicon per m^2 (kg/m^2)	0.42
Value of silicon metal in module(euro)	1.05
Total mass of module	17.9
% silicon in total mass module	3.7%
link to cell data	
shape of cells	Pseudosquare
Wp per cell (Wp)	3.68
Si Weight per cell (g)	11.13
Frontglass	
thickness (mm)	3.2
weight per m^2 (kg)	8
share in BOM (%)	71.4%

4.3 Conclusions and recommendations

In this Task 4 of the Preparatory Study a range of technical improvements have been identified and analysed for:

- photovoltaic modules at wafer, cell and product level,
- inverters at product and component level, and
- systems in respect of design, operation and maintenance practices.

Based on this analysis base cases have been identified for the three products that form the scope of the Preparatory Study. In order to facilitate the modelling of future improvement potential of each of the products, a range of design options have been selected that may be candidates to be either a Best Available Technology (BAT) or Best Not Yet Available Technology (BNAT) at product level. These design options will be included within the modelling in Task 6.

4.3.1 Module design options

The base case for the reference year of 2016, as defined previously in Task 2, has been identified as a polysilicon module based on back contact cells also known as Back Surface Field (BSF) metallisation. With a cell efficiency of 14.7% this technology accounted for the majority (more than 70%) of module products on the market at the time.

Although a thorough analysis is carried out in Task 6 to determine it, the possible candidates for the Best Available Technology (BAT) at module and cell level are CIGS and CdTe thin films, as well as modules consisting of PERC/PERT, back contact, heterojunction and bifacial crystalline silicon cell designs. Despite the cell efficiency and degradation rate of CIGS and CdTe appear to be inferior to the crystalline silicon cell technologies identified; initial evidence suggests that their life cycle performance for the functional unit of 1 kWh may be superior.

Traditionally the focus of attention for module design options has been on efficiency, the highest efficiency products in the market are PERC/PERT, HTJ and backcontact on monocrystalline wafers. However measurements of efficiency under standard conditions do not take into account all of the performance parameters in the field. Thin film and HTJ products demonstrate improved performance under certain conditions in the field. An energy rating according to IEC 61583-3 would take into account other parameters such as temperature coefficients, low-light/irradiance performance, incidence angle, etc. thereby capturing improvements on performance under a broader set of real life conditions.

Additional module design options that could be combined with these cell designs primarily relate to interconnections, encapsulation and backsheets:

- Interconnections: the electrical efficiency of crystalline technologies can be improved by using thinner busbars, multi wire design or electro-conductive backsheets to eliminate busbars, and the use of half cells. A trade-off exists between some of these options in which the use of silver can be reduced whilst more lead must be introduced into solder compounds and metallisation paste. Lead-free compounds are understood to have been demonstrated at commercial-scale but more information is required on their durability and the extent of their application field.
- Encapsulation: In relation to encapsulation, material selection can contribute to the reduction of water ingress and permeation, which in the field evidence suggest can result in subsequent chemical reactions that contribute to material and performance degradation. Material selection can also improve resistance to UV degradation. These material options may therefore improve module performance and durability along the lifetime. Glass-glass encapsulation could also minimise the potential for breakage of cells but would introduce a trade off in terms of material impacts - due to the greater environmental burden of glass.
- Backsheet: Material selection can influence the durability, recyclability and water permeability of a module. The fire protection properties must also be taken into consideration and in this respect there appears to be a trade-off between cost, durability and the potential need for flame retardants – although more information is needed about the latter.

Opportunities also exist to reduce failure and performance degradation mechanisms at a number of stages in the process of bringing a product to market. These include, in addition to those already noted in relation to encapsulants, the potential at the following stages:

- Product design stage: Implement accelerated life testing routines that combine environmental testing in order to provide feedback to the design and material selection processes. This may result in multiple improvements rather than a single identifiable design option.

- Manufacturing stage: Minimise manufacturing defects by implementing a series of factory quality testing and inspection routines;
- Transport stage: Minimise transport damage by considering the packaging used to ship products and to distribute modules to installation sites;
- Use stage: Ensure that bypass diodes can be accessed and readily exchanged in order to minimise total or partial power loss.

Whilst warrantied product performance providing extended coverage of manufacturing defects and more stable long-term efficiency is currently offered by some manufacturers, these have limited validation based on standardised product testing and performance in the field. This is particularly the case for PERC/PERT and bifacial cells, which have had limited deployment in the field. Proxies for improved performance could include accelerate life testing with multiple stress factors applied to a single product.

Candidates for the Best Not Yet Available Technology (BNAT) include modules consisting of crystalline silicon cells created by lift-off or epitaxial growth – thereby reducing silicon waste - or where the crystalline silicon cell is in a tandem formation with perovskite thin films – offering a further improvement in cell efficiency. Design for dismantling and ease of disassembly for repairing are currently considered to be BNAT practices given the limited examples of products. In the short term modules could include marking of the materials content in order to facilitate sorting and recycling, and in some to identify the presence of specific materials and chemistries that may hinder the recycling process.

4.3.2 Inverter design options

The base cases for the reference year of 2016, as defined previously in Task 2, have been identified according to their application field – 1 string inverter (residential segment), 3 string inverter (commercial segment) and central inverter (utility scale segment). The Euroefficiency of the base cases will be set at a level that accounts for the majority (of inverter products on the market at the time in the relevant application field. A performance of 97.5% is proposed as a base case euroefficiency.

In addition to this efficiency, Maximum Power Point Tracking (MPPT) is an important variable. This value is also proposed to be defined within the base case.

Although a thorough analysis is carried out in Task 6 to determine it, the possible candidates for the Best Available Technology (BAT) include:

- Micro-inverters, which offer benefits at system level because of their module-level Maximum Power Point Tracking (MPPT) and warrantied reliability that is intended to match the 25 year+ lifespan of modules. Validation of the extended warranty periods being offered based on lifetime testing and feedback from the field would, however, be required in order to support BAT status;
- Inverters that incorporate wide band gap metal-oxide-semiconductor field-effect transistors (MOSFET) which are able to maintain high performance at higher operating temperatures. They also allow for a reduction in the bill of materials although the possible trade-off in terms of the impacts of manufacturing the distinct electronic components requires further analysis.

Whilst it is understood that central inverters are commonly repaired and their primary components replaced during their relatively long lifespan (20-30 years), more information is needed for other inverter types on the potential for repair and replacement of components identified as the common cause of failures – namely main circuit board, AC contactors, fuses, capacitors and fans. It appears that water ingress and high operating temperatures may be key causes of failures.

The main candidates for the Best Not Yet Available Technology (BNAT) are inverter designs based on wider band gap semi-conductors (MOSFET). Whilst some products are understood to have entered the market in 2018 – suggesting that they could eventually be candidates for BAT - more information is needed on their commercialisation status.

The complementary role of optimisers installed at module-level in providing the function of Maximum Power Point Tracking (MPPT) can also be highlighted.

4.3.3 Photovoltaic system design options

The system base cases are proposed as consisting of representative systems for the market segments of residential (3 kW), commercial (20 kW) and utility scale (1.5 MW). These three segments are considered representative of the system scales, electrical configurations and siting conditions that are tracked by market intelligence, the IEA PVPS programme and as the basis for analysis of system cost and performance.

In order to ensure comparability it is proposed as a starting point that each base case incorporates the same module product – based on multi-crystalline aluminium back surface field cells – and only system-level performance improvements are then introduced as the basis for modelling. Later packages of module and inverter combinations could be introduced, selected based on the outcomes of the BAT and LLCC analysis.

Although a thorough analysis is carried out in Task 6 to determine it, the possible candidates for system-level BAT focus mainly on the potential to transfer optimised performance improvement practices from the utility scale segment to the residential and commercial segment where equipment selection, Performance Ratios and maintenance routines are typically less optimised. This could initially include the energy rating of modules under more representative conditions, more reliable/repairable inverters which are also smart-enabled to support monitoring, the minimisation of module mismatch and cabling losses.

The focus for system design improvements should extend to then support operation & maintenance practices. This should be with a focus on optimising energy yield by addressing derating factors such as soiling, and by diagnosing failures in the inverters and on the AC side. The two main improvement options that have been identified are as follows:

- Optimised design and yield forecasting: The use of more dynamic simulation yield modelling and forecasting software with a higher probability of accuracy (e.g. P90 exceedance level). This could include installation of a class C monitoring system on inverters to later monitor the yield with a high granularity.
- Optimised monitoring and maintenance: The potential to follow-up module and inverter failure identification with the repair of key components should be addressed. The use of remote field inspection in order to make fault diagnosis is also a possibility. This could include the application of IR imaging across multiple residential systems.

In terms of system components, the installation of bifacial modules in combination with the treatment of roof surfaces to improve reflectance, as well as the incorporation of single axis trackers to improve yield are proposed.

An additional option for system modelling is the inclusion of battery electrical storage. This is not yet considered to be a potential BAT as the environmental benefits have not yet been analyses in detail.

For the end of life the decommissioning plan is becoming a requirement for large systems and facilities and processes are now being developed to handle modules as waste arising increase into the future. The state of the art is represented by a mechanical dismantling and in some cases via chemical processing of the semiconductor. More information is needed on the inverter end of life routes.

5 Task 5: Environmental and economic assessment of base case

5.1 General introduction

The current Task 5 involves undertaking an environmental and economic assessment of the base cases identified in Task 4 using the EcoReport Tool. The EcoReport tool developed as part of the Methodology for the Ecodesign of Energy Related Products (MEErP) is used in all Ecodesign Preparatory Studies. The tool provides a streamlined life cycle assessment of the product, together with a life cycle cost assessment. The purpose of this assessment is to provide an indication of the representative environmental impacts of a typical product across the different life cycle phases. This allows the importance of a range of different environmental impacts and at different life cycle stages to be analysed. The EcoReport tool includes a set of parameters and calculations and a set of product specific inputs have been developed in order to generate the environmental and cost assessment outputs.

Task 5 comprises the following subtasks:

- Subtask 5.1 - Product specific inputs
- Subtask 5.2 - Base-Case Environmental Impact Assessment (using EcoReport 2014)
- Subtask 5.3 - Base-Case Life Cycle Cost for consumers
- Subtask 5.4 - EU totals

Task 5 collects from the previous tasks the most appropriate information for each of the Base-Cases. Using the EcoReport tool and the above inputs, the emission/resources categories in MEErP format are calculated for the different life cycle stages of a photovoltaic system and for the different Base-Cases. In addition, the Life Cycle Costs for consumers are calculated. Subsequently the Base-Case environmental impact data and the Life Cycle Cost data will be aggregated to EU-27 level, using stock and market data from Task 2.

5.2 MEErP LCA and LCC assessments

5.2.1 Product specific inputs

Aim:

This section collects all the relevant quantitative Base-Case information from previous tasks, which is needed for the life cycle assessment and life cycle costing.

5.2.1.1 Selection of base cases

In this subtask Base-Cases for modules for inverters and for systems will be considered. The selected Base-Case for modules is a module consisting of multicrystalline Silicon cells back surface field (BSF) design[347]. For inverters, 3 Base-Cases have been selected, a 2500 W string 1 phase inverter, a 20 kW string 3 phase inverter and a central inverter. The selected Base-Cases for systems are presented in Table 78. The selection was based on Task 4 for technical characteristics and Task 2 for the market data. The climate conditions that form the basis for the yield calculation are initially based in one reference location in central Europe (Strasbourg)[348].

[347] See Task 4 for a description of back surface silicon cells

[348] The modelling is based on an optimum orientation and angle for the given location, and according to IEC 61853 part 3 and the parameters defined in this IEC standard.

Table 78: Overview of selected Base-Cases for systems

	Base-case 1	Base-case 2	Base-case 3
Module type	Multi crystalline Si BSF	Multi crystalline Si BSF	Multi crystalline Si BSF
Market segment	residential	commercial	utility
Inverter type	String 1 phase inverter 2500W	String 3 phase inverter 20 kW	Central inverter 1500kW 3 strings of 500 kW
Mounting	Roof	Roof	Ground
Rated capacity DC (modules based)	3 kW	24.4 kW	1.875 MW
Module lifetime	30 years	30 years	30 years
Inverter lifetime	10 years	10 years	30 years[349]
System lifetime	30 years	30 years	30 years
Climate condition	Reference EU location	Reference EU location	Reference EU location
Reference yield before PR (in year 1)	1331 kWh/kWp	1331 kWh/kWp	1331 kWh/kWp
Performance Ratio	0.75	0.825	0.825
AC:DC ratio	0.83	0.83	0.80
Performance degradation rate of the modules (% per year	0.70 %	0.70 %	0.70 %
Failure rate (%/year) **Module** **Inverter**	 0.005-0.1 10	 0.005-0.1 Below 10	 0.005-0.1 Below 10
Availability	TBD	98%	98%

Sources for the data:
Performance degradation rate:
Performance ratio: PV LCOE report July 2015. For locations such as London, Munich and Stockholm
DC:AC ratio: Becquerel Institute 2018 and GTM Research 2018
Downtime: IEA, *Task 13 report: Technical Assumptions Used in PV Financial Models - Review of Current Practices and Recommendations*, May 2017
Performance degradation: as proposed by JRC C2 unit, see also Jordan, D. C., Silverman, T. J., Wohlgemuth, J. H., Kurtz, S. R., & VanSant, K. T. (2017). Photovoltaic failure and degradation modes. Progress in Photovoltaics: Research and Applications, 25(4), 318–326. https://doi.org/10.1002/pip.2866

The performance ratios for the three system sizes are based on monitored performance of systems in the field. In order to stablish performance ratios for system designs, derate factors reflecting real life performance would have to be defined. The more factors that influence performance that can be taken into account, the more accurate the predicted performance will be.

[349] *The components of the inverter are progressively repaired and replaced along their lifetime*

5.2.1.2 Functional unit for the LCA

Task 1 of this study defines the functional unit of analysis for PV modules, inverters and systems as follows:

- For PV modules: 1 kWh of DC power output under predefined climatic and installation conditions as defined for a typical year and for a service life of 30 years

- For inverters: 1 kWh of AC power output from a reference photovoltaic system (incorporating the efficiency of a specific inverter) under predefined climatic and installation conditions as defined for a typical year and for a service life of 10 years.

- For systems: 1 kWh of AC power output supplied under fixed climatic and installation conditions as defined for a typical year (with reference to IEC 61853- 4) and for a service life of 30 years.

This extended service life allows to take into account operation and maintenance activities, failure probability and degradation rates along the lifetime of the system and its components.

Modules

One of the main sources of life cycle inventory data is the PEF screening study. It provides life cycle inventory data for 1m^2 of modules. The data have to be translated to the functional unit, being 1 kWh of DC electricity. The input parameters for the calculation of the area of modules needed to produce 1 kWh is provided in Table 79.

Table 79: System parameters for calculation of functional unit

	Module parameters
Module Size (m^2/module)	1.6
Module conversion efficiency (%)	14.7
Wafer thickness (micrometer)	200
Cell size (mm^2)	156*156
Technology	Average technology mix of front/back cell connection, diffusion and front collection grid
Main data source	De Wild-Scholten (2014)
Rated power (Wp/m^2)	147
Cells area per module (%)	95.39%
System yield - Yf (in year 1) (kWh$_{DC}$/kWp)	997
Expected lifetime (years)	30
Module area per kWh energy produced (m^2)	**2.45E-04**

With a PR of 0.75, the average annual electricity would be 997 kWh/kWp (1331 kWh/kWp*0.75)

Inverters

Calculations of the number of inverters needed per functional unit are detailed below in Table 80. According to the IEA PVPS report on recent trends[350], there is a predictive maintenance practice whereby an inverter replacement is usually planned just after year 10 of the PV system operation. Therefore, the inverter will be replaced 2 times in 30 years life span (at 10 yrs and at 20 yrs).

For larger central inverter systems it is assumed that the inverter lasts 30 years but during this period major components are replaced. The housing cabinet, connectors and distribution boxes will be kept because they won't wear out.

[350] *IEA PVPS, Technical Assumptions Used in PV Financial Models. Review of Current Practices and Recommendations. 2017.*

Table 80: Calculation of functional unit for inverters

	BC1	BC2	BC3	unit
System	3	24.4	1875	kWp
Inverter	2.5	20	1500	kW
Inverter:module DC capacity	1:1.20	1:1.20	1:1.25	
Life span system	30	30	30	years
Life span inverter	10	10	30	years
Inverter units in the LC	3	3	1 (replacement of parts)	unit
Electricity output system	81	662	50862	MWh
Inverter units per FU (1kWh)	3.69E-05	4.53E-06	1.97E-08	inverters per kWh

5.2.1.3 Life cycle cost and Levelised cost of electricity

The MEErP methodology is usually based on an analysis of life cycle cost (LCC). An LCC calculation provides a summation of all of the costs incurred along the life cycle of the product. This makes it relevant to consumers because this cost can then be related to potential savings.

The concept of Levelised Cost of Electricity (LCOE) is widely used in the electricity sector to express the total life cycle cost of delivering electricity to the grid. The difference of LCOE with respect of LCC is that it is normalized to the unit of power generated. This enables comparisons to be made between different power generation options. LCOE is defined by the European Photovoltaic Technology Platform as the average generation cost, i.e., including all the costs involved in supplying PV at the point of connection to the grid.

The PV LCOE, expressed in €/kWh in real money, can be defined by equation:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n}[OPEX(t)/(1+WACC_{Nom})^t]}{\sum_{t=1}^{n}[Utilisation_0 \cdot (1-Degradation)^t/\,(1+WACC_{Real})^t]}$$

where

t = time (in years)

n = economic lifetime of the system (in years)

CAPEX = total investment expenditure of the system, made at t=0 (in €/kWp)

OPEX (t) = operation and maintenance expenditure in year t (in €/kWp)

$WACC_{Nom}$ = nominal weighted average cost of capital (per annum)

$WACC_{Real}$ = real weighted average cost of capital (per annum)

$Utilisation_0$ = initial annual utilisation in year 0 without degradation (in kWh/kWp)

Degradation = annual degradation of the nominal power of the system (per annum)

and $WACC_{Real} = (1 + WACC_{Nom}) / (1 + Inflation) - 1$

where Inflation is the annual inflation rate.

Furhter explanation and analysis using LCOE can be found in section 5.3

5.2.1.4 Stock and/or sales

Information on the stock of modules has been taken from Task 2 report. The selected Base-Cases cover 45% of the market.

The EU stock for modules inverters and systems must be estimated because only aggregated figures for shipped stock capacity and installed stock capacity have been found to be available. The stock has first been estimated based assumptions of the average size of systems installed in the different market segments that have been analysed – residential (3 kW), commercial (20 kW) and utility scale (1500 kW). As was noted in Task 2 the inverter data is derived based on DC:AC ratios for the market segments.

In order to derive units of modules and inverters sold assumptions are then applied to obtain module and inverter stock estimates. The estimated technology shares presented in Task 2 for each market segment form the starting point for the stock model. The 'typical' module and inverter size (e.g. 200 W modules, 5 kW inverter) sold to each market segment is then used as the main assumption for deriving the units of stock sold.

A further refinement of the stock model is later proposed based on data points for the size of each system installed. In some cases this data may be restricted to those systems in receipt of public subsidies. It is proposed that this data is obtained from selected Member States that account for the majority of the EU stock – namely Germany, France, Italy, Spain and the United Kingdom.

Therefore the 2015 annual sales will serve as a reference. These total EU sales calculations will be done in a later update of the current Task.

5.2.1.5 Product service life

The base assumption is that modules will have a technical lifetime of 30 years, in line with the typical product performance warranty period provided by manufacturers (see task 2, section 2.3.2.2).

According to an IEA Task 13 report on the financing of PV systems the technical life of an inverter is considered to be between 10-15 years. For the purpose of this study a minimum technical lifetime of 10 years is assumed for an inverter (see Task 2, section 2.2.2.1).

5.2.1.6 Purchase price and repair and maintenance cost

The input data for life cycle cost (LCC) calculations related to capital (CAPEX) and operational (OPEX) expenditures is summarized in Table 81. It builds on input data sourced from Tasks 2-4.

The final data will be added after completion of Tasks 2 and 4, for this first draft the data in Table 81 will be used (sample data only).

Table 81 Input data for Life Cycle Cost calculations

	Frequency	**Base-case 1**	**Base-case 2**	**Base-case 3**
Cell type		Multi Si BSF	Multi Si BSF	Multi Si BSF
Scale		residential	commercial	utility
Inverter		String 2500W	String 20 kW	Central 1500 kW
Mounting		Roof	Roof	Ground
VAT		incl.	excl.	excl.
CAPEX modules(€/W)	1 @ start	0,61 €	*0,61 €*	*0,45 €*
CAPEX inverter(€/kVA)	1 @ start	0,17 €	*0,09 €*	*0,07 €*
CAPEX BOS other (€/W)	1 @ start	0,493 €	*0,493 €*	*0,335 €*
CAPEX design labour (€/plant)	1 @ start	153,00 €	*1.020,00 €*	*52.500,00 €*
CAPEX install. labour (€/W)	1 @ start	0,315 €	*0,315 €*	*0,05 €*
CAPEX(-) scrap value (€/W)	1 @ EoL	*TBD €*	*TBD €*	*TBD €*
CAPEX uninstall labour (€/W)	1 @ EoL	*< 0,315 €*	*< 0,315 €*	*< 0,05 €*
CAPEX recycle modules (€/module)	1 @ EoL	*TBD €*	*TBD €*	*TBD €*
OPEX modules failures (€/W)	see Task 4	=CAPEX mod.	=CAPEX mod.	=CAPEX mod.
OPEX inverter failures (€/kVA)	see Task 4	=CAPEX inv.	=CAPEX inv.	=CAPEX inv.
OPEX labour spot repair	see Task 4	*Modules:* *3-41€/repair* *Inverters:* *550-950€/unit*	*Modules:* *2-38 €/repair* *Inverters:* *550-950€/unit*	*Modules:* *1 - 35 €/repair* *Inverters:* *TBD*
OPEX O&M (€/kW/year)	0 for BC1 1/year for BC2/3	*5-9 €*	*10-18 €*	*13-20 €*

Notes
PV Technology Platform, PV LCOE in Europe, 2014-2030, 2015
Task 2, Table 15
Strupeit.L and Neij.L , 2017
Solar bankability, 2017
Repair cost range is per component, depending on the component and its failure rate
Secondsol, the photovoltaic market place:
https://www.secondsol.com/en/services/pv_wechselrichter_reparatur.htm
https://www.secondsol.com/en/services/reparaturmodule.htm

5.2.1.7 Other economic parameters

The MEErP 'discount rate' is set at 4%, following rules for EU impact assessments.

The MEErP defines an 'escalation rate' for energy costs. The default 'escalation rate' is set at 4%. In the case of this product group, the functional unit for comparison is the cost of generating 1 kWh of electricity. PV installations produce their own electricity and due to this the market price of electricity has little impact on this task, analyses will be based on the cost of the PV system to produce energy. As a result the escalation rate is not required in the calculation because energy sales or savings are not taken into account.

More information on the concept of life cycle costing and the levelized cost of electricity (LCOE) is given in a later section 5.4.

Other sources of economic data for LCC/LCOE which can be used for sensitivity analysis in Task 7 are:

- The European Commission has recently developed a better regulation toolbox of which Chapter 8 tool #58 discusses discount rate assumptions. The recommended social discount rate herein is 4%. This 4% rate is intended to be applied in real terms and is therefore applied to costs and benefits expressed in constant prices.

- The JRC[351] calculated the PV LCOE in 2014 for developing cost maps for unsubsidised photovoltaic electricity with a discount rate of 5 %.

5.2.2 Product life cycle information

5.2.2.1 Production phase

This section provides the bill of material (BOM) information for the selected Base-Cases. BOM information is provided in EcoReport format. In EcoReport, BOMs associated with material use for repair or replacement of products is assigned to the production phase. This is as opposed to the EN 15804 standard for construction products where it is assigned to the use phase

Some of the materials used to manufacture a PV module and inverter are not included as standard materials in EcoReport. The latest version of EcoReport, developed in 2011, enables the user to enter impact assessment data for other materials. The materials which have been added to the EcoReport tool are specified in Annex 5A and impact assessment data was obtained by modelling the materials with the same impact categories as in EcoReport but within Simapro, using inventory data from Ecoinvent, as well as primary data from the PEF pilot. The energy use and related emissions which occur during manufacturing have been added to the tool as well.

5.2.2.1.1 BOM multi Si module

Material input for the multi Si module has been taken from the data collection exercise carried out for the PEF Screening study[352]. This is considered to provide the most up to date and representative dataset for the silicon wafer based cells, as validated by the data quality rating (DQR) contained within the PEF pilot.

The solar cells are assumed to be produced in China, but assembly of the modules is done in Europe. The data are presented per m^2. For this assessment, packaging materials, some auxiliaries and the end of life treatment of the production waste have been omitted. The PEF data provided the input of photovoltaic cells per m^2, not per kg. The weight of the photovoltaic cells has been calculated based on the wafer thickness. The wafer has a thickness of 200 micrometer (in the PEF screening study). The specific weight cell weight is 0.5587 kg/m^2cell. The cell area per m^2 module is 95,39% (from the PEF screening study), which results in a cell weight of 0.533 kg/m^2 module.

The materials which were not available and have been added to the EcoReport tool are: multi Si photovoltaic cell, tin, lead, ethylvinylacetate, polyvinylfluoride, silicone, solar glass and tempering (Table 82). Annex 5A provides more details on the modelling of these additional materials.

Energy use and emissions occurring during the production have been added to the tool as well. Table 83 provides an overview of the non-material related inputs for the manufacturing of 1m^2 multi-Si modules. The data have been taken from the PEF screening study[352].

[351] https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/cost-maps-unsubsidised-photovoltaic-electricity

[352] Wyss F., Frischknecht R., de Wild-Scholten M., Stolz P. 2015. PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots

Table 82: BOM multi-Si module

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014			Document subject to a legal notice (see below)	
ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS		EcoReport 2014: INPUTS Environmental Impact		Assessment of
Nr	multi Si panel 1 kWh Products	Date	Author vito	
Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?

Pos nr	Description of component	Weight in g	Category	Material or Process	Recyclable?
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell, multi-Si, at plant/m2/CN U	1.27E-01	8-Extra	102-photovoltaic cell, multi-Si, at plant/m2/CN	
4					
5	**interconnection**				
6	Tin, at regional storage/RER U	3.08E-03	8-Extra	103-Tin, at regional storage/RER U	
7	Lead, at regional storage/RER U	1.73E-04	8-Extra	104-Lead, at regional storage/RER U	
8	Copper, at regional storage/RER U and Wire drawing, copp	2.45E-02	4-Non-ferro	30 - Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil, at plant/RER U	2.09E-01	8-Extra	105-Ethylvinylacetate, foil, at plant/RER U	
12					
13	**backsheet**				
14	Polyvinylfluoride film, at plant/US U	2.67E-02	8-Extra	106-Polyvinylfluoride film, at plant/US U	
15	Polyethylene terephthalate, granulate, amorphous, at plan	8.26E-02	1-BlkPlastics	10 - PET	
16					
17	**pottant & sealing**				
18	Silicone product, at plant/RER U	2.91E-02	8-Extra	107-Silicone product, at plant/RER U	
19					
20	**frame**				
21	Aluminium alloy, AlMg3, at plant/RER U	5.08E-01	4-Non-ferro	27 - Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron, at regional storage/RER U & Temperir	2.11E+00	8-Extra	108-solar glass and tempering	
25					
26	**junction box**				
27	Diode, unspecified, at plant/GLO U	6.72E-04	6-Electronics	49 - SMD/ LED's avg.	
28	Polyethylene, HDPE, granulate, at plant/RER U	5.68E-03	1-BlkPlastics	2 - HDPE	
29	Glass fibre reinforced plastic, polyamide, injection mouldin	7.05E-02	2-TecPlastics	19 - E-glass fibre	

Table 83: Energy inputs and emissions occurring during the manufacturing of the multi Si module (per m^2)

Input manufacturing	**Amount**	**Unit**
European medium voltage electricity	3.7312	kWh
Diesel + emissions from diesel combustion	0.00875	MJ
NMVOC	0.0080625	kg
CO_2	0.021812	kg

5.2.2.1.2 BOM 2500 W inverter

Material input for the 2500 W inverter has been taken from a study made by Tschümperlin et al. (Treeze)[353]. This study provides the most recent primary data for commercial inverter products. The data are presented below per unit of inverter. For this assessment, packaging materials and the end of life treatment of production waste have been omitted. The benefit of this detailed BOM is that later on in Task 6 the impact from repair can be modelled whereas previous Ecodesign preparatory studies using the MEErP tool have aggregated the Printed Circuit Board including electronic components. The inverter is replaced two times during the life span of the 30 years.

Tin is the only materials which was not available and has been added to the EcoReport tool (Table 85). Annex 5A provides more details on the modelling of the additional materials.

Energy use for production has been added to the tool as well. Table 84 provides an overview of the energy inputs for the manufacturing of a 2500 W inverter (1 unit). The data have been taken from Tschümperlin et al. (Treeze)[353].

Table 84: Energy inputs for manufacturing of 2500 W

Input manufacturing	Amount	Unit
European medium voltage electricity	10.6	kWh
Light fuel oil burned in industrial furnace	0.226	MJ
Natural gas (burned)	3.57	MJ
Heat	9.21	MJ

353 Tschümperlin L, Stolz P., Frischknecht R. 2016. Life cycle assessment of low power solar inverters (2.5 to 20 kW). Available online: http://treeze.ch/fileadmin/user_upload/downloads/Publications/Case_Studies/Energy/174-Update_Inverter_IEA_PVPS_v1.1.pdf

Table 85: BOM 2500 W inverter (1 unit)

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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS Assessment of Environmental Impact

Nr	2500 W inverter - 1 unit Products	Date	Author Vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	4.77E+03	4-Non-ferro	28 -Al diecast	
3	aluminium alloy, AlMg3, at plant	2.12E+02	4-Non-ferro	28 -Al diecast	
4	copper, at regional storage	1.91E+03	4-Non-ferro	31 -Cu tube/sheet	
5	steel, low-alloyed, at plant	9.07E+02	3-Ferro	22 -St sheet galv.	
6	polypropylene, granulate, at plant	8.82E+02	1-BlkPlastics	4 -PP	
7	polycarbonate, at plant	2.02E+02	2-TecPlastics	13 -PC	
8	cable, connector for computer, without plugs, at plant	1.31E+02	4-Non-ferro	30 -Cu wire	
9	inductor, ring core choke type, at plant	8.71E+02	2-TecPlastics	13 -PC	
10	integrated circuit, IC, logic type, at plant	6.61E+01	6-Electronics	47 -IC's avg., 5% Si, Au	
11	ferrite, at plant	3.49E+01	3-Ferro	25 -Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	2.99E+01	1-BlkPlastics	8 -PVC	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	1.31E+02	2-TecPlastics	12 -PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	3.29E+02	6-Electronics	51 -PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	9.59E+00	8-Extra	109-Tin, at regional storage/RER U	
17	connector, clamp connection, at plant	2.44E+01	4-Non-ferro	32 -CuZn38 cast	
18	inductor, ring core choke type, at plant	1.31E+02	2-TecPlastics	13 -PC	
19	inductor, miniature RF chip type, MRFI, at plant	1.10E+00	2-TecPlastics	13 -PC	
20	integrated circuit, IC, logic type, at plant	1.55E+02	6-Electronics	47 -IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	1.87E+00	6-Electronics	47 -IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	1.92E+01	6-Electronics	49 -SMD/ LED's avg.	
23	transistor, SMD type, surface mounting, at plant	4.17E+01	6-Electronics	49 -SMD/ LED's avg.	
24	diode, glass-, SMD type, surface mounting, at plant	2.01E+00	6-Electronics	49 -SMD/ LED's avg.	
25	light emitting diode, LED, at plant	1.44E-02	6-Electronics	49 -SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	1.66E+02	4-Non-ferro	32 -CuZn38 cast	
27	capacitor, electrolyte type, > 2cm height, at plant	2.57E+02	4-Non-ferro	28 -Al diecast	
28	capacitor, electrolyte type, < 2cm height, at plant	6.71E+00	4-Non-ferro	28 -Al diecast	
29	capacitor, SMD type, surface-mounting, at plant	1.33E+00	6-Electronics	49 -SMD/ LED's avg.	
30	resistor, wirewound, through-hole mounting, at plant	1.12E+00	6-Electronics	49 -SMD/ LED's avg.	
31	resistor, SMD type, surface mounting, at plant	4.57E+00	6-Electronics	49 -SMD/ LED's avg.	
32	ferrite, at plant	2.55E-02	3-Ferro	25 -Ferrite	
33	transformer, low voltage use, at plant	4.01E+01	3-Ferro	25 -Ferrite	
34	plugs, inlet and outlet, for network cable, at plant	2.79E+02	1-BlkPlastics	8 -PVC	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	2.56E+01	2-TecPlastics	12 -PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	2.40E-01	4-Non-ferro	30 -Cu wire	
37					

5.2.2.1.3 BOM 20 kW inverter

Material input for the 20 kW inverter have been taken from a study made by Tschümperlin et al. (Treeze)[353]. This study provides the most recent primary data for commercial inverter products. The data are presented below per unit of inverter. For this assessment, packaging materials, and end of life treatment of production waste have been omitted. The benefit of this detailed BOM is that later on in Task 6 the impact from repair can be modelled, whereas previous Ecodesign preparatory studies using the MEErP tool have aggregated the Printed Circuit Board including electronic components.

The inverter is replaced two times during the life span of the 30 years. The material that was not available and has been added to the EcoReport tool was tin (Table 86). Annex 5A provides more details on the modelling of the additional materials.

Energy use for production has been added to the tool as well.

Table 86: BOM 20 kW inverter (1 unit)

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014				Document subject to a legal notice (see below)	
	ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS		EcoReport 2014: INPUTS Environmental Impact	Assessment of	
Nr	20 kW inverter - 1 unit Products		Date	Author Vito	
Pos nr	**MATERIALS Extraction & Production Description of component**	**Weight in g**	**Category Click &select**	**Material or Process select Category first !**	**Recyclable?**
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	1.96E+04	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	8.70E+02	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	7.86E+03	4-Non-ferro	31-Cu tube/sheet	
5	steel, low-alloyed, at plant	3.73E+03	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	3.63E+03	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	8.32E+02	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	5.40E+02	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	3.58E+03	2-TecPlastics	13 - PC	
10	integrated circuit, IC, logic type, at plant	2.72E+02	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	1.44E+02	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	1.23E+02	1-BlkPlastics	8 - PVC	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	5.37E+02	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	1.36E+03	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	3.94E+01	8-Extra	109-Tin, at regional storage/RER U	
17	connector, clamp connection, at plant	1.00E+02	4-Non-ferro	32 - CuZn38 cast	
18	inductor, ring core choke type, at plant	5.37E+02	2-TecPlastics	13 - PC	
19	inductor, miniature RF chip type, MRFI, at plant	4.53E+00	2-TecPlastics	13 - PC	
20	integrated circuit, IC, logic type, at plant	6.39E+02	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	7.70E+00	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	7.89E+01	6-Electronics	49 - SMD/ LED's avg.	
23	transistor, SMD type, surface mounting, at plant	1.72E+02	6-Electronics	49 - SMD/ LED's avg.	
24	diode, glass-, SMD type, surface mounting, at plant	8.25E+00	6-Electronics	49 - SMD/ LED's avg.	
25	light emitting diode, LED, at plant	5.92E-02	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	6.84E+02	4-Non-ferro	32 - CuZn38 cast	
27	capacitor, electrolyte type, > 2cm height, at plant	1.06E+03	4-Non-ferro	28 - Al diecast	
28	capacitor, electrolyte type, < 2cm height, at plant	2.76E+01	4-Non-ferro	28 - Al diecast	
29	capacitor, SMD type, surface-mounting, at plant	5.49E+00	6-Electronics	49 - SMD/ LED's avg.	
30	resistor, wirewound, through-hole mounting, at plant	4.60E+00	6-Electronics	49 - SMD/ LED's avg.	
31	resistor, SMD type, surface mounting, at plant	1.88E+01	6-Electronics	49 - SMD/ LED's avg.	
32	ferrite, at plant	1.05E-01	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	1.65E+02	3-Ferro	25 - Ferrite	
34	plugs, inlet and outlet, for network cable, at plant	1.15E+03	1-BlkPlastics	8 - PVC	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	1.05E+02	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	9.86E-01	4-Non-ferro	30 - Cu wire	
37					
38					
39					

Table 87 provides an overview of the energy inputs for the manufacturing of a 20 kW inverter (1 unit). The data have been taken from Tschümperlin et al. (Treeze)[353].

Table 87: Energy inputs for manufacturing of 20 W

Input manufacturing	**Amount**	**Unit**
European medium voltage electricity	43.4	kWh
Light fuel oil burned in industrial furnace	0.928	MJ
Natural gas (burned)	14.7	MJ
Heat	3.79	MJ

5.2.2.1.4 BOM central inverter

The central inverter consists of 3 strings of 500 kW each. Material input for the central inverter has been taken from Ecoinvent database. Other data sources such as GaBi have to be reviewed further for their representativeness. The data is presented below per unit of inverter (comprised of three strings of 500 kW each). For this assessment, packaging materials and end of life treatment of produced waste have been omitted. Previous Ecodesign preparatory studies have used an aggregated Printed Circuit Board including electronic components. However, in this study a detailed BOM has been identified for use and as a result it will be possible that later on in Task 6 the impact of repair can be modelled.

In the central inverter, replacements take place. Some parts are replaced two times during the life span of the inverter. It is assumed that the entire print board assembly will be replaced after 10 and 20 years. All other components (aluminium, HDPE, copper, steel and glass fibre reinforced polyamide) are not replaced during the life span of the inverter.

Table 88: BOM 1500 kW inverter (1 unit consisting of 3 strings of 500 kW each)

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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS — EcoReport 2014: INPUTS — Assessment of Environmental Impact

Nr	3*500 kW inverter		Date	Author	
	Products			Vito	
Pos nr	**MATERIALS Extraction & Production Description of component**	**Weight in g**	**Category Click&select**	**Material or Process select Category first !**	**Recyclable?**
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	7.15E-03	4-Non-ferro	28 - Al diecast	
3	Polyethylene, HDPE, granulate, at plant/RER U	1.20E-03	1-BlkPlastics	2 - HDPE	
4	copper, at regional storage	1.83E-02	4-Non-ferro	31-Cu tube/sheet	
5	steel, low-alloyed, at plant	7.85E-02	3-Ferro	22 - St sheet galv.	
6	Alkyd paint, white, 60% in solvent, at plant/RER U	1.20E-03			
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	6.28E-03	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	Printed wiring board, through-hole, at plant/GLO U	1.20E-04	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
17	connector, clamp connection, at plant	7.77E-03	4-Non-ferro	32 - CuZn38 cast	
18	inductor, ring core choke type, at plant	5.75E-05	2-TecPlastics	13 - PC	
20	integrated circuit, IC, logic type, at plant	4.59E-06	6-Electronics	47 - IC's avg., 5% Si, Au	
22	Transistor, wired, small size, through-hole mounting, at plant/GLO U	6.23E-06	6-Electronics	49 - SMD/ LED's avg.	
24	Diode, glass-, through-hole mounting, at plant/GLO U	7.70E-06	6-Electronics	49 - SMD/ LED's avg.	
26	Capacitor, film, through-hole mounting, at plant/GLO U	5.59E-05	4-Non-ferro	32 - CuZn38 cast	
27	capacitor, electrolyte type, > 2cm height, at plant	4.19E-05	4-Non-ferro	28 - Al diecast	
28	Capacitor, Tantalum-, through-hole mounting, at plant/GLO U	4.52E-06	4-Non-ferro	28 - Al diecast	
30	Resistor, metal film type, through-hole mounting, at plant/GLO U	7.54E-07	6-Electronics	49 - SMD/ LED's avg.	

All materials except one were sourced from the MEErP EcoReport tool. Alkyd paint was not available and it has been omitted from the assessments.

Energy use for production has been added to the tool as well. Table 89 provides an overview of the energy inputs for the manufacturing of a 1500 kW central inverter. The data have been taken from Ecoinvent.

Table 89. Energy inputs for manufacturing of 1500 kW

Input manufacturing	Amount	Unit
European medium voltage electricity	13733.4	kWh

5.2.2.2 Additional material loss in the manufacturing phase

The EcoReport tool contains fixed impacts on weight basis for manufacturing of components. These data have been used in the study. The only variable that can be edited in this section is the percentage of sheet metal scrap. The default value given by the EcoReport tool is 25%. This value is reduced to 10%, which is a recommended value for folded sheets mentioned in the MEErP methodology report.

5.2.2.3 Distribution phase

For the distribution phase the EcoReport tool requires the volume of the final packaged product to be entered as an input. Based on this volume, the impact of transport of the product to the site of installation is calculated.

In addition, replies to the EcoReport key questions regarding the product type and installation were given as follows:

Multi Si-modules

- 'Is it an ICT or consumer electronic product less than 15 kg? No
- 'Is it an installed appliance? Yes'
- The volume of the packaged module is assumed to be 0.2 m^3 (1m*1m*0.2m).

2500 W inverter

- 'Is it an ICT or consumer electronic product less than 15 kg? No.
- 'Is it an installed appliance? Yes.
- The volume of the packaged inverter is assumed to be 0.02 m^3 (355 mm*419 mm*138 mm[354]).

20 kW inverter

- 'Is it an ICT or consumer electronic product less than 15 kg? No.
- 'Is it an installed appliance? Yes.
- The volume of the packed module is assumed to be 0.083 m^3 (707 mm*492 mm*240 mm[355]).

1500 kW inverter

- 'Is it an ICT or consumer electronic product less than 15 kg? No.
- 'Is it an installed appliance? Yes.
- The volume of the packaged inverter is assumed to be 18.85 m^3 (2912 mm*4403 mm*1470 mm[356]).

The reply 'Yes' introduces burdens associated air freight, as this is the assumed modes of shipment for electronic products. However photovoltaic products are usually sea freight.

5.2.2.4 Use phase

The use phase input data aspects are related to the system level, because only a system with modules and inverter can be operational.

Use phase data will be sourced from previous Tasks. Note that the Performance Ratio as defined in Task 3 includes the inverter efficiency that is included in Task 4.

The final data will be updated following further consultation with stakeholders, so for this first draft the data in Table 90 will be used.

[354] *https://www.ebay.com/itm/Inverter-Growatt-MTL-2500-3000-3600-4200-5000-Watts-select-PV-energie/183050798999?hash=item2a9ead8797:m:mN3dAPUYPQESh9mjeheAkag:rk:6:pf:0*

[355] *http://www.sofarsolar.com/product-detail/406/Sofar%2020000TL*

[356] *https://library.e.abb.com/public/130d0dd62e4f47a992e1eaf9e4ee26e5/ULTRA-EN-Rev%20E.pdf*

Table 90. Use phase input data

	Base-case 1	Base-case 2	Base-case 3
Scale	residential	commercial	utility
Reference yield, Yr(hours) (in year 1)	See Table 78	See Table 78	See Table 78
Performance Ratio (in year 1)	See Table 78	See Table 78	See Table 78
Performance degradation rate (% per year)	See Table 78	See Table 78	See Table 78
Number of maintenance operations during the lifetime	0	1	1
Travel distance for maintenance (km)	Not relevant	50	50

5.2.2.5 End-of-life

Default end-of-life values from the MEErP EcoReport tool have been used. They are provided in

Table **91**.

The aluminium frame of the multi Si-module is part of the non-ferrous section and 95% goes to recycling. The glass is part of the 'extra' materials and 60% goes to recycling.

In the EcoReport tool, end-of-life scenarios are assigned to material categories. It is not possible to assign end-of-life scenarios to individual components. The recent publication from Duflou et al. (2018)[357] gives additional insights into end-of-life treatment strategies of photovoltaic modules.

Table 91. End-of-life scenario's from EcoReport tool. Default values in red.

Per fraction (post-consumer)	1	2	3	4	5	6	7a	7b	7c	8	9	
	Bulk Plastics	TecPlastics	Ferro	Non-ferro	Coating	Electronics	Misc., excluding refrigant & Hg	refrigerant	Hg (mercury), in mg/unit	Extra	Auxiliaries	*TOTAL (CARG avg.)*
current fraction, in % of total mass (or mg/unit Hg)	2.8%	2.3%	0.0%	17.2%	0.0%	0.0%	0.0%	0.0%	0.0	77.7%	0.0%	*100.0%*
fraction x years ago, in % of total mass	2.8%	2.3%	0.0%	17.2%	0.0%	0.0%	0.0%	0.0%	0.0	77.7%	0.0%	100.0%
CAGR per fraction r, in %	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	
current product mass in g	*373*	*298*	*0*	*2250*	*0*	*3*	*0*	*0*	*0*	*10186*	*0*	*13110*
stock-effect, total mass in g/unit	0	0	0	0	0	0	0	0	0.0	0	0	*0*
EoL available, total mass ('arisings') in g/unit	373	298	0	2250	0	3	0	0	0.0	10186	0	*13110*
EoL available, subtotals in g		671		2250		3	0	0	0.0	10186	0	*13110*
												AVG
EoL mass fraction to re-use, in %						1%			1%		5%	*1.0%*
EoL mass fraction to (materials) recycling, in %	29%	29%		94%		50%	64%	30%	39%	60%	30%	*64.2%*
EoL mass fraction to (heat) recovery, in %	15%	15%		0%		0%	1%	0%	0%	0%	10%	*0.8%*
EoL mass fraction to non-recov. incineration, in %	22%	22%		0%		30%	5%	5%	5%	10%	10%	*8.9%*
EoL mass fraction to landfill/missing/fugitive, in %	33%	33%		5%		19%	29%	64%	55%	29%	45%	*25.1%*
TOTAL	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100.0%*
EoL recyclability****, (click& select: 'best', '>avg', 'avg' (basecase); '< avg'.; 'worst')	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	**avg**	***avg***

[357] *Duflou J., Peeters J., Altamirano D., Bracquene E., Dewulf W. 2018. Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery. CIRP Annals – Manufacturing technology67 (2018) 29-32*

5.3 Base Case Environmental Impact Assessment (using EcoReport 2014)

Life cycle environmental impacts have been calculated for the Base-Cases using the EcoReport tool 2014. The data and assumptions used are listed in the previous section (section 5.2).

Emission and resource use have been expressed as results for each of the different impact categories which are required by the MEErP methodology for the life cycle stages:

- Raw Materials Use and Manufacturing;
- Distribution;
- Use phase;
- End-of-Life Phase.

In the sub-sections below the results are expressed as relative values (contribution of the life cycle phase to the total environmental impact). Absolute results for each Base-Case are provided in Annex D.

The graphs in the sub-sections below show the environmental impact profile of the different base cases. On the X-axis of the graphs the environmental impact categories to be considered in MEErP studies are given. The environmental impact categories have different units, so it is not possible to show the absolute values in one graph per base case. In the graphs, the total environmental impact is set at 100% (production, distribution, use and end-of-life) per impact category. The bar is then split up into the different life cycle stages and shows the importance of the life cycle stages per environmental indicator.

5.3.1 Scaling the EcoReport results to the functional unit

In Task 1 several functional units were discussed and an agreement was reached to use the following functional unit definitions

- 1 kWh of DC power output under predefined climatic and installation conditions defined for 1 year and for a service life of 30 years
- 1 kWh of AC power output from a reference photovoltaic system (excluding the efficiency of the inverter) under predefined climatic and installation conditions for 1 year and assuming a service life of 10 years
- "1 kWh of AC power output supplied under fixed climatic conditions for 1 year (with reference to IEC 61853 part 4) and assuming a service life of 30 years".

The approach for Task 5 is to analyze the LCA impacts with the MEErP tool for both PV modules and inverters first individually and then to incorporate them as components into the functional unit at system level. This will allow to assess improvement options in Task 6. In any case the data will be available to process other options when deemed necessary later on in Task 6/7. This means that for example the inverter efficiency is taken into account at system level trough the Performance Ratio, see input defined in section 5.2.2.4.

5.3.2 Results Base-Case for modules

The bill of materials for a multi Si module is available in section 5.2.2.1. Modules are not assumed to be replaced during the lifespan.

5.3.2.1 Multicrystalline Silicon BSF

This section discusses the LCA results for the multicrystalline Si module. Table 92 provides the LCIA results in absolute values for 1 kWh produced by a multi Si BSF PV module. Figure 111 provides a graphical presentation of the life cycle of a multi-Si module. From this figure it can be concluded that the production phase is the most important life cycle phase. The impact from the use phase is very limited.

The default in MEErP of 1% of BOM added to represent spare parts is included. The category 'extra' contains all the added materials, being the photovoltaic cell, tin, lead, ethylvinylacetate, polyvinylfluoride, silicone, solar glass and tempering.

Table 92. EcoReport results for Multi Si module (per kWh)

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EcoReport 2014: OUTPUTS Assessment of Environmental Impact

ECO-DESIGN OF ENERGY-RELATED PRODUCTS

Life Cycle Impact (per unit) of Multi Si panel (1 kWh)

Nr	Life cycle Impact per product:	Reference year	Author
0	Multi Si panel (1 kWh)	2014	Vito

Nr	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**8.83E-02**		**8.83E-04**	4.90E-02	4.01E-02	0.00E+00	**0.00E+00**
2	TecPlastics	g			**7.05E-02**		**7.05E-04**	3.92E-02	3.20E-02	0.00E+00	**0.00E+00**
3	Ferro	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
4	Non-ferro	g			**5.32E-01**		**5.32E-03**	2.69E-02	5.11E-01	0.00E+00	**0.00E+00**
5	Coating	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
6	Electronics	g			**6.72E-04**		**6.72E-06**	3.33E-04	3.46E-04	0.00E+00	**0.00E+00**
7	Misc.	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
8	Extra	g			**2.50E+00**		**0.00E+00**	9.85E-01	1.54E+00	0.00E+00	**-2.50E-02**
9	Auxiliaries	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
10	Refrigerant	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
	Total weight	g			**3.19E+00**		**6.92E-03**	1.10E+00	2.12E+00	0.00E+00	**-2.50E-02**
									see note!		
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	6.40E-01	2.45E-02	**6.65E-01**	**1.57E-01**	**6.40E-03**	1.48E-02	-1.71E-01		**6.72E-01**
12	of which, electricity (in primary MJ)	MJ	4.59E-03	8.78E-03	**1.34E-02**	**1.36E-04**	**4.59E-05**	0.00E+00	-7.44E-04		**1.28E-02**
13	Water (process)	ltr	3.18E+00	1.51E-04	**3.18E+00**	**0.00E+00**	**3.18E-02**	0.00E+00	-7.87E-01		**2.43E+00**
14	Water (cooling)	ltr	2.23E-02	4.05E-03	2.63E-02	0.00E+00	2.23E-04	0.00E+00	-3.47E-03		2.31E-02
15	Waste, non-haz./ landfill	g	4.81E+00	6.48E-02	**4.87E+00**	**7.14E-02**	**4.81E-02**	3.05E-01	-1.21E+00		**4.08E+00**
16	Waste, hazardous/ incinerated	g	4.19E-02	1.48E-05	**4.19E-02**	**1.42E-03**	**4.19E-04**	0.00E+00	-1.03E-02		**3.34E-02**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	4.68E-02	1.27E-03	**4.81E-02**	**1.19E-02**	**4.68E-04**	8.39E-05	-1.23E-02		**4.83E-02**
18	Acidification, emissions	g SO2 eq.	3.87E-01	5.22E-03	**3.92E-01**	**4.11E-02**	**3.87E-03**	1.34E-03	-1.01E-01		**3.38E-01**
19	Volatile Organic Compounds (VOC)	g	7.61E-03	6.68E-05	**7.68E-03**	**2.11E-03**	**7.61E-05**	5.47E-07	-1.39E-03		**8.47E-03**
20	Persistent Organic Pollutants (POP)	ng i-Teq	1.36E-02	5.83E-04	**1.41E-02**	**4.04E-04**	**1.36E-04**	2.78E-05	-3.71E-03		**1.10E-02**
21	Heavy Metals	mg Ni eq.	1.04E-01	1.71E-03	**1.05E-01**	**3.64E-03**	**1.04E-03**	7.67E-04	-2.60E-02		**8.47E-02**
22	PAHs	mg Ni eq.	5.66E-02	1.64E-04	**5.67E-02**	**2.44E-03**	**5.66E-04**	0.00E+00	-2.07E-02		**3.91E-02**
23	Particulate Matter (PM, dust)	g	5.09E-02	7.46E-04	**5.17E-02**	**5.34E-02**	**5.09E-04**	1.50E-03	-1.37E-02		**9.35E-02**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	3.86E-02	8.99E-05	**3.87E-02**	**1.12E-04**	**3.86E-04**	4.98E-05	-1.20E-02		**2.72E-02**
25	Eutrophication	g PO4	1.70E-02	1.59E-04	**1.72E-02**	**1.89E-06**	**1.70E-04**	2.17E-03	-4.19E-03		**1.53E-02**

Figure 111. Environmental profile of a multi Si module per kWh

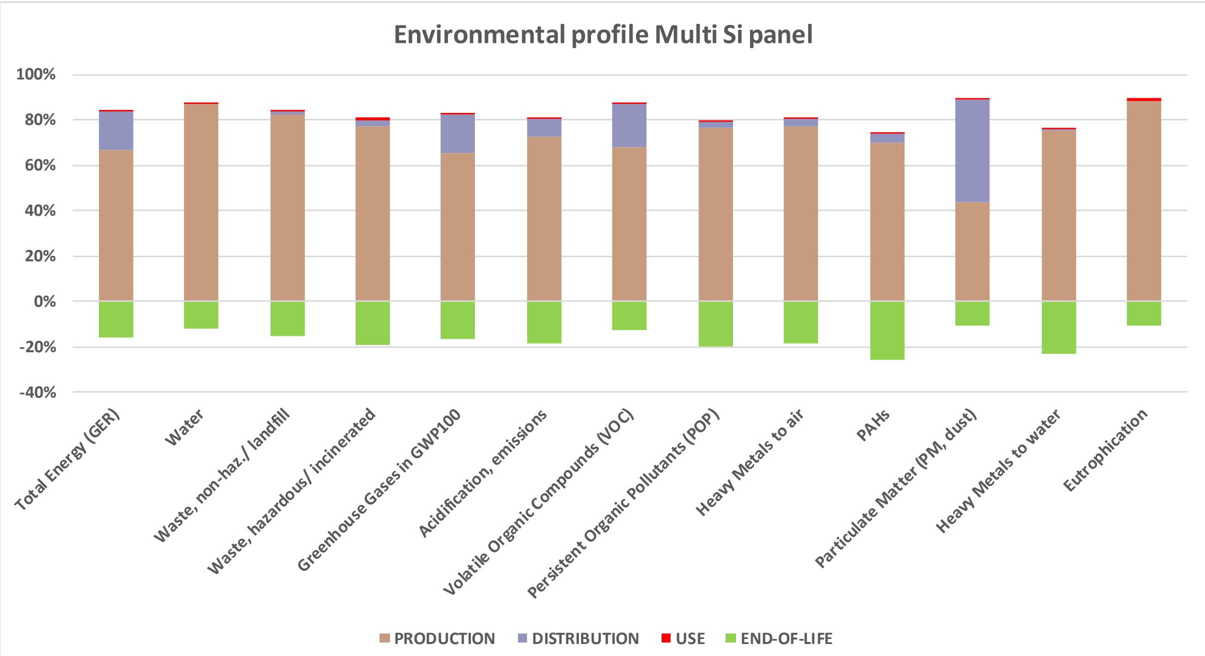


Table 93 gives a more detailed insight in the production stage. The table shows the relative contribution of the different materials to a certain impact category. The heavy metals (Sn, Pb, Cu) used for interconnections are listed separately. The

photovoltaic cell herein is mainly silicon but also contains some other materials such as silver for electrodes (contained in the metallization paste of the electrodes). The photovoltaic cell gives the greatest contribution across the majority of the impact categories considered in MEErP. The aluminium frame for PAH and HMw and to a lesser extent GWP, POP and PM. Also notable is the consumption of water in relation to the glass fiber in the junction box.

Table 93. Results for production (material input) of 1 kWh by a multi Si module using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	4%	72%	0%	98%	91%	79%	80%	70%	77%	91%	12%	76%	35%	86%
interconnection - Tin	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	1%	0%	0%
interconnection - Lead	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
interconnection - Copper	1%	0%	0%	0%	0%	0%	2%	0%	1%	1%	0%	0%	6%	0%
encapsulation - ethylvinylacetate	7%	3%	0%	0%	1%	1%	0%	9%	0%	1%	0%	0%	0%	3%
backsheet - PVF	1%	1%	0%	0%	1%	1%	1%	2%	1%	1%	0%	0%	0%	2%
backsheet - PET	3%	1%	13%	0%	0%	1%	1%	2%	0%	0%	0%	1%	0%	0%
pottant & sealing	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%	0%
alu frame	16%	15%	0%	0%	4%	11%	9%	1%	19%	2%	87%	17%	46%	0%
solar glass	66%	6%	0%	0%	4%	6%	6%	15%	2%	4%	0%	3%	2%	6%
junction box - diode	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
junction box - HDPE	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
junction box - glass fibre	2%	1%	84%	1%	0%	1%	1%	0%	0%	0%	0%	1%	9%	1%

contribution to impact category	X > 50%
contribution to impact category	25% < X < 50%
contribution to impact category	10% < X < 25%
contribution to impact category	<10%

5.3.3 Results Base-Cases for inverters

The bill of materials for inverters are available in 5.2.2.1.

5.3.3.1 String 1 phase inverter, 2500 W

This section discusses the LCA results for the 2500 W inverter. Table 94 provides the LCIA results in absolute value for the production of 1 kWh by an inverter of 2500 W.

Figure 112 provides a graphical presentation of the life cycle of the 2500 W inverter. From this figure it can be concluded that the production phase is the most important life cycle phase. The impact from the use phase is very limited. The default in MEErP of 1% of BOM added to represent spare parts is included. Replacements will be considered at system level.

Table 94. EcoReport results for 1 kWh by a 2500 W inverter

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014	Document subject to a legal notice (see below)
ECO-DESIGN OF ENERGY-RELATED PRODUCTS	EcoReport 2014: OUTPUTS of Environmental Impact — Assessment

Life Cycle Impact (per unit) of Products: 1 kWh, 2500 W inverter

Nr	Life cycle Impact per product:	Reference year	Author
0	Products: 1 kWh, 2500 W inverter	2014	Vito

Nr	Life Cycle phases --> Resources Use and Emissions	unit	PRODUCTION Material	Manuf.	Total	DISTRI-BUTION	USE	END-OF-LIFE Disposal	Recycl.	Stock	TOTAL
	Materials	unit									
1	Bulk Plastics	g			4.07E-02		4.07E-04	2.26E-02	1.85E-02	0.00E+00	0.00E+00
2	TecPlastics	g			4.65E-02		4.65E-04	2.58E-02	2.11E-02	0.00E+00	0.00E+00
3	Ferro	g			3.35E-02		3.35E-04	1.69E-03	3.22E-02	0.00E+00	0.00E+00
4	Non-ferro	g			2.55E-01		2.55E-03	1.29E-02	2.45E-01	0.00E+00	0.00E+00
5	Coating	g			0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6	Electronics	g			2.12E-02		2.12E-04	1.05E-02	1.09E-02	0.00E+00	0.00E+00
7	Misc.	g			0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	Extra	g			3.27E-04		0.00E+00	1.29E-04	2.02E-04	0.00E+00	-3.27E-06
9	Auxiliaries	g			0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
10	Refrigerant	g			0.00E+00		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total weight	g			3.97E-01		3.97E-03	7.36E-02	3.28E-01	0.00E+00	-3.27E-06
									see note!		
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	9.57E-02	1.31E-02	1.09E-01	4.05E-03	9.57E-04	2.75E-03	-2.20E-02		9.46E-02
12	of which, electricity (in primary MJ)	MJ	7.02E-02	3.86E-03	7.40E-02	1.99E-06	7.02E-04	0.00E+00	-1.45E-02		6.02E-02
13	Water (process)	ltr	8.68E-03	3.17E-04	9.00E-03	0.00E+00	8.68E-05	0.00E+00	-1.76E-03		7.33E-03
14	Water (cooling)	ltr	8.58E-03	2.53E-03	1.11E-02	0.00E+00	8.58E-05	0.00E+00	-1.31E-03		9.89E-03
15	Waste, non-haz./ landfill	g	2.17E-01	2.82E-02	2.46E-01	2.80E-03	2.17E-03	6.86E-03	-6.01E-02		1.97E-01
16	Waste, hazardous/ incinerated	g	2.41E-02	8.93E-05	2.42E-02	5.57E-05	2.41E-04	0.00E+00	-4.95E-03		1.95E-02
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	5.73E-03	7.29E-04	6.46E-03	3.30E-04	5.73E-05	1.22E-05	-1.34E-03		5.52E-03
18	Acidification, emissions	g SO2 eq.	3.99E-02	3.23E-03	4.32E-02	1.02E-03	3.99E-04	1.56E-04	-9.73E-03		3.50E-02
19	Volatile Organic Compounds (VOC)	g	5.80E-04	7.04E-05	6.50E-04	3.27E-05	5.80E-06	5.41E-08	-1.24E-04		5.65E-04
20	Persistent Organic Pollutants (POP)	ng i-Teq	8.22E-03	1.21E-04	8.34E-03	1.58E-05	8.22E-05	4.02E-06	-3.07E-03		5.37E-03
21	Heavy Metals	mg Ni eq.	8.33E-03	4.49E-04	8.78E-03	1.43E-04	8.33E-05	5.10E-05	-2.28E-03		6.77E-03
22	PAHs	mg Ni eq.	3.79E-03	1.30E-04	3.92E-03	1.25E-04	3.79E-05	0.00E+00	-1.41E-03		2.67E-03
23	Particulate Matter (PM, dust)	g	2.45E-03	6.30E-04	3.08E-03	7.92E-04	2.45E-05	7.00E-05	-6.58E-04		3.31E-03
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	3.44E-02	2.81E-05	3.44E-02	4.38E-06	3.44E-04	8.55E-05	-7.87E-03		2.70E-02
25	Eutrophication	g PO4	2.45E-04	8.09E-05	3.26E-04	7.43E-08	2.45E-06	3.86E-05	-4.99E-05		3.17E-04

Figure 112. Environmental profile of 1 kWh by a 2500 W inverter

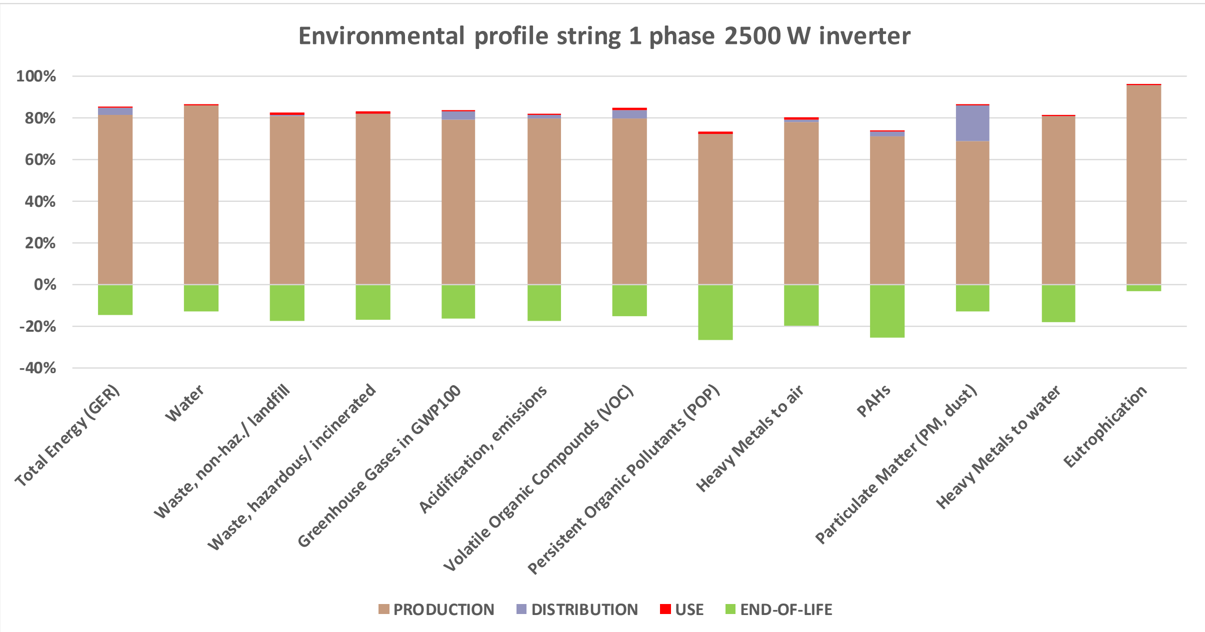


Table 95 gives a more detailed insight in the production stage. The table shows the relative contribution of the different materials to a certain impact category. Aluminium generates the largest share of the impact in the impact categories POP and PAH. The integrated circuit boards are most important in GER, GWP, AD, VOC, HMa and EUP. The printed wiring board is the most important contributor to the impact categories process water and hazardous waste.

Table 95. Results for production (material input) of 1 kWh by a 2500 W inverter using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
aluminium	43%	10%	0%	0%	12%	11%	7%	2%	70%	2%	79%	27%	3%	0%
copper	17%	3%	0%	0%	0%	3%	10%	0%	8%	27%	9%	4%	7%	2%
steel	8%	1%	0%	0%	25%	2%	1%	1%	10%	1%	0%	3%	0%	1%
pp	8%	2%	8%	1%	0%	1%	0%	0%	0%	0%	0%	1%	0%	2%
PC	10%	5%	31%	2%	3%	4%	3%	0%	0%	0%	0%	11%	0%	8%
cable	1%	1%	0%	0%	0%	0%	3%	0%	0%	3%	1%	1%	1%	0%
integrated circuits	2%	64%	0%	7%	31%	67%	53%	90%	5%	41%	3%	22%	83%	66%
ferrite	0%	0%	0%	0%	2%	0%	0%	1%	1%	1%	0%	3%	0%	1%
PVC	3%	1%	4%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	1%
PA	1%	1%	7%	0%	0%	1%	1%	0%	0%	0%	0%	1%	1%	4%
PWB	3%	4%	37%	88%	21%	3%	11%	2%	1%	9%	2%	17%	4%	11%
tin	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	3%	0%	1%
transistor/diode/resistor	1%	7%	13%	1%	3%	7%	9%	3%	0%	12%	0%	5%	0%	2%
capacitor	4%	1%	0%	0%	1%	1%	1%	0%	5%	4%	5%	2%	0%	0%

contribution to impact category	X > 50%
contribution to impact category	25% < X < 50%
contribution to impact category	10% < X < 25%
contribution to impact category	<10%

5.3.3.2 String 3 phase inverter, 20 kW

This section discusses the LCA results for the 20 kW inverter. Table 96 provides the LCIA results in absolute value for the production of 1 kWh by an inverter of 20 kW. Figure 113 provides a graphical presentation of the life cycle of 1 kWh by a 20 kW inverter. From this figure it can be concluded that the production phase is the most important life cycle phase. The impact from the use phase is very limited. The default in MEErP of 1% of BOM added to represent spare parts is included Replacements will be considered at system level.

Table 96. EcoReport results for 20 kW inverter (per kWh)

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014		Document subject to a legal notice (see below)	
ECO-DESIGN OF ENERGY-RELATED PRODUCTS	EcoReport 2014: OUTPUTS Environmental Impact		Assessment of

Life Cycle Impact (per unit) of Products: 1 kWh, 20 kW inverter

Nr	Life cycle Impact per product:	Reference year	Author
0	Products: 1 kWh, 20 kW inverter	2014	Vito

Nr	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	ND-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**2.06E-02**		**2.06E-04**	1.14E-02	9.35E-03	0.00E+00	**0.00E+00**
2	TecPlastics	g			**2.35E-02**		**2.35E-04**	1.30E-02	1.07E-02	0.00E+00	**0.00E+00**
3	Ferro	g			**1.70E-02**		**1.70E-04**	8.56E-04	1.63E-02	0.00E+00	**0.00E+00**
4	Non-ferro	g			**1.29E-01**		**1.29E-03**	6.52E-03	1.24E-01	0.00E+00	**0.00E+00**
5	Coating	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
6	Electronics	g			**1.08E-02**		**1.08E-04**	5.32E-03	5.54E-03	0.00E+00	**0.00E+00**
7	Misc.	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
8	Extra	g			**1.65E-04**		**0.00E+00**	6.51E-05	1.02E-04	0.00E+00	**-1.65E-06**
9	Auxiliaries	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
10	Refrigerant	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
	Total weight	g			**2.01E-01**		**2.01E-03**	3.72E-02	1.66E-01	0.00E+00	**-1.65E-06**
									see note!		
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	4.85E-02	6.62E-03	**5.51E-02**	**5.71E-04**	**4.85E-04**	1.39E-03	-1.11E-02		**4.64E-02**
12	of which, electricity (in primary MJ)	MJ	3.55E-02	1.95E-03	**3.75E-02**	**9.94E-07**	**3.55E-04**	0.00E+00	-7.35E-03		**3.05E-02**
13	Water (process)	ltr	4.40E-03	1.61E-04	**4.56E-03**	**0.00E+00**	**4.40E-05**	0.00E+00	-8.91E-04		**3.71E-03**
14	Water (cooling)	ltr	4.34E-03	1.28E-03	5.62E-03	0.00E+00	4.34E-05	0.00E+00	-6.63E-04		5.00E-03
15	Waste, non-haz./ landfill	g	1.10E-01	1.42E-02	**1.24E-01**	**3.75E-04**	**1.10E-03**	3.47E-03	-3.04E-02		**9.88E-02**
16	Waste, hazardous/ incinerated	g	1.22E-02	4.52E-05	**1.22E-02**	**7.44E-06**	**1.22E-04**	0.00E+00	-2.51E-03		**9.86E-03**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	2.90E-03	3.69E-04	**3.27E-03**	**4.19E-05**	**2.90E-05**	6.16E-06	-6.76E-04		**2.67E-03**
18	Acidification, emissions	g SO2 eq.	2.02E-02	1.63E-03	**2.19E-02**	**1.21E-04**	**2.02E-04**	7.91E-05	-4.92E-03		**1.73E-02**
19	Volatile Organic Compounds (VOC)	g	2.94E-04	3.55E-05	**3.29E-04**	**7.44E-06**	**2.94E-06**	2.74E-08	-6.27E-05		**2.77E-04**
20	Persistent Organic Pollutants (POP)	ng i-Teq	4.15E-03	6.12E-05	**4.22E-03**	**2.12E-06**	**4.15E-05**	2.03E-06	-1.55E-03		**2.71E-03**
21	Heavy Metals	mg Ni eq.	4.22E-03	2.26E-04	**4.44E-03**	**1.90E-05**	**4.22E-05**	2.58E-05	-1.15E-03		**3.38E-03**
22	PAHs	mg Ni eq.	1.92E-03	6.54E-05	**1.98E-03**	**2.64E-05**	**1.92E-05**	0.00E+00	-7.14E-04		**1.31E-03**
23	Particulate Matter (PM, dust)	g	1.24E-03	3.19E-04	**1.56E-03**	**1.20E-03**	**1.24E-05**	3.55E-05	-3.33E-04		**2.47E-03**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	1.74E-02	1.41E-05	**1.74E-02**	**5.90E-07**	**1.74E-04**	4.33E-05	-3.98E-03		**1.37E-02**
25	Eutrophication	g PO4	1.24E-04	4.08E-05	**1.65E-04**	**9.93E-09**	**1.24E-06**	1.96E-05	-2.53E-05		**1.60E-04**

Figure 113. Environmental profile for 1 kWh by a 20 kW inverter

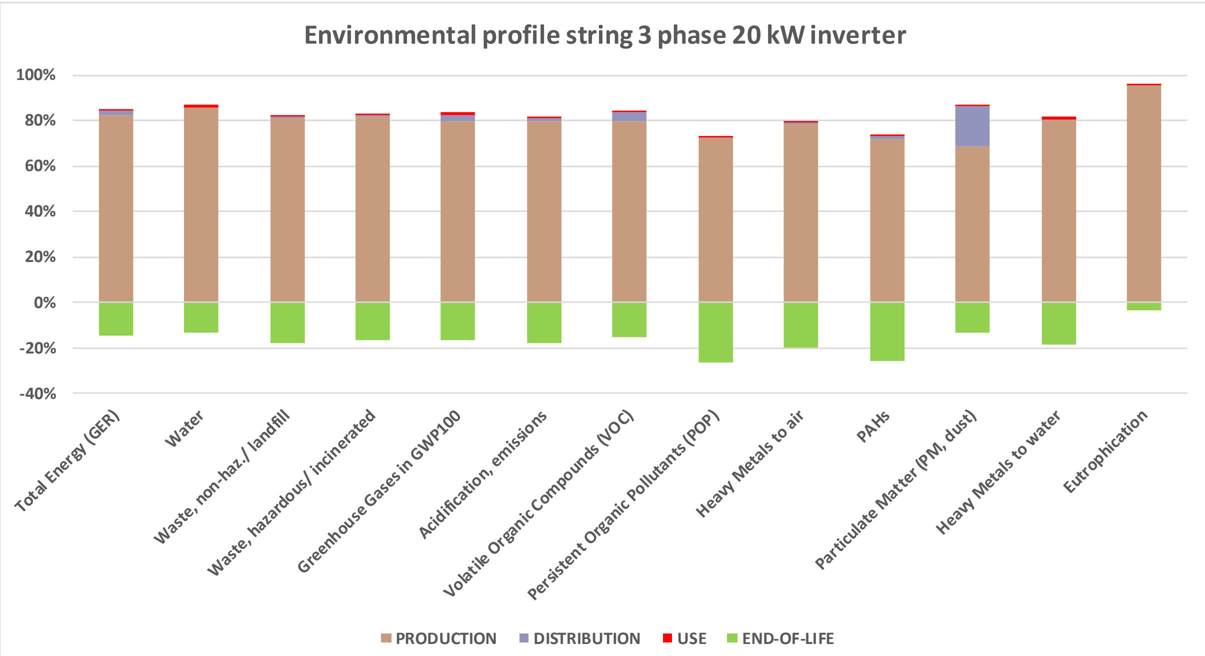


Table 97 gives a more detailed insight in the production stage. The table shows the relative contribution of the different materials to a certain impact category. The conclusions are the same as for the 2500 W inverter (see Table 95).

Table 97. Results for production (material input) 20 kW inverter using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
aluminium	43%	10%	0%	0%	12%	11%	7%	2%	70%	2%	79%	27%	3%	0%
copper	17%	3%	0%	0%	0%	3%	10%	0%	8%	27%	9%	4%	7%	2%
steel	8%	1%	0%	0%	25%	2%	1%	1%	10%	1%	0%	3%	0%	1%
pp	8%	2%	8%	1%	0%	1%	0%	0%	0%	0%	0%	1%	0%	2%
PC	10%	5%	31%	2%	3%	4%	3%	0%	0%	0%	0%	11%	0%	8%
cable	1%	1%	0%	0%	0%	0%	3%	0%	0%	3%	1%	1%	1%	0%
integrated circuits	2%	64%	0%	7%	31%	67%	53%	90%	5%	41%	3%	22%	83%	66%
ferrite	0%	0%	0%	0%	2%	0%	0%	1%	1%	1%	0%	3%	0%	1%
PVC	3%	1%	4%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	1%
PA	1%	1%	7%	0%	0%	1%	1%	0%	0%	0%	0%	1%	1%	4%
PWB	3%	4%	37%	88%	21%	3%	11%	2%	1%	9%	2%	17%	4%	11%
tin	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	3%	0%	1%
transistor/diode/resistor	1%	7%	13%	1%	3%	7%	9%	3%	0%	12%	0%	5%	0%	2%
capacitor	4%	1%	0%	0%	1%	1%	1%	0%	5%	4%	5%	2%	0%	0%

contribution to impact category	X > 50%
contribution to impact category	25% < X < 50%
contribution to impact category	10% < X < 25%
contribution to impact category	<10%

5.3.3.3 Central inverter

This section discusses the LCA results for the 1500 kW central inverter. Table 98 provides the LCIA results in absolute value for the production of 1 kWh by an inverter of 1500 kW. Figure 114 provides a graphical presentation of the life cycle of 1 kWh by a 1500 kW inverter. From this figure it can be concluded that the production phase is the most important life cycle phase. The impact from the use phase is very limited. Instead of using the default in MEErP of 1% of BOM added to represent spare parts, the BOM for the inverter is increased to represent the replacement of parts during the lifetime Replacements will be considered at system level.

- **Table 98.** EcoReport results for 1500 kW central inverter (per kWh)

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014

Document subject to a legal notice (see below)

EcoReport 2014: OUTPUTS Environmental Impact

Assessment of

ECO-DESIGN OF ENERGY-RELATED PRODUCTS

Life Cycle Impact (per unit) of Products: 1500 kW inverter, incl replacement over 25 years life span

Nr	Life cycle Impact per product:	Reference year	Author
0	Products: 1500 kW inverter, incl replacement	2014	Vito

Nr	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**1.20E-03**		**1.20E-05**	6.67E-04	5.46E-04	0.00E+00	**0.00E+00**
2	TecPlastics	g			**6.34E-03**		**6.34E-05**	3.52E-03	2.88E-03	0.00E+00	**0.00E+00**
3	Ferro	g			**7.85E-02**		**7.85E-04**	3.97E-03	7.54E-02	0.00E+00	**0.00E+00**
4	Non-ferro	g			**3.33E-02**		**3.33E-04**	1.68E-03	3.20E-02	0.00E+00	**0.00E+00**
5	Coating	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
6	Electronics	g			**1.39E-04**		**1.39E-06**	6.89E-05	7.17E-05	0.00E+00	**0.00E+00**
7	Misc.	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
8	Extra	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
9	Auxiliaries	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
10	Refrigerant	g			**0.00E+00**		**0.00E+00**	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
	Total weight	g			**1.20E-01**		**1.20E-03**	9.91E-03	1.11E-01	0.00E+00	**2.78E-17**
									see note!		
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	5.25E-03	4.66E-03	**9.91E-03**	**1.04E-03**	**5.25E-05**	5.04E-05	-1.80E-03		**9.26E-03**
12	of which, electricity (in primary MJ)	MJ	3.83E-04	1.15E-03	**1.54E-03**	**2.92E-06**	**3.83E-06**	0.00E+00	-1.06E-04		**1.44E-03**
13	Water (process)	ltr	1.77E-04	2.25E-05	**2.00E-04**	**0.00E+00**	**1.77E-06**	0.00E+00	-3.23E-05		**1.69E-04**
14	Water (cooling)	ltr	1.43E-03	5.27E-04	**1.96E-03**	**0.00E+00**	**1.43E-05**	0.00E+00	-2.38E-04		**1.73E-03**
15	Waste, non-haz./ landfill	g	1.39E-01	1.07E-02	**1.49E-01**	**4.70E-04**	**1.39E-03**	1.66E-03	-5.28E-02		**1.00E-01**
16	Waste, hazardous/ incinerated	g	3.60E-04	3.68E-06	**3.64E-04**	**9.34E-06**	**3.60E-06**	0.00E+00	-6.98E-05		**3.07E-04**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	3.75E-04	2.33E-04	**6.07E-04**	**6.74E-05**	**3.75E-06**	2.53E-07	-1.30E-04		**5.48E-04**
18	Acidification, emissions	g SO2 eq.	2.46E-03	9.33E-04	**3.39E-03**	**2.06E-04**	**2.46E-05**	2.80E-06	-8.72E-04		**2.75E-03**
19	Volatile Organic Compounds (VOC)	g	1.22E-05	1.80E-05	**3.02E-05**	**2.12E-05**	**1.22E-07**	2.45E-10	-4.51E-06		**4.71E-05**
20	Persistent Organic Pollutants (POP)	ng i-Teq	2.67E-03	1.14E-04	**2.79E-03**	**2.66E-06**	**2.67E-05**	1.13E-06	-1.02E-03		**1.79E-03**
21	Heavy Metals	mg Ni eq.	1.35E-03	3.64E-04	**1.72E-03**	**2.38E-05**	**1.35E-05**	1.49E-06	-5.16E-04		**1.24E-03**
22	PAHs	mg Ni eq.	2.62E-04	4.51E-05	**3.07E-04**	**4.54E-05**	**2.62E-06**	0.00E+00	-9.94E-05		**2.55E-04**
23	Particulate Matter (PM, dust)	g	3.19E-04	1.27E-04	**4.46E-04**	**3.52E-03**	**3.19E-06**	3.17E-06	-1.14E-04		**3.86E-03**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	1.42E-03	2.15E-05	**1.45E-03**	**7.48E-07**	**1.42E-05**	1.36E-06	-4.74E-04		**9.88E-04**
25	Eutrophication	g PO4	1.86E-05	4.35E-05	**6.21E-05**	**1.25E-08**	**1.86E-07**	2.28E-06	-4.52E-06		**6.00E-05**

Figure 114. Environmental profile of 1 kWh by a 1500 kW central inverter

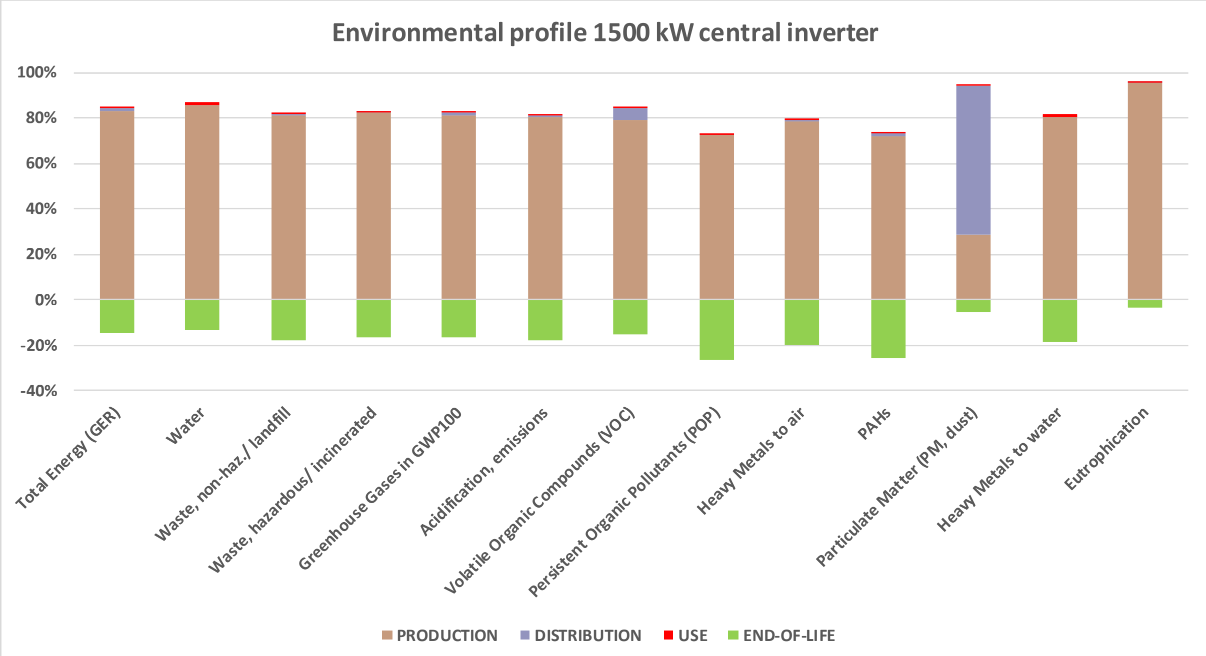


Table 99 gives a more detailed insight in the production stage. The table shows the relative contribution of the different materials to a certain impact category. Steel, copper and PA are the components that have the most significant contribution to all impact categories. The printed wiring board has the most significant contribution to the impact category hazardous waste.

Table 99. Results for production (material input) 1500 kW central inverter using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
aluminium	6%	8%	0%	0%	1%	7%	5%	4%	9%	0%	48%	9%	3%	0%
copper	22%	23%	0%	1%	0%	17%	58%	1%	14%	78%	48%	11%	53%	7%
steel	65%	50%	0%	0%	98%	59%	24%	88%	76%	21%	2%	67%	20%	27%
HDPE	1%	2%	3%	2%	0%	1%	0%	2%	0%	0%	0%	0%	0%	0%
PC	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
alkyd paint	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
integrated circuits	0%	1%	0%	0%	0%	1%	1%	3%	0%	0%	0%	0%	1%	1%
ferrite	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
PVC	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
PA	5%	14%	92%	33%	1%	14%	10%	0%	0%	0%	1%	11%	22%	63%
PWB	0%	1%	4%	63%	0%	1%	2%	1%	0%	1%	0%	1%	1%	2%
tin	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
transistor/diode/resistor	0%	1%	1%	1%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%
capacitor	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

contribution to impact category	X > 50%
contribution to impact category	25% < X < 50%
contribution to impact category	10% < X < 25%
contribution to impact category	<10%

5.3.4 Results Base-Cases for systems

This section presents the results for the system Base-Cases. The Base-Cases at system level are defined in section 5.2.1.1. Parameters for the calculation of the functional unit are available in Table 79 (modules) and Table 80 (inverters). Replacements of inverters during the 30 years life span of the systems are accounted for in the product stage, not in the use stage. The 2500 W inverter and 20 kW inverter are replaced twice during the life span of the system. For the central inverter, only parts are replaced. These parts are replaced twice during the life span of the system.

5.3.4.1 Results Base-Case 1: 3 kW system (modules plus inverter)

This section discusses the LCA results for the 3 kW system (Base-Case 1). The results are expressed per functional unit, being 1 kWh. Table 100 provides the LCIA results in absolute values for a 3 kW system. Figure 115 provides a graphical presentation of the life cycle of the 3 kW system. From this figure it can be concluded that the production phase is the most important life

cycle phase. The contribution to the production phase mainly comes for the multi Si module. The impact from the use phase is very limited. The default in MEErP of 1% of BOM added to represent spare parts is included. Replacements are taken into account in the production stage.

The relatively high contribution of the distribution phase is accounted for by the choice of transport packaging which is then linked to a default assumption that air freight is used. This choice is to be reviewed as the option of an 'installed appliance' may be more representative.

Table 100. EcoReport results for Base-Case 1: 3 kW system with multi Si module and 2500 W inverter (per kWh)

Nr	Life cycle Impact per product:	Reference year	Author
0	system level 3 kWp system	2014	Vito

Nr	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**1.29E-01**	**0.00E+00**	**1.29E-03**	**7.16E-02**	**5.86E-02**	**0.00E+00**	**0.00E+00**
2	TecPlastics	g			**1.17E-01**	**0.00E+00**	**2.95E+00**	**1.64E+02**	**1.34E+02**	**0.00E+00**	**0.00E+00**
3	Ferro	g			**3.35E-02**	**0.00E+00**	**3.35E-04**	**1.69E-03**	**3.21E-02**	**0.00E+00**	**0.00E+00**
4	Non-ferro	g			**7.88E-01**	**0.00E+00**	**2.23E+01**	**1.13E+02**	**2.14E+03**	**0.00E+00**	**0.00E+00**
5	Coating	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
6	Electronics	g			**2.19E-02**	**0.00E+00**	**2.83E-02**	**1.40E+00**	**1.46E+00**	**0.00E+00**	**0.00E+00**
7	Misc.	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
8	Extra	g			**2.50E+00**	**0.00E+00**	**0.00E+00**	**4.45E+03**	**6.96E+03**	**0.00E+00**	**-1.13E+02**
9	Auxiliaries	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
10	Refrigerant	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
	Total weight	g			**3.59E+00**	**0.00E+00**	**2.90E+01**	**4.94E+03**	**9.41E+03**	**0.00E+00**	**-1.13E+02**
									see note!		
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	7.37E-01	3.76E-02	7.74E-01	1.73E-01	7.37E-03	1.76E-02	-1.93E-01	0.00E+00	7.79E-01
12	of which, electricity (in primary MJ)	MJ	7.47E-02	1.26E-02	8.73E-02	1.38E-04	7.47E-04	0.00E+00	-1.52E-02	0.00E+00	7.30E-02
13	Water (process)	ltr	1.38E-02	4.68E-04	1.42E-02	0.00E+00	1.38E-04	0.00E+00	-2.58E-03	0.00E+00	1.18E-02
14	Water (cooling)	ltr	3.09E-02	6.58E-03	3.74E-02	0.00E+00	3.09E-04	0.00E+00	-4.78E-03	0.00E+00	3.30E-02
15	Waste, non-haz./ landfill	g	5.03E+00	9.30E-02	5.12E+00	8.66E-02	5.03E-02	3.12E-01	-1.27E+00	0.00E+00	4.30E+00
16	Waste, hazardous/ incinerated	g	6.60E-02	1.04E-04	6.61E-02	1.72E-03	6.60E-04	0.00E+00	-1.53E-02	0.00E+00	5.32E-02
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	5.26E-02	2.00E-03	5.46E-02	1.34E-02	5.26E-04	9.61E-05	-1.36E-02	0.00E+00	5.50E-02
18	Acidification, emissions	g SO2 eq.	4.27E-01	8.45E-03	4.35E-01	4.51E-02	4.27E-03	1.50E-03	-1.10E-01	0.00E+00	3.76E-01
19	Volatile Organic Compounds (VOC)	g	8.19E-03	1.37E-04	8.33E-03	2.16E-03	8.19E-05	6.02E-07	-1.52E-03	0.00E+00	9.06E-03
20	Persistent Organic Pollutants (POP)	ng i-Teq	2.18E-02	7.05E-04	2.25E-02	4.89E-04	2.18E-04	3.19E-05	-6.78E-03	0.00E+00	1.64E-02
21	Heavy Metals	mg Ni eq.	1.12E-01	2.15E-03	1.14E-01	4.41E-03	1.12E-03	8.18E-04	-2.83E-02	0.00E+00	9.21E-02
22	PAHs	mg Ni eq.	6.04E-02	2.93E-04	6.07E-02	3.20E-03	6.04E-04	0.00E+00	-2.21E-02	0.00E+00	4.24E-02
23	Particulate Matter (PM, dust)	g	5.34E-02	1.38E-03	5.48E-02	5.43E-02	5.34E-04	1.57E-03	-1.43E-02	0.00E+00	9.69E-02
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	7.30E-02	1.18E-04	7.31E-02	1.36E-04	7.30E-04	1.35E-04	-1.99E-02	0.00E+00	5.42E-02
25	Eutrophication	g PO4	1.73E-02	2.40E-04	1.75E-02	2.30E-06	1.73E-04	2.21E-03	-4.24E-03	0.00E+00	1.57E-02

Figure 115. Environmental profile Base-Case 1, 3 kW system

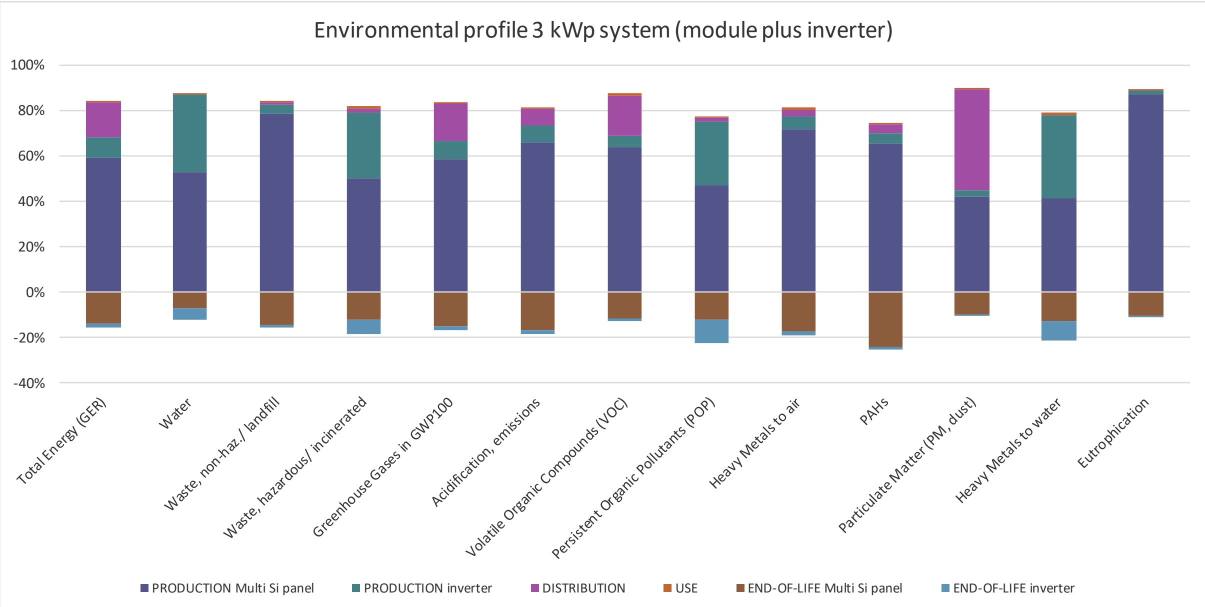


Table 101 gives a more detailed insight in the production stage. The table shows the relative contribution of the different system components to a certain impact category/flow. Modules are the components of the installation that have the most significant contribution to all impact/flow categories. Significant contributions can be seen however from the inverter to non-hazardous waste impact category and the Heavy Metals to water impact flow.

Table 101. Results for production (components input) for a 3 kW PV system using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
module	89%	86%	99%	95%	63%	88%	90%	92%	63%	92%	94%	94%	53%	98%
inverter	11%	14%	1%	5%	37%	12%	10%	8%	37%	8%	6%	6%	47%	2%

contribution to impact category	X > 50%
contribution to impact category	25% < X < 50%
contribution to impact category	10% < X < 25%
contribution to impact category	<10%

5.3.4.2 Results Base-Case 2: 24.4 kW system (modules plus inverter)

This section discusses the LCA results for the 24.4 kW system (Base-Case 2). The results are expressed per functional unit, being 1 kWh.

Table 102 provides the LCIA results in absolute values for a 24.4 kW system. Figure 116 provides a graphical presentation of the life cycle of the 24.4 kW system. From this figure it can be concluded that similarly to the 3 kW system case, the production phase is the most important life cycle phase here as well. The contribution to the production phase mainly comes for the multi Si module. The impact from the use phase is very limited. The default in MEErP of 1% of BOM added to represent spare parts is included Replacements are taken into account in the production stage.

The relatively high contribution of the distribution phase is accounted for by the choice of transport packaging which is then linked to a default assumption that air freight is used. This choice is to be reviewed as the option of an 'installed appliance' may be more representative.

Table 103 gives a more detailed insight in the production stage. The table shows the relative contribution of the different PV system components to a certain impact/flow category. Modules are the components of the installation that have the most significant contribution to all impact/flow categories. Minor contributions of around 30% can be seen from the inverters to Non-hazardous waste impact category and the Heavy Metals to water impact flow.

Table 102. EcoReport results for Base-Case 2: 24.4 kWp system with multi Si module and 20 kW inverter (per kWh)

Nr	Life cycle Impact per product:						Reference year		Author		
0	system level 24,4 kWp system						2014		Vito		
	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**1.09E-01**	**0.00E+00**	**1.09E-03**	**6.05E-02**	**4.95E-02**	**0.00E+00**	**0.00E+00**
2	TecPlastics	g			**9.40E-02**	**0.00E+00**	**9.40E-04**	**5.22E-02**	**4.27E-02**	**0.00E+00**	**0.00E+00**
3	Ferro	g			**1.70E-02**	**0.00E+00**	**1.70E-04**	**8.56E-04**	**1.63E-02**	**0.00E+00**	**0.00E+00**
4	Non-ferro	g			**6.61E-01**	**0.00E+00**	**6.61E-03**	**3.34E-02**	**6.35E-01**	**0.00E+00**	**0.00E+00**
5	Coating	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
6	Electronics	g			**1.14E-02**	**0.00E+00**	**1.14E-04**	**5.66E-03**	**5.89E-03**	**0.00E+00**	**0.00E+00**
7	Misc.	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
8	Extra	g			**2.50E+00**	**0.00E+00**	**0.00E+00**	**9.86E-01**	**1.54E+00**	**0.00E+00**	**-2.50E-02**
9	Auxiliaries	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
10	Refrigerant	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
	Total weight	g			**3.39E+00**	**0.00E+00**	**8.93E-03**	**1.14E+00**	**2.29E+00**	**0.00E+00**	**-2.50E-02**
									see note!		
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	6.89E-01	3.11E-02	7.20E-01	1.69E-01	6.89E-03	1.62E-02	-1.82E-01	0.00E+00	7.31E-01
12	of which, electricity (in primary MJ)	MJ	4.01E-02	1.07E-02	5.09E-02	1.37E-04	4.01E-04	0.00E+00	-8.09E-03	0.00E+00	4.33E-02
13	Water (process)	ltr	9.47E-03	3.12E-04	9.78E-03	0.00E+00	9.47E-05	0.00E+00	-1.72E-03	0.00E+00	8.16E-03
14	Water (cooling)	ltr	2.66E-02	5.33E-03	3.19E-02	0.00E+00	2.66E-04	0.00E+00	-4.13E-03	0.00E+00	2.81E-02
15	Waste, non-haz./ landfill	g	4.92E+00	7.91E-02	5.00E+00	8.41E-02	4.92E-02	3.09E-01	-1.24E+00	0.00E+00	4.20E+00
16	Waste, hazardous/ incinerated	g	5.41E-02	6.00E-05	5.41E-02	1.67E-03	5.41E-04	0.00E+00	-1.28E-02	0.00E+00	4.35E-02
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	4.97E-02	1.64E-03	5.14E-02	1.31E-02	4.97E-04	9.01E-05	-1.29E-02	0.00E+00	5.21E-02
18	Acidification, emissions	g SO2 eq.	4.07E-01	6.85E-03	4.14E-01	4.42E-02	4.07E-03	1.42E-03	-1.06E-01	0.00E+00	3.58E-01
19	Volatile Organic Compounds (VOC)	g	7.90E-03	1.02E-04	8.01E-03	2.13E-03	7.90E-05	5.74E-07	-1.46E-03	0.00E+00	8.76E-03
20	Persistent Organic Pollutants (POP)	ng i-Teq	1.77E-02	6.45E-04	1.84E-02	4.75E-04	1.77E-04	2.99E-05	-5.27E-03	0.00E+00	1.38E-02
21	Heavy Metals	mg Ni eq.	1.08E-01	1.93E-03	1.10E-01	4.28E-03	1.08E-03	7.93E-04	-2.72E-02	0.00E+00	8.87E-02
22	PAHs	mg Ni eq.	5.85E-02	2.29E-04	5.87E-02	3.09E-03	5.85E-04	0.00E+00	-2.14E-02	0.00E+00	4.10E-02
23	Particulate Matter (PM, dust)	g	5.22E-02	1.07E-03	5.32E-02	5.47E-02	5.22E-04	1.54E-03	-1.40E-02	0.00E+00	9.60E-02
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	5.60E-02	1.04E-04	5.61E-02	1.32E-04	5.60E-04	9.31E-05	-1.60E-02	0.00E+00	4.09E-02
25	Eutrophication	g PO4	1.71E-02	2.00E-04	1.73E-02	2.23E-06	1.71E-04	2.19E-03	-4.22E-03	0.00E+00	1.55E-02

Figure 116. Environmental profile Base-Case 2, 24.4 kWp system

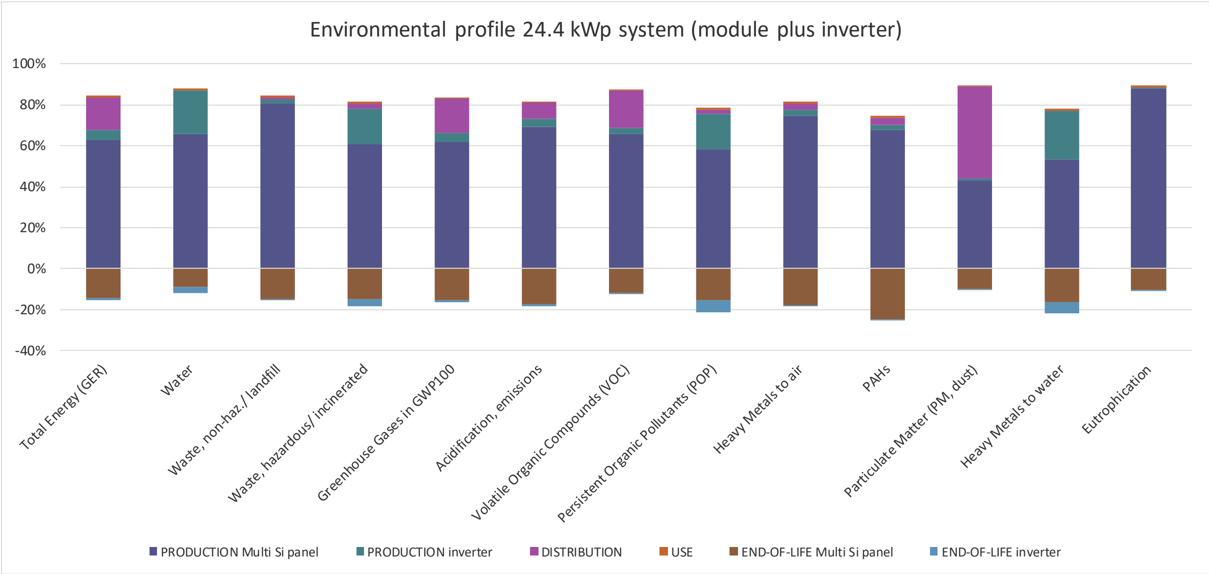


Table 103. Results for production (components input) for a 24.4 kW PV system using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
Module	94%	92%	100%	98%	77%	94%	95%	96%	77%	96%	97%	97%	69%	99%
Inverter	6%	8%	0%	2%	23%	6%	5%	4%	23%	4%	3%	3%	31%	1%

5.3.4.3 Results Base-Case 3: 1875 kW system (modules plus inverter)

This section discusses the LCA results for the 1875 kW system (Base-Case 3). The results are expressed per functional unit, being 1 kWh. Table 104 provides the LCIA results in absolute value for 1 kWh by a 1875 kW system. Replacements in the inverter are considered within the production stage. The print board assembly is replaced twice during the life span of the system. The other components of the central inverter are not replaced.

Figure 117: Environmental profile Base-Case 3, 1875 kW system

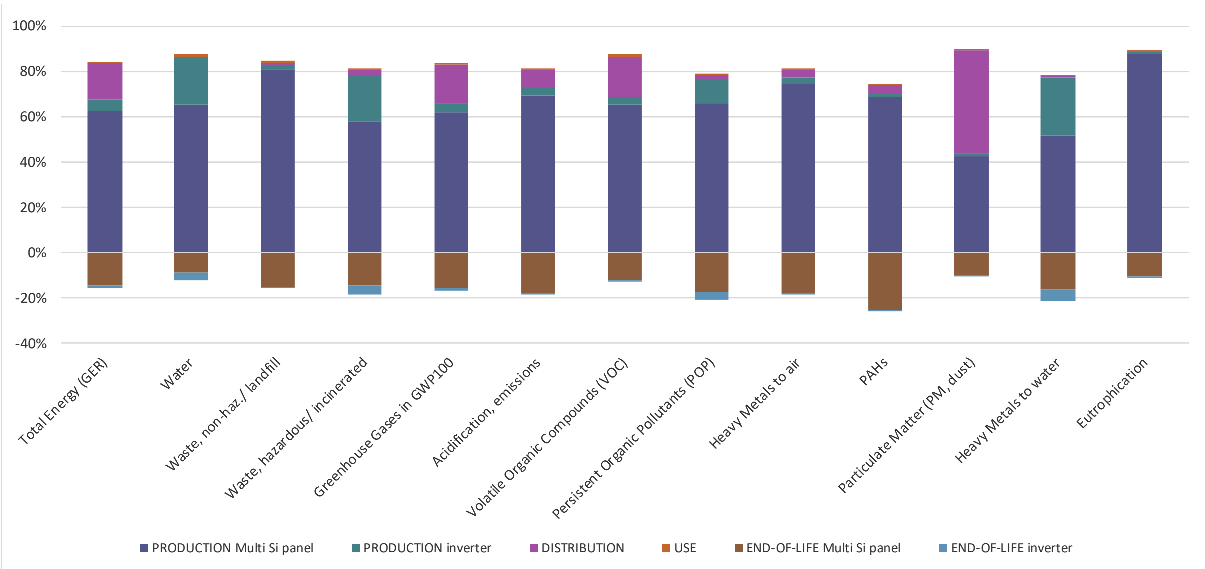


Figure 117 provides a graphical presentation of the life cycle of the production of 1 kWh by a 1875 kWp system. From this figure it can be concluded that the production phase is the most important life cycle phase. The contribution to the production

phase mainly comes for the multi Si module. The impact from the use phase is very limited. Instead of using the default in MEErP of 1% of BOM added to represent spare parts, the BOM for the inverter is increased to represent the replacement of parts during the lifetime.

Table 104. EcoReport results for Base-Case 3: 1875 kW system with multi Si module and 1500 W inverter (per kWh)

Nr	Life cycle Impact per product:							Reference year	Author		
0	system level 1875 kWp							2014	Vito		
	Life Cycle phases -->		PRODUCTION			DISTRI-	USE	END-OF-LIFE			TOTAL
	Resources Use and Emissions		Material	Manuf.	Total	BUTION		Disposal	Recycl.	Stock	
	Materials	**unit**									
1	Bulk Plastics	g			**8.95E-02**	**0.00E+00**	**8.95E-04**	**4.97E-02**	**4.07E-02**	**0.00E+00**	**0.00E+00**
2	TecPlastics	g			**7.68E-02**	**0.00E+00**	**7.68E-04**	**4.27E-02**	**3.49E-02**	**0.00E+00**	**0.00E+00**
3	Ferro	g			**7.85E-02**	**0.00E+00**	**7.85E-04**	**3.97E-03**	**7.54E-02**	**0.00E+00**	**0.00E+00**
4	Non-ferro	g			**5.66E-01**	**0.00E+00**	**5.66E-03**	**2.86E-02**	**5.43E-01**	**0.00E+00**	**0.00E+00**
5	Coating	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
6	Electronics	g			**8.11E-04**	**0.00E+00**	**8.11E-06**	**4.02E-04**	**4.18E-04**	**0.00E+00**	**0.00E+00**
7	Misc.	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
8	Extra	g			**2.50E+00**	**0.00E+00**	**0.00E+00**	**9.85E-01**	**1.54E+00**	**0.00E+00**	**-2.50E-02**
9	Auxiliaries	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
10	Refrigerant	g			**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**	**0.00E+00**
	Total weight	g			**3.31E+00**	**0.00E+00**	**8.11E-03**	**1.11E+00**	**2.24E+00**	**0.00E+00**	**-2.50E-02**
									see note!		
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	6.46E-01	2.91E-02	6.75E-01	1.70E-01	6.46E-03	1.48E-02	-1.72E-01	0.00E+00	6.94E-01
12	of which, electricity (in primary MJ)	MJ	4.97E-03	9.94E-03	1.49E-02	1.39E-04	4.97E-05	0.00E+00	-8.50E-04	0.00E+00	1.42E-02
13	Water (process)	ltr	5.25E-03	1.74E-04	5.43E-03	0.00E+00	5.25E-05	0.00E+00	-8.56E-04	0.00E+00	4.62E-03
14	Water (cooling)	ltr	2.37E-02	4.57E-03	2.83E-02	0.00E+00	2.37E-04	0.00E+00	-3.71E-03	0.00E+00	2.48E-02
15	Waste, non-haz./ landfill	g	4.94E+00	7.55E-02	5.02E+00	8.42E-02	4.94E-02	3.07E-01	-1.26E+00	0.00E+00	4.20E+00
16	Waste, hazardous/ incinerated	g	4.22E-02	1.85E-05	4.23E-02	1.67E-03	4.22E-04	0.00E+00	-1.04E-02	0.00E+00	3.40E-02
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	4.72E-02	1.50E-03	4.87E-02	1.31E-02	4.72E-04	8.42E-05	-1.24E-02	0.00E+00	5.00E-02
18	Acidification, emissions	g SO2 eq.	3.89E-01	6.15E-03	3.95E-01	4.43E-02	3.89E-03	1.35E-03	-1.01E-01	0.00E+00	3.43E-01
19	Volatile Organic Compounds (VOC)	g	7.62E-03	8.48E-05	7.71E-03	2.15E-03	7.62E-05	5.47E-07	-1.40E-03	0.00E+00	8.53E-03
20	Persistent Organic Pollutants (POP)	ng i-Teq	1.62E-02	6.98E-04	1.69E-02	4.76E-04	1.62E-04	2.90E-05	-4.74E-03	0.00E+00	1.29E-02
21	Heavy Metals	mg Ni eq.	1.05E-01	2.07E-03	1.07E-01	4.29E-03	1.05E-03	7.69E-04	-2.65E-02	0.00E+00	8.66E-02
22	PAHs	mg Ni eq.	5.68E-02	2.09E-04	5.70E-02	3.11E-03	5.68E-04	0.00E+00	-2.08E-02	0.00E+00	4.00E-02
23	Particulate Matter (PM, dust)	g	5.13E-02	8.74E-04	5.21E-02	5.70E-02	5.13E-04	1.51E-03	-1.38E-02	0.00E+00	9.74E-02
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	4.00E-02	1.11E-04	4.01E-02	1.32E-04	4.00E-04	5.11E-05	-1.25E-02	0.00E+00	2.82E-02
25	Eutrophication	g PO4	1.70E-02	2.03E-04	1.72E-02	2.23E-06	1.70E-04	2.17E-03	-4.20E-03	0.00E+00	1.54E-02

The relatively high contribution of the distribution phase is accounted for by the choice of transport packaging which is then linked to a default assumption that air freight is used. This choice is to be reviewed as the option of an 'installed appliance' may be more representative.

Table 105 gives a more detailed insight in the production stage. The table shows the relative contribution of the different system components to a certain impact/flow category. Modules are the components of the installation that have the most significant contribution to all impact/flow categories. It can be seen that with the raise in the capacity of the installation, the contribution of the inverters tends to be reduced. In this case of a utility scale system, only the Persistent Organic Pollutants are an impact category influenced by inverters, to a reduced contribution of 16%. The rest of impact/flow categories have contributions from the inverters below 5%.

Table 105. Results for production (components input) for a 1875 kW PV system using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
Module	96%	99%	100%	97%	99%	99%	99%	100%	84%	98%	99%	99%	96%	100%
Inverter	4%	1%	0%	3%	1%	1%	1%	0%	16%	2%	1%	1%	4%	0%

5.4 Base case life cycle cost for consumer

5.4.1 Introduction to Life Cycle Costing and the relationship with the Levelized Cost of electricity and functional unit of a PV system

The total cost of ownership (TCO) or Life Cycle Cost (LCC) is a concept that aims to estimate the full cost of a system. Therefore, the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) are calculated. CAPEX is used to acquire the photovoltaic installation and consists mainly of product and installation costs. The OPEX is the ongoing cost of running the photovoltaic system and consists mainly of costs for inverter or module repair/replacement and cleaning.

The purpose of the discount rate in LCC/LCOE calculations is to convert all life cycle costs to their net present value (NPV) taking into account operational expenditures (OPEX) for energy and other consumables.

The life cycle costing (LCC) in MEErP studies is to be calculated using the formula:

$$LCC[€]= \Sigma CAPEX + \Sigma(PWF\ x\ OPEX)$$

where,

LCC is the life cycle costing,

CAPEX is the purchase price (including installation) or so-called capital expenditure,

OPEX are the operating expenses per year or so-called operational expenditure,

PWF is the present worth factor with PWF = $(1 - 1/(1+r)^N)/r$,

N is the product life in years,

r is the discount rate which represents the return that could be earned in alternative investments (see 5.2.1.7).

As it was discussed in section 5.1.1.3, the LCOE is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel and cost of capital. It is commonly applied to evaluate PV system costs[358]. The Levelized cost of electricity (LCOE) is defined for the purpose of these calculations as:

$$\text{LCOE}[€/\text{kWh}] = \frac{\text{net present value of sum of costs of generation over its lifetime}}{\textit{sum of electrical energy produced over its life time}}$$

The LCOE calculation of costs per kWh generated aligns with the functional unit defined in Task 1. In this definition the life cycle environmental impacts of the PV system or component are normalized to 1 kWh of electricity produced by the system/component.

Relationship of the LCOE to the Functional unit and LCC:

Task 1 of this study defines the functional unit of analysis for PV modules, inverters and systems as follows:

- For PV modules: 1 kWh of DC power output under predefined climatic and installation conditions as defined for a typical year and for a service life of 30 years

- For inverters: 1 kWh of AC power output from a reference photovoltaic system (excluding the efficiency of the inverter) under predefined climatic and installation conditions as defined for a typical year and assuming a service life of 10 years

- For systems: 1 kWh of AC power output supplied under fixed climatic conditions as defined for a typical year (with reference to IEC 61853 part 4) and assuming a service life of 30 years.

This extended service life allows to take into account operation and maintenance activities, failure probability and degradation rates along the lifetime of the system and its components.

The consequence of this is that:

- A PV system for further analysis according to the functional unit will have to be scaled down until 1 kWh (over its lifetime).
- When **PV systems** are **scaled according to their 'functional unit'** their **Life Cycle Cost(LCC) is the Levelized cost of electricity(LCOE)**.

[358] *https://setis.ec.europa.eu/sites/default/files/reports/Cost-Maps-for-Unsubsidised-Photovoltaic-Electricity.pdf*

5.4.2 LCC for individual components of the PV system

The life cycle cost of individual system components such as inverters and PV modules is simply the purchase price. Therefore calculations are not needed and please consult the input data. At system level all cost of the components will be included, see the next section.

5.4.3 LCC and LCOE results base cases for systems

Given the complexity of the LCC of a PV system and LCOE calculation, a separate calculation spreadsheet had to be created because the EcoReport tool does not allow for calculation of the LCOE.

The first draft results for BC 1 are included in Table 106 based on the input from Table 107 and Table 108. All data has been sourced from previous sections. All module and inverter replacements in the system over its lifetime are modelled in cost at 1 year after midlife of the system, see 'average all repairs' in Table 107.

Table 106. Calculated LCC and LCOE for BC 1 (residential system)

LCOE or LCC per functional unit	0.078	euro/kWh
LCC of PV system	6384.06	euro/installation
Electrical energy produced over its lifetime	81379.43	kWh

Table 107. Input data used for LCC and LCOE performance modelling

Reference Yield, Yr(kWh/kW) (in year 1)	1331.00
PR	0.75
Lifetime (y)	30.00
r (discount rate=interest - inflation)	4.0%
Performance degradation rate	0.7%
Failure rate modules(%/year)	0.03%
Failure rate inverters(%/year)	10.0%
Base Case	1
PV modules Capacity (W)	3000
Amount of modules	12
KVA inverter	2.5
Average module repairs/life	0.9%
Average inverter repair/life	300.0%
Insurance, monitoring & admin. (EUR/kW/year)	28

Table 108. CAPEX and OPEX input data and calculated results

OPEX and CAPEX processing based on LCC input data							
event	**Year**	**PWF**	**CAPEX**	**OPEX**	**Y**	**NPV**	**Electricity**
		ratio	**euro**	**euro**	**h**	**euro**	**kWh/year**
installation	1	1	4,832.00 €	87	998.3	4,919.00 €	2994.75
O&M	2	0.925		87	991.3	80.44 €	2973.79
O&M	3	0.889		87	984.3	77.34 €	2952.97
O&M	4	0.855		87	977.4	74.37 €	2932.30
O&M	5	0.822		87	970.6	71.51 €	2911.77
O&M	6	0.790		87	963.8	68.76 €	2891.39
O&M	7	0.760		87	957.1	66.11 €	2871.15
O&M	8	0.731		87	950.4	63.57 €	2851.05
O&M	9	0.703		87	943.7	61.13 €	2831.10
Replace	10	0.676		1,324.75 €	937.1	894.95 €	2811.28
O&M	11	0.650		87	930.5	56.51 €	2791.60
O&M	12	0.625		87	924.0	54.34 €	2772.06
O&M	13	0.601		87	917.6	52.25 €	2752.65
O&M	14	0.577		87	911.1	50.24 €	2733.38
O&M	15	0.555		87	904.8	48.31 €	2714.25
O&M	16	0.534		87	898.4	46.45 €	2695.25
O&M	17	0.513		87	892.1	44.66 €	2676.38
O&M	18	0.494		87	885.9	42.95 €	2657.65
O&M	19	0.475		87	879.7	41.29 €	2639.05
Replace	20	0.456		1,324.75 €	873.5	604.60 €	2620.57
O&M	21	0.439		87	867.4	38.18 €	2602.23
O&M	22	0.422		87	861.3	36.71 €	2584.01
O&M	23	0.406		87	855.3	35.30 €	2565.93
O&M	24	0.390		87	849.3	33.94 €	2547.96
O&M	25	0.375		87	843.4	32.64 €	2530.13
O&M	26	0.361		87	837.5	31.38 €	2512.42
O&M	27	0.347		87	831.6	30.17 €	2494.83
O&M	28	0.333		87	825.8	29.01 €	2477.37
O&M	29	0.321		87	820.0	27.90 €	2460.03
EoL	30	0.308	481.50 €	0.00 €	843.4	148.46 €	2530.13
Total					904.2	7862.46	81379.43

5.5 Base Case Life Cycle Costs for society

Calculations of the external costs for modules and inverters are available in Annex B.

The societal costs for Base-Case 1 (residential system) are 0.00764 euro per kWh for the module and 0.000659 euro per kWh for the inverter. The total external costs for the system are 0.0083 euro. The life cycle costs per kWh for this system are 0.078 euro per kWh (Table 106). The total life cycle costs for society for Base-Case 1 are thus 0.0883 euro.

The societal costs for Base-Case 2 (commercial system) are 0.00764 euro per kWh for the module and 0.000341 euro per kWh for the inverter. The total external costs for the system are 0.0080 euro. The life cycle costs per kWh for this system are 0.08 euro per kWh. The total life cycle costs for society for Base-Case 1 are thus 0.088 euro.

The societal costs for Base-Case 3 (utility system) are 0.00764 euro per kWh for the module and 0.000114 euro per kWh for the inverter. The total external costs for the system are 0.0078 euro. The life cycle costs per kWh for this system are 0.05 euro per kWh. The total life cycle costs for society for Base-Case 1 are thus 0.0578 euro.

5.6 EU totals

For the energy impact of the current stock of PV systems has been estimated.

5.6.1 Module stock estimates for the EU

According to the method described in 5.1.1.4 the module stock for the EU has been estimated for the reference year 2016. The reference module capacity per technology and segment is shown in Table 109. The values have been taken from the ITRPV Roadmap[359], which tracks the module rated power for different cell technologies.

Table 109. Reference size in Wp of modules installed per segment and technology for the year of reference 2016.

	Multi	Mono	CdTe	aSi	CIGS	HighEff
Rated power residential	270	285	-	-	145	245
Rated power commercial	270	285	-	-	145	245
Rated power utility	325	340	118	-	-	375

Then the number of installed units in EU can be calculated from the technology shares per market segment that were provided in Task 2 (shown in Table 110).

Table 110. Number of installed units (thousands) of modules per technology and segment estimated for the reference year 2016

	Multi	Mono	CdTe	CIGS	HighEff	Total
Residential	2,898	1,580	-	256	283	5,018
Commercial	4,255	2,455	-	434	361	7,505
Utility-scale	3,861	2,047	1,159	-	262	7,329
Total	11,014	6,082	1,159	690	906	19,852

5.6.2 Inverter stock estimates for the EU

According to the method described in 5.1.1.4 the inverter stock for the EU has been estimated for the reference year 2016. The reference inverter capacity per technology and segment is shown in Table 109. The values have been taken from the market research by GTM and Becquerel Institute[360], which tracks the inverter capacities for different technologies.

Table 111. Reference size of inverters installed per segment and technology.

	Micro	String 1 phase	String 3 phase	Central
Rated power residential (W)	250	3000	1000	-
Rated power commercial (kW)	-	-	25	-
Rated power utility (kW)	-	-	-	1,500

[359] *http://www.itrpv.net/Reports/Downloads/*

[360] *See task 2 of the Preparatory study*

Then the number of installed units in EU can be calculated from the technology shares per market segment that were provided in Task 2 (shown in Table 110)

Table 112. Number of installed units (thousands) of modules per technology and segment estimated for the reference year 2016

	Micro	String 1 phase	String 3 phase	Central
Residential	345,713	365,060	687,517	-
Commercial	-	-	83,338	-
Utility- scale	-	-	-	1,056

5.6.3 System sales estimates for the EU

At the system level, and in agreement with the previous sections for the estimation of modules and inverter sales, the system sales has been estimated.

Table 113. Number of installed units of systems per segment estimated for the reference year 2016

	Residential	Commercial	Utility
Average capacity (kW)	3	24.4	1875
Total capacity (MW)	1339.44	2540.8	2333.55
Units	446480	104131.1475	1244.56

5.6.4 EU totals for systems

EU totals have been calculated for the system Base-Cases using the sales in the reference year 2016 from Table 110, the reference yield (1311 kWh/kW before PR) provided in Table 78 and the calculated environmental impacts for the different Base-Cases. The calculated environmental impacts for the residential Base-Case are available in Table 100, for the commercial Base-Case in Table 102 and for the Utility scale Base Case in Table 104. EU totals are then shown in Table 114.

The EU total greenhouse gas emissions (for sales 2016) are 0.006% of the total EU greenhouse gas emissions of the year 2011. The EU total emissions in 2011 were 5054 mt CO_2 eq (EcoReport Tool, sourced from EEA3).

5.7 EU Ecolabel and GPP criteria

The aim of this section is to systematically assess the environmental impacts that are associated with the different products to be addressed within the scope in a standardised manner. This will allow for the identification of hot-spots for environmental impacts across different life cycle stages, and at the level of specific material flows/inputs and emissions. This in turn will facilitate the identification of potential criteria for EU Ecolabel and GPP.

The identification of environmental impacts which are not detected through standard LCA tools and PEF, or non-environmental impacts of relevance (e.g. health or social related issues) shall also take place.

Table 114. EU Total impacts for system market segments

		Residential	Commercial	Utility	Total EU
Other Resources & Waste					
Total Energy (GER)	MJ	1.04E+09	2.04E+09	1.75E+09	4.83E+09
of which, electricity (in primary MJ)	MJ	9.76E+07	1.21E+08	3.60E+07	2.54E+08
Water (process)	ltr	1.58E+07	2.28E+07	1.17E+07	5.02E+07
Water (cooling)	ltr	4.41E+07	7.83E+07	6.26E+07	1.85E+08
Waste, non-haz./ landfill	g	5.74E+09	1.17E+10	1.06E+10	2.80E+10
Waste, hazardous/ incinerated	g	7.11E+07	1.21E+08	8.58E+07	2.78E+08
Emissions (Air)					
Greenhouse Gases in GWP100	kg CO_{2eq}	7.35E+07	1.45E+08	1.26E+08	3.45E+08
Acidification, emissions	g SO_{2eq}	5.02E+08	9.98E+08	8.66E+08	2.37E+09
Volatile Organic Compounds (VOC)	G	1.21E+07	2.44E+07	2.15E+07	5.81E+07
Persistent Organic Pollutants (POP)	ng i-Teq	2.20E+07	3.84E+07	3.25E+07	9.29E+07
Heavy Metals	mg Ni_{eq}	1.23E+08	2.47E+08	2.18E+08	5.89E+08
PAHs	mg Ni_{eq}	5.67E+07	1.14E+08	1.01E+08	2.72E+08
Particulate Matter (PM, dust)	g	1.29E+08	2.68E+08	2.46E+08	6.43E+08
Emissions (Water)					
Heavy Metals	mg Hg/20	7.25E+07	1.14E+08	7.12E+07	2.58E+08
Eutrophication	g PO4	2.09E+07	4.32E+07	3.89E+07	1.03E+08

5.7.1 Systematic assessment of LCA related literature

The main requirement of the EU Ecolabel and Green Public Procurement is that criteria should be based on scientific evidence and should focus on the most significant environmental impacts during the whole life cycle of products. The purpose of this section is to respond to this requirement by using the best available scientific evidence to identify the environmental "hot spots" in the life cycle of Photovoltaic Modules, Inverters and Systems. This evidence can also be used to cross check and complement the results that emerged from the MEErP analysis of the base cases.

5.7.1.1 Overview of LCA studies on solar photovoltaic modules, inverters and systems

In the first step, relevant Life Cycle Assessment (LCA) literature regarding the environmental assessment and improvement potential of Photovoltaic Modules, Inverters and Systems, was identified and critically reviewed for the robustness of the results (methodology, data quality, age etc.).

This section presents an overview of existing LCA studies together with an initial screening categorising them according to the following quality criteria:

- Subject of the studies: The analysed products should have representative features of the product group, sub-categories, technologies or specifications.

- Time-related coverage of data: This refers to the year the inventory data of the analysis is based on; studies should ideally be less than 4 years old (publication year 2015 or later).
- Comprehensiveness and robustness: this refers to which environmental impacts are considered in the study? The impact Categories should be comprehensive, ideally following recognised LCA methodologies, and scientifically. Ideally studies are cradle-to-grave.

5.7.1.2 Selection of LCA studies for further analysis

A literature search has been performed with the aim of identifying relevant literature. An overview of this screening has been made and is available in Annex C. For all papers, the following information is available:

- General information: Year of publication, Authors, Journal/source, Title, Region
- Life cycle stages considered: Manufacture, Use, End-of-life, System boundaries
- Technical aspects: Technology, Functional unit, Lifetime, Capacity, Type of system
- Methodological aspects: Environmental impact categories, Assessment method, Main database used, Software, Data quality and data quality rating
- Results and interpretation: Hot spots, Technology comparison
- Notes

In total 30 recent studies have been identified. The comparative LCA studies seem to be most relevant for further analysis as in comparative assessments the same methodology is followed to analyse different systems.

The six studies identified to be of suitable quality for detailed analysis are:

- Wyss F., Frischknecht R., de Wild-Scholten M., Stolz P. 2015. PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots.
- Frischknecht R., Itten R., Sinha P., de Wild-Scholten M., Zhang J., Fthenakis V., Kim H.C., Raugei M., Stucki M. 2015. Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, International Energy Agency (IEA) PVPS Task 12, Report T12-04:2015.
- UNEP. 2016. Green Energy Choices: The benefits, risks, and trade-offs of low-carbon technologies for electricity production. Report of the International Resource Panel. E.G.Hertwich, J. Aloisi de Larderel, A. Arvesen, P. Bayer, J. Bergesen, E. Bouman, T. Gibon, G. Heath, C. Peña, P. Purohit, A. Ramirez, S. Suh.
- Lecissi E., Raugei M., Fthenakis V. 2016. The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update. Energies 9, 622; doi:10.3390/en9080622.
- Chatzisideris M., Espinosa N., Laurent A., Krebs F. 2016. Ecodesign perspective of thin-film photovoltaic technologies: A review of life cycle assessment studies. Solar Energy Materials & Solar Cells.
- Tschümperlin L. Stolz P., Frischknecht R. . 2016 Life cycle assessment of low power solar inverters (2.5 to 20 kW)

5.7.1.3 Detailed analysis of the selected LCA studies

In this detailed analysis we will look at the base parameters of the selected studies (investigated products and type of system), the goal and scope and functional unit, system boundaries and lifetime. Next, information on impact categories and impact assessment, assumptions, data and data quality is are identified. In the final part of the analysis, the results of the identified studies are discussed.

5.7.1.3.1 Base parameters of the selected studies

Some details of the products investigated in the selected studies are outlined in Table 115

Table 115. Description of the investigated studies

Study	Products investigated	Type of system/capacity
Wyss et al. 2015	CdTe, CIS, microcrystalline -Si[361], multicrystalline-Si, monocrystalline-Si Modules and cabling Sensitivity assessment with inverter	3 kWp integrated in roof, 3 kWp mounted on roof and 570 kWp open ground
Frischknecht et al. 2015	mono-and multi-crystalline Si, CdTe and high concentration (HC) PV additional inventory data describing different mounting structures, electrical components (cabling, inverter, transformer)	93 kWp slanted-roof installation, single-Si laminates; 280 kWp flat-roof installation, single-Si modules; 156 kWp flat-roof installation, multi-Si modules; 1.3 MWp slanted-roof installation, multi-Si modules; 324 kWp flat-roof installation, single-Si modules; 450 kWp flat-roof installation, single-Si modules; 569 kWp open ground installation, multi-Si modules; 570 kWp open ground installation, multi-Si modules
UNEP. 2016	Poly Si, CdTe, CIGS, inverters, transformers, wiring, mounting and construction	Ground and rooftop mounted systems
Lecissi et al. 2016	Mono-c-Si, multi-c-Si, CdTe, CIGS PV modules, including BOS (mechanical and electrical components such as inverters, transformers, and cables).	Fixed-Tilt Ground-Mounted Photovoltaic Systems and comparison to 1-Axis Tracking Installations
Chatzisideris et al. 2016	Review paper of 31 thin-film PV LCA studies covering the technologies: CdTe; CIGS; a-Si; nc-Si; CZTS; Zn_3P_2; PSC; OPV; DSSC; QDPV; GaAs	Review paper of 31 LCA studies with a focus on BIPV applications, thus thin-film PV systems.
Tschümperlin L. et al. 2016	Average European inverter 2.5 kW; Average European inverter 5 kW; average European inverter 10 kW and average European inverter 20 kW.	Inverters of 2.5 kW, 5 kW, 10 kW and 20 kW.

The selected studies are five comparative life cycle assessment studies and one review paper. The comparative studies all look at system level. The BOS is included in all studies, sometimes only partly (e.g. Wyss et al. (2015) include the inverter in a sensitivity assessment). The review paper from Chatzisideris et al. (2016) reviewed 31 thin-film LCA studies. They concluded that only a small part of the investigated studies included the BOS. The technologies covered by the selected papers are Poly Si, Mono Si, micromorphous Si, CdTe, CI(G)S and HCPV. The review paper from Chatzisideris et al. (2016) looked at different thin-film applications. The study from Tschümperlin et al. (2016) looked only at inverters.

5.7.1.3.2 Goal and scope

The goal and scope of the studies should be compliant to the goal and scope of this report section, being to identify the environmental “hot spots” in the life cycle of Photovoltaic Modules, Inverters and Systems based on the best available scientific evidence. The goal and scope of the selected studies can be divided into two broad categories:

- Studies that focus on an individual photovoltaic technology or system component. The goals of the study typically include hotspot analysis analyses for product improvement options, reporting and or documenting product performance, benchmarking products usually with a functional equivalent.
- Studies assessing photovoltaic systems in a context perspective, typically at meso and large-scale. These studies are primarily associated with goals oriented towards policy analysis or decision- and policy-making at urban, national or regional scales.

Most of the analysed studies fall into the first category with the exception of one study (UNEP 2016). The selected studies are mainly comparative life cycle assessments (Wyss et al. 2016, UNEP. 2016 and Lecissi et al. 2016). The paper from

[361] *Microcrystalline Silicon is amorphous Silicon, but also contains small crystals*

Chatzisideris et al. (2016) is a review paper on different thin film technologies. The scope of the study from Frishknecht et al. 2015 is compiling life cycle inventory data on the manufacturing. See Table 116 below.

Table 116. Goal and scope of the studies

Study	Goal of the study	Scope of the study
Wyss et al. 2015	Pilot the use of the PEF methodology in order to determine how to use it as the basis for product category rules for photovoltaic modules.	To analyse the whole life cycle of five subcategories of PV modules used in photovoltaic systems. The LCA follows the PEF methodology, from cradle to grave (product stage, construction stage, operation stage and end-of-life stage)
Frischknecht et al. 2015	To present the latest consensus LCA results among the authors, PV LCA experts in North America, Europe and Asia. At this time consensus is limited to five technologies for which there are well-established and up-to-date LCI data: mono- and multi-crystalline Si, CdTe, CIGS, and high concentration PV (HCPV) using III/V cells. The LCA indicators shown herein include Energy Payback Times (EPBT), Greenhouse Gas emissions (GHG), criteria pollutant emissions, and heavy metal emissions. To present LCI data for the above mentioned technologies including detailed inputs and outputs for manufacturing of the cell, wafer, module and BOS.	To provide updated life cycle inventory data of five subcategories of PV modules used in photovoltaic systems and of the BOS. To provide inventory data for different sizes of PV power plants in Europe.
UNEP. 2016	To provide a comprehensive comparison of greenhouse gas mitigation potential of various energy generation technologies, including hydro, solar, geothermal and wind and it examines the environmental and human health impacts of these options and their implications for resource use.	High level comparison of different technologies. Details regarding the followed methodology are not provided in the report.
Lecissi et al. 2016	Update of life cycle assessment (LCA) and net energy analysis (NEA) perspectives for the main commercially relevant large-scale PV technologies as of today, namely: single-crystalline Si (sc-Si), multi-crystalline Si (mc-Si), CdTe, and CIGS providing input for long-term energy strategy decisions.	To compare commercially relevant large scale PV technologies from cradle to grave. The comparative life cycle assessment following ISO 14040 and ISO 14044 and the IEA guidelines.
Chatzisideris et al. 2016	To investigate how results of past LCA studies of thin-film PVs can be used to identify bottlenecks and opportunities for technological improvement and mitigation of environmental impacts and to highlight the value the value of using LCA as a strategic decision-support by identifying and critically reviewing ecodesign aspects of LCA studies across thin-film technologies.	Review paper of LCA studies BIPV applications and thus thin-film PV systems with focus on ecodesign aspects of the studies (so not only climate change and energy related indicators) and all life cycle stages (not only production, to avoid burden shifting).
Tschümperlin et al. 2016	The objective of this study is to compile life cycle inventories of different power scales of solar inverters. Compiling this new life cycle inventory is necessary due to significant changes in the technology used in inverters the past few years.	To generate life cycle inventories for inverters and to compare the environmental impacts caused by the solar inverters analysed in this study with the environmental impacts calculated based on the already existing life cycle inventory of a 2.5 kW inverter for the life cycle stages manufacturing (incl. raw material production) and disposal.

5.7.1.3.3 Functional unit, system boundaries and lifetime

According to ISO 14040/44, the functional unit refers to a quantified performance of a product system for use for comparisons on the basis for functional equivalence in LCA studies. The system boundary describes which processes are taken

into account in the LCA analysis and which processes are not. The lifetime is the reference duration that the products to be analysed will be in service.

The functional unit is 1 kWh of electricity generated in Wyss et al. (2016), Frischknecht et al. (2015) and UNEP (2016). Lecissi et al. (2016) express the results per kWp and per kWh. The paper from Chatzisideris et al. (2016) is a review paper of 31 different studies.

All papers consider the product stage while the majority exclude the end of life stage. Wyss et al. (2016) considers the entire life cycle excluding end-of-life while UNEP (2016) only considers the dismantling part of the end-of-life stage. The review paper from Chatzisideris et al. (2016) identified 6 studies covering the entire life cycle, 10 studies covering production and use stage, 13 studies covering only the production and 2 studies which cover production and end-of-life.

Table 117 provides an overview of the functional unit, system boundaries and lifetime considered in the selected LCA studies.

Table 117: Functional unit, System boundaries and considered lifetime

Study	**Functional unit**	**System boundaries**	**Lifetime**
Wyss et al. 2015	1 kWh (Kilowatt hour) of DC electricity generated by a PV module	Product stage, construction stage, operation stage and end-of-life stage. Modules and cabling are included, the impact of the inverter is investigated in a sensitivity assessment	Service life of 30 years
Frischknecht et al. 2015	1 kWh of electricity fed into the grid.	Included in the product system are the modules, the mounting system, the cabling, the inverters, and all further components needed to produce electricity and supply the grid.	Modules: 30 years for mature module technologies, may be lower for foil-only encapsulation; Inverters: 15 years for small plants; 30 years with 10% part replacement every 10 yrs. for large size plants; Transformers: 30 yrs.; Structure: 30 yrs. for roof-top and facades, and between 30-60 yrs. for ground mount installations on metal supports; Cabling: 30 yrs. (Fthenakis, 2011[238])
UNEP. 2016	Results are expressed per unit of power production (1 kWh).	The assessment covers production, construction, maintenance and dismantling	Not mentioned
Lecissi et al. 2016	Results are expressed per kWp and per kWh	Production, system operation and maintenance. End of life (EOL) management and decommissioning of the PV systems were not included including manufacturing, operation and maintenance	30
Chatzisideris et al. 2016	Review paper: depends on the study	Review paper of 31 studies, depends on the study: 6 studies cover the entire life cycle; 10 studies cover production and use stage; 13 studies cover only the production and 2 cover production and end-of-life	Review paper: depends on the paper
Tschümperlin et al. 2016	One solar inverter of a given power output with a lifetime of 15 years	The product system includes the supply of materials and energy used in the production and mounting, the production processes, packaging and the disposal of packaging material and of the product itself after the use phase.	15

5.7.1.3.4 Impact categories and impact assessment

Wyss et al. (2015) calculated the 15 mandatory PEF environmental impact categories complemented by three additional categories, being renewable cumulative energy demand, non-renewable cumulative energy demand and nuclear waste. Frischknecht et al. (2015) report greenhouse gas emissions and two energy related parameters (Primary energy demand and Energy payback time).

The life cycle inventory established in Frischknecht et al. (2015) can however be used to calculate other environmental impact categories as well. UNEP (2016) reports carbon footprint, human health related environmental impacts (ionizing radiation, photochemical oxidant formation, particulate matter, human toxicity, ozone depletion), ecosystem related environmental impacts (freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, terrestrial acidification, terrestrial ecotoxicity) and results for land occupation and resource use. Lecissi et al. (2016) report 5 impact categories, global warming potential, cumulative energy demand, acidification potential, ozone layer depletion and energy pay-back time.

The papers reviewed by Chatzisideris et al. (2016) report many different environmental impacts (see Table 118). Tschümperlin et al. report the environmental impacts of inverters for six impact categories previously identified as most relevant for PV electricity generation (Stolz et al. 2016[362]): global warming, human toxicity (cancer effects), human toxicity (non-cancer effects), particulate matter, freshwater ecotoxicity, mineral, fossil and renewable resource depletion.

The majority of studies use the Ecoinvent database and SimaPro software. The impact categories, method used, database used and software used for life cycle impact assessment are detailed in Table 118.

5.7.1.3.5 Assumptions

Table 119 lists some of the main assumptions made in the selected LCA papers and provides assumptions made on average yield, degradation rate, irradiation level, performance ration and average efficiency.

Wyss et al. (2015) report an average yield of 975 kWh/kWp and a degradation rate of 0.7% per year. Average yield and degradation rate are not mentioned in the other publications. The irradiation rate used by Wyss et al. (2015) is 1090 kWh/m^2/yr. This is the annual average yield of optimally oriented modules in Europe, weighted according to the cumulative installed photovoltaic power when excluding degradation effects (Wyss et al., 2015).

Frischknecht et al. (2015) use an irradiation of 1700 kWh/m^2/yr, representative for Southern European (Mediterranean) conditions. Lecissi et al. (2016) calculated results for three different levels which are representative of irradiation on a south-facing, latitude-tilted plane in Central-Northern Europe (1000 kWh/(m^2_yr)), Central-Southern Europe (1700 kWh/(m^2_yr)), and the Southwestern United States (2300 kWh/(m^2_yr)). Wyss et al. (2015), Frischknecht et al. (2015) and Lecissi et al. (2016) report efficiencies which are in these comparative LCA studies always lower for thin film compared to Si technologies.

The study from Tschümperlin et al (2016) investigates inverters. The assumptions listed in Table 119 are not relevant for inverters.

[362] Stolz P., Frischknecht R., Wyss F. and de Wild Scholten M. (2016) PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots, version 2.0. treeze Ltd. commissioned by the Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation", Uster, Switzerland.

Table 118. Impact categories, impact assessment method, database and software

Study	Impact categories	Method	Database	Software
Wyss et al. 2015	15 impact categories: Gobal Warming; Ozone depletion; Human toxicity, cancer; Human toxicity, non-cancer; Particulate matter; ionizing radiation; Photochemical Ozone formation; Acidification; Eutrophication, terrestrial; Eutrophication, aquatic; Ecotoxicity, freshwater; Land transformation; Resource depletion, water; Resource depletion, mineral, fossil, renew;. 3 additional indicators: Renewable cumulative energy demand, Non-renewable cumulative energy demand and Nuclear waste	Impact assessment methods according to PEF Guide	Ecoinvent 2.2 – with some adaptations	SimaPro 7.3.3
Frischknecht et al. 2015	Primary energy demand, Energy payback time, Greenhouse Gas emissions	For GHG: IPCC method (Fthenakis, 2011[238])	Ecoinvent v2.2	Not mentioned in the report
UNEP. 2016	Carbon footprint, human health (ionizing radiation, photochemical oxidant formation, particulate matter, human toxicity, ozone depletion), ecosystems (freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, terrestrial acidification, terrestrial ecotoxicity), land occupation, resource use	Not mentioned, high level report	Not mentioned in the report	Not mentioned in the report
Lecissi et al. 2016	Cumulative Energy Demand, Global warming, Acidification, Ozone depletion One additional indicator:Energy payback time	CML	Ecoinvent 3.1	SimaPro 8
Chatzisideris et al. 2016	Primary energy demand, Global warming, Acidification Ozone depletion, Photochemical Ozone formation, Eutrophication, Ecotoxicity freshwater, Terrestrial ecotoxicity, Human toxicity, cancer; Human toxicity, non-cancer, Respiratory in-organics, ionising radiation, Land use, Agricultural land occupation, urban land occupation, natural land transformation, resource depletion water, Abiotic depletion non fossil, Abiotic depletion fossil, Solid waste, Cumulative energy demand	Eco-indicator 95/99, CML and ReCiPe were the most commonly used LCIA methodologies among the reviewed LCA studies.	Not relevant – review paper	Not relevant – review paper
Tschümperlin et al. 2016	Global warming, human toxicity (cancer effects), human toxicity (non-cancer effects), particulate matter, freshwater ecotoxicity, mineral, fossil and renewable resource depletion.	ILCD midpoint 2011 (only selected impact categories – see previous column)	Ecoinvent 2.2	SimaPro v8.0.6

5.7.1.3.6 Data quality requirements and data sources

Data quality level and sources of primary and secondary data should be documented. The time-related, geographical and technological representativeness of the selected LCA studies are summarised in Table 120. This table also contains information on data sources of primary and secondary data.

Table 119. Assumptions made in the selected papers

Study	Average yield	Degradation rate	Irradiation	Performance ratio	Average efficiency
Wyss et al. 2015	975 kWh/kWp	0.7% per year	1090 kWh/m²/yr	/	CdTe: 14% CIS: 10.8% Micro-Si: 10% Multi-Si: 14.7% Mono-Si: 15.1%
Frischknecht et al. 2015	/	/	1700 kWh/m²/yr	0.75	Multi-Si: 14.2% Mono-Si: 14.5% CdTe: 11.3%
UNEP. 2016	/	/	/	/	/
Lecissi et al. 2016	/	/	1000 kWh/m²/yr; 1700 kWh/m²/yr 2300 kWh/m²/yr	0.8	Sc-Si PV: 17% mc-Si: 16% CdTe PV: 15.6% CIGS PV: 14%
Chatzisideris et al. 2016	/	/	/	/	/
Tschümperlin et al. 2016	Not relevant, inverters	Not relevant, inverters	Not relevant, inverters	Not relevant, inverters	Not relevant, inverters

The foreground data provided in Frischknecht et al. (2015) are less than 10 years old. The data used by Wyss et al. (2016) are less than 5 years old, except for input data on CIGS, which are from 2010. Lecissi et al. (2016) collected foreground data for CdTe. The other data are taken from the IEA task 12 report (Frischknecht et al. 2015). The data presented in Frischknecht et al. (2015) are company specific data (e.g. data from FirstSolar for CdTe; data from Amonix for HCPV) or average data based on input from several companies (for mono and multi Si data from 11 companies collected during the Crystalclear project). Regarding the geographical representativeness, regionalized data have been used in Wyss et al. (2015), Frischknecht et al. (2015) and Lecissi et al. (2016). The foreground data collected by Tschümperlin et al. (2016) are most likely less than 5 years old.

Table 120: Time-related, geographical and technological representativeness of data and data sources of primary and secondary data

Study	Time-related representativeness	Geographical representativeness	Technological representativeness	Data sources of primary data	Data sources of secondary data
Wyss et al. 2015	Inventory data describing the supply chain of the monocrystalline-Si, and multicrystalline-Si PV modules were provided by leading manufacturers representative of 2012. Inventory data describing the supply chain of thin film PV modules stem from FirstSolar (CdTe), Oerlikon Solar (now TEL, micromorphous silicon) representative of 2012. Avancis and Solar Frontier (CIGS). The CIGS inventory data are from 2010 and published by SmartGreenScans in 2014 (de Wild-Scholten 2014). All data come with uncertainty information	Europe, regionalised electricity mixes have been used within the supply chain	Data collected from leading manufacturers during the study, CIGS inventory data were from 2010. Representative for current technology (at the time of the study)	Manufacturers. For CIGS: publication from SmartGreenScans	Ecoinvent
Frischknecht et al. 2015	Primary data: The LCI datasets presented in this report correspond to the status in 2011 for crystalline Si, 2010-2011 for CdTe, 2010 for CIGS	Crystalline Si-PV modules: data from 11 companies from the CrystalClear project; CdTe PV: First Solar's CdTe PV manufacturing plant in Perrysburg (USA);	Data collected from leading manufacturers	Crystalline Si-PV modules: 11 commercial European and U.S. photovoltaic module manufacturing; CdTe: First Solar	Ecoinvent
UNEP. 2016	No information on time related representativeness of input data	No information on geographical representativeness in the publication	Regionalised electricity mixes are used	Not mentioned	Not mentioned
Lecissi et al. 2016	CdTe modules: foreground data on the production provided directly by First Solar BOS CdTe ground mounted system: foreground data provided by First Solar c-Si PV and CIGS technologies: IEA-photovoltaic power systems (PVPS) Task 12 Report from 2015 The efficiencies of all the PV technologies as well as the electric mixtures used in the Si supply chain and for PV module production have been updated to reflect the current (2015) situation	Real geographic location of each component has been considered.	Data collected from leading manufacturers	CdTe: First Solar, BOS: First Solar c-Si PV and CIGS technologies: IEA-photovoltaic power systems (PVPS) Task 12 Report from 2015	Ecoinvent 3.1

Chatzisideris et al. 2016	Not relevant, review paper	Not relevant, review paper	Not relevant, review paper	Not relevant, review paper	Not relevant, review paper
Tschümperlin et al. 2016	Primary data are collected from three European inverter manufacturers. The year for which the data are representative is not mentioned, but the study is published in 2016 and the aim of the study was to compile a life cycle inventory for inverters	Europe, data provided by three European manufacturers	Data collected for current technology (2016). Inverter mass has been extrapolated to the power outputs of 2.5 kW, 5 kW, 10 kW and 20 kW using a non-linear formula proposed by Caduff et al. (2011)[363]: $M = 6.03 * P^{0.68}$ (where M = Mass and P = Power output)	The data gathered differ considerably in the level of detail. Only one manufacturer provided data for each component mounted on their print board assembly. The data for the print board components have been taken directly from one single manufacturer. This is mentioned in the study as a clear limitation of the study	Ecoinvent 2.2

[363] *Caduff M., Huijbregts M. A. J., Althaus H.-J. and Hendriks A. J. (2011) Power-Law Relationships for Estimating Mass, Fuel Con-sumption and Costs of Energy Conversion Equipments. In: Environmental Science & Technology, 45(2), pp. 751-754.*

5.7.1.3.7 Results of the selected LCA studies

PEF screening report (Wyss et al., 2015) and PEFCR (Technical Secretariat, 2018)

Depending on the PV technology the environmental impacts vary depending on the application. The overall weighted results show that CdTe modules have the lowest impact (2.02 10^{-6} pt/kWh), followed by CIS (3.29 10^{-6} pt/kWh), micro Si (4.73 10^{-6} pt/kWh), multi Si (5.68 10^{-6} pt/kWh), and finally mono Si (9.28 10^{-6} pt/kWh). Within each technology, the roof-mounted systems cause the lowest impacts per kWh of electricity produced, followed by the ground-mounted systems. The latter cause the highest environmental impact of the systems analyzed. These differences are due to the land use, the mounting system and the cabling.

Based on the outcomes and findings of all environmental footprint screening studies, the method for weighting has been updated after the publication of the screening study. During the PEF PV screening study an anomaly on the characterisation factor for indium has been identified. This anomaly was responsible for the high contribution of CIGS modules to the impact category mineral, fossil, renewable resource depletion. Using the updated method in the PEFCR 2018 has lead to different results compared to the results published in the screening report.

The environmental performance of a kWh of DC electricity produced with the average PV module mix in Europe and most impact categories are mainly influenced by the production of the modules, with the exception of human toxicity cancer effects, freshwater ecotoxicity and eutrophication as well as cumulative energy demand (CED) renewable (see Figure 118). However, it is to be noted that these impact categories are not reported in the updated PEFCR 2018.

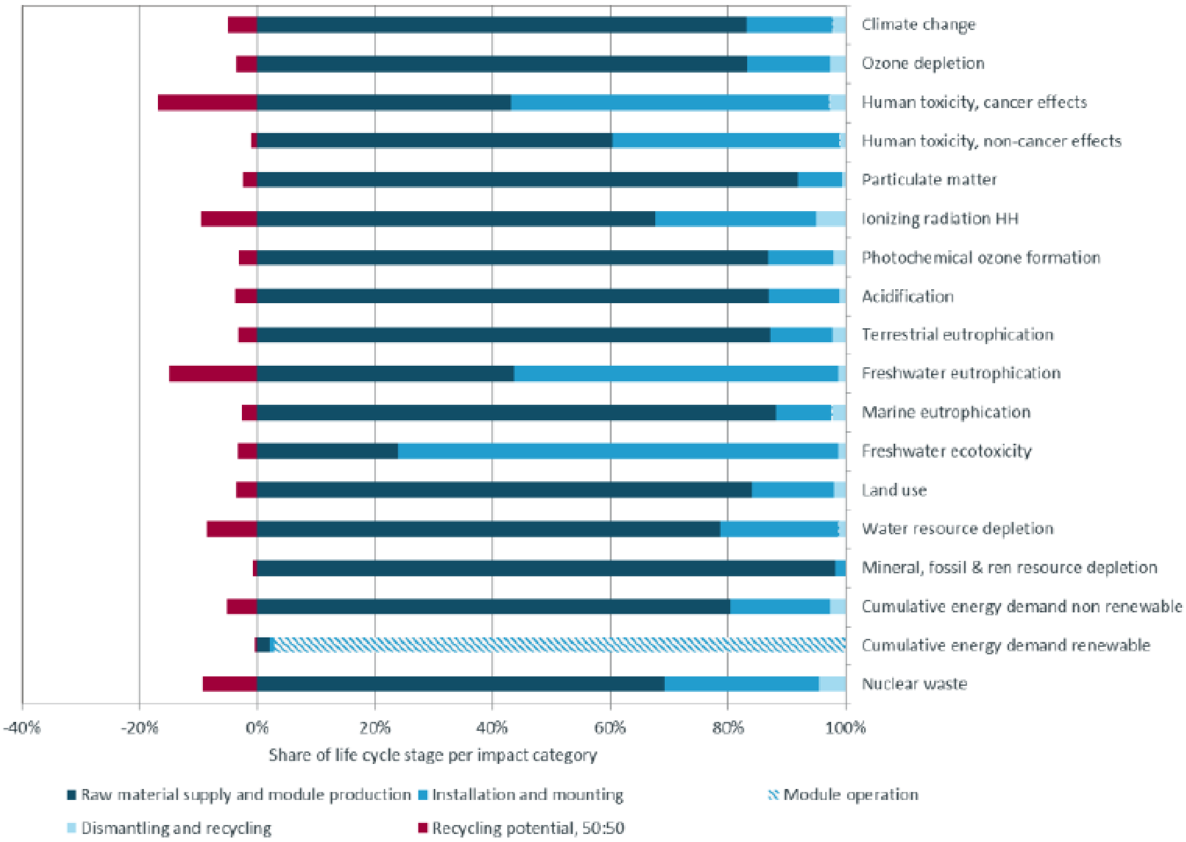
In the case of CIS and CdTe PV modules, the production and the construction stages are the most significant life cycle stages on average for all impact categories. The impact category that dominates the environmental impact is climate change followed by the resource use (minerals and metals), resource use (fossils) and particulate matter.

For the silicon based PV technologies, the production stage is the most relevant life cycle stage on average for all impact categories. The environmental impacts of Chinese electricity production contribute strongly to the weighted result in addition to the supply of mineral resources.

The use phase across all technologies was not found to be significant for the majority of impact categories except for the CED renewable (harvested solar energy). The end-of-life stage contributes to overall impacts between 0 % to 5 % while the potential benefits from recycling can result in a credit of -17 % for human toxicity, cancer effects, shortly followed by freshwater eutrophication, ionising radiation and water resource depletion.

The production of 1 kWh DC electricity with an average residential scale PV system mounted on a rooftop causes on average 65 grams of CO2-eq and requires 0.795 MJ of non-renewable primary energy. The particulate matter emissions amount to 86.9 mg per kWh and 1 kWh of DC electricity produced with PV modules requires 32.1 mg Sb-eq of abiotic resources and consumes 72.5 g water-eq of water.

Figure 118. (taken from Wyss et al., 2015): Environmental impact results (characterized, indexed to 100 %) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with average PV modules mounted on a slanted roof. The potential benefits due to recycling are illustrated relative to the overall environmental impacts from production to end-of-life.

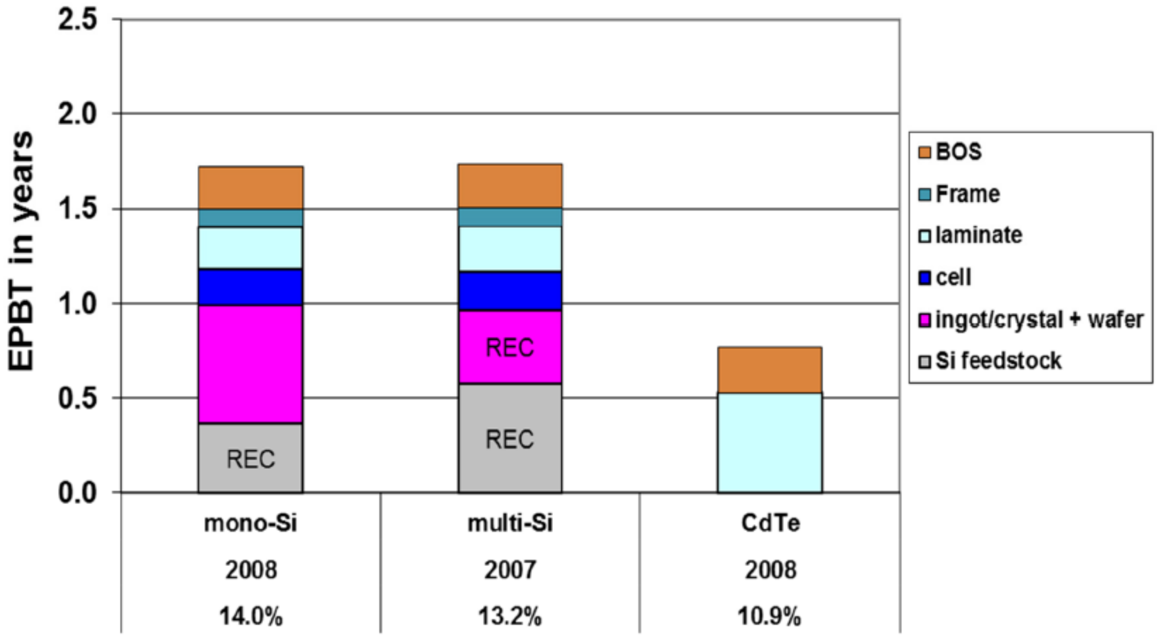


<u>IEA, PVPS task 12 (Frischknecht et al., 2015)</u>

A strong focus of this study was the relationship between the primary energy consumed during the production stage of the modules and primary energy generated in the use stage. In order to relate these figures the energy payback time is calculated. Figure 119 gives the energy payback time (EPBT) estimates of three major commercial PV module types, i.e. mono-Si, multi-Si, and cadmium telluride (CdTe). Data was harmonized for the system boundary and performance ratios, according to IEA Task 12 LCA Methodology Guidelines. REC corresponds to REC product-specific Si production; the corresponding LCI data are not publicly available.

The EPBT for a typical rooftop installation in south Europe, (i.e., irradiation of 1700 kWh/m^2/yr), corresponds to 1.7 years, 1.7 years and 0.8 years for mono-Si, multi-Si, and CdTe PV technologies, respectively. The impact of the BOS is not very important for the three investigated systems. For mono-Si and multi-Si the largest share of the impact is generated during production of the Si feedstock and ingot/crystal and wafer production. For CdTe, the largest impact comes from laminate production.

Figure 119. (taken from Frischknecht et al. 2015) Energy payback time (EPBT) of rooftop mounted PV systems for European production and installation under Southern European irradiation of 1700 kWh/m2/yr and performance ratio of 0.75. Data adapted from de Wild Scholten (2009) and Fthenakis et al. (2009).



UNEP (2016)

This report compares PV technologies with other energy technologies. It concludes that PV technologies show clear environmental benefits in terms of climate change, particulates, ecotoxicity, human health and eutrophication relative to fossil fuel technologies. However, PV electricity requires a greater amount of metals, especially copper, and, for roof-mounted PV, aluminium.

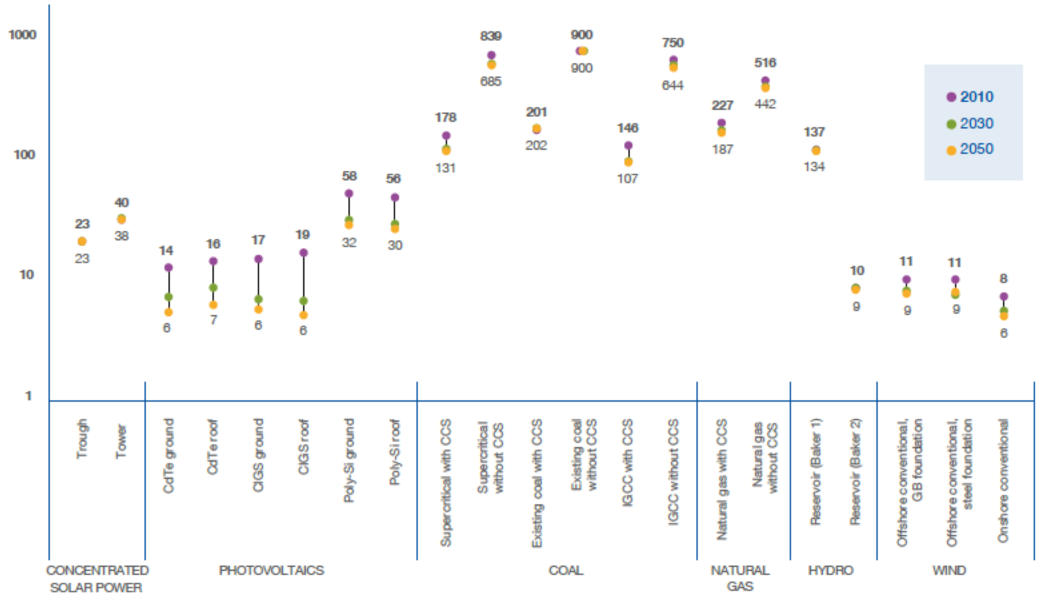
When looking at the life cycle of the PV systems, UNEP (2016) identified that energy use during the manufacturing process contributes the most to climate change, particulates and toxicity. The largest contributors to metal use in PV systems are the inverters, transformers, wiring, mounting and construction.

On the comparison of PV technologies, UNEP (2016) writes that generally thin film technologies show lower environmental impacts than crystalline silicon. Crystalline silicon requires a greater quantity of electricity and has higher direct emissions during production of metallurgical grade silicon, polycrystalline silicon wafers and modules.

UNEP also analyses the use of critical raw materials in PV. They mention that PV uses substantial amounts of silver as a conductor for cell electrodes. Thin film technologies rely on semiconductor layers composed of by-product metals, namely cadmium, tellurium, gallium, indium and selenium. As the thin film technologies using these elements capture larger market shares, they may encounter shortages if the recovery of these metals from primary copper and zinc production is not increased. Metal supply shortage is a particular concern for tellurium in CdTe technology. Due to the toxicity of the involved metals, proper recovery and recycling is important. See Figure 120 to Figure 122.

Figure 120. (taken from UNEP 2016) Life-cycle GHG emissions of different energy technologies, in g CO_{2e}/kWh, reflecting application of technology in Europe

Figure 1: Life-cycle GHG emissions of different energy technologies, in gCO2e/kWh, reflecting application of the technology in Europe [12].
The numbers for future years reflect a reduction of emissions expected due to technical progress and the reduced emissions in the production of equipment following the implementation of a mitigation scenario.



12 Data for other regions is available in the full report. Abbreviations: CdTe – Cadmiumtelluride, CIGS – Copper Indium Gallium Selenide, Poly-Si – Polycrystalline Silicon, CCS – CO2 Capture and Storage, IGCC – Integrated Gasification Combined Cycle, GB – Gravity-Based Foundation.

Figure 121. (taken from UNEP 2016) Human health impact in disability adjusted life years (DALY) per 1 TWh of electricity generated, for Europe 2010.

Figure 2: Human health impact in disability adjusted life years (DALY) per 1TWh of electricity generated, for Europe 2010 [20].

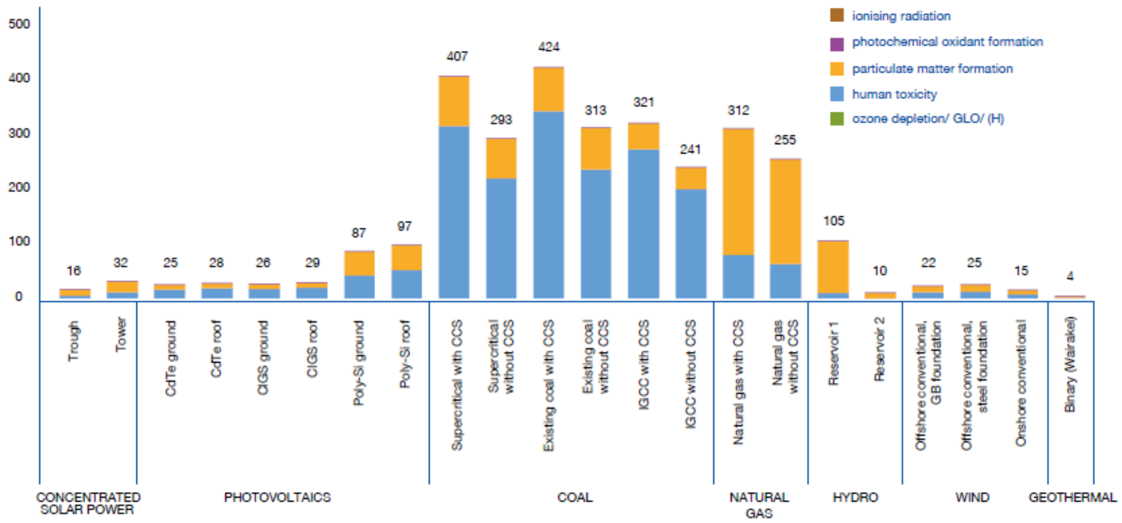


Figure 122: (taken from UNEP 2016): Ecosystem impacts in species-year affected per 1000 TWh of electricity following different damage pathways, reflecting Europe 2010.

Figure 3: Ecosystem impacts in species-year affected per 1000 TWh of electricity following different damage pathways, reflecting Europe 2010 [23].

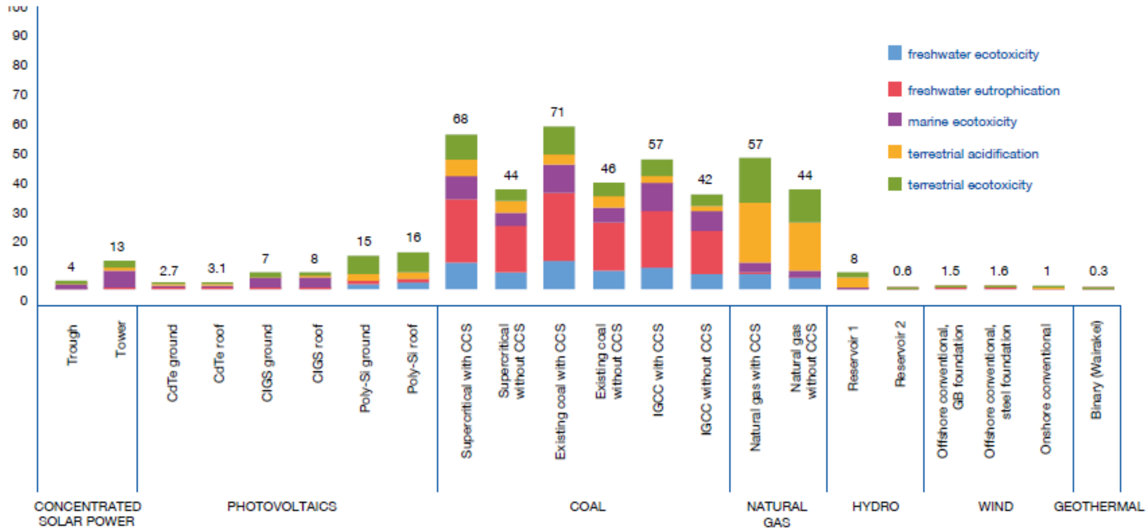
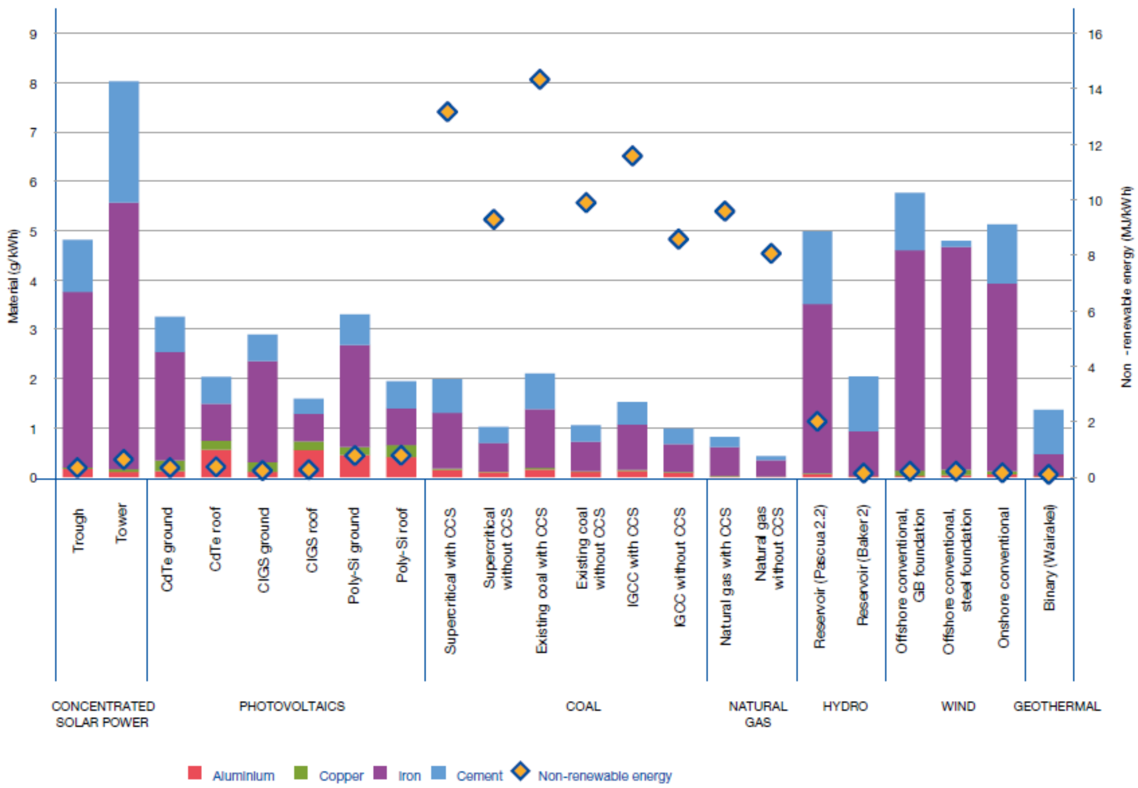


Figure 123. (taken from UNEP 2016) Bulk material and non-renewable energy requirements per unit power produced.

Figure 5: Bulk material and non-renewable energy requirements per unit power produced.[28]

Fossil technologies have high cumulative non-renewable energy demand (CED) and low bulk material requirements.



Lecissi et al., 2016

Lecissi et al. 2016 calculated the energy pay-back time (EPBT) for 4 fixed-tilt ground mounted installations. The EPBT range from 0.5 years for CdTe PV at high-irradiation (2300 kWh/(m^2/yr)) to 2.8 years for sc-Si (mono-crystalline) PV at low-irradiation (1000 kWh/(m^2/yr)) (see Table 121). The Global warming potential (GWP) per kWh_{el} varies between ~10 g for CdTe PV at high irradiation, and up to ~80 g for Chinese sc-Si PV at low irradiation. In general, the results point to CdTe PV as the best performing technology from an environmental life-cycle perspective, also showing animprovement for current production modules in comparison with previous generations.

The results clearly show that the most impacting step for crystalline Si technologies is from solar grade Si supply to finished PV cells, which includes ingot/crystal growth and wafer and cell production. The BOS contribution is generally fairly low, with the partial exception of the acidification potential results, which are negatively affected by the comparatively large amounts of copper and aluminium required. For CdTe PV and CIGS PV, the contribution of the BOS becomes relatively more important, due to the lower impact of the PV module production compared to crystalline Si.

Finally, Lecissi et al. 2016 determined that one-axis tracking installations can improve the environmental profile of PV systems by approximately 10% for most impact metrics.

Table 121. Energy pay-back time calculated by Lecissi et al. 2016

Table 1. Energy pay-back time (EPBT) of the analysed PV systems (mean values for the various production sites), corresponding to the three considered irradiation levels.

Irradiation and Grid Efficiency (η)	sc-Si PV	mc-Si PV	CdTe PV	CIGS PV
1000 kWh/(m^2·yr); η = 0.3	2.8	2.1	1.1	1.9
1700 kWh/(m^2·yr); η = 0.3	1.6	1.2	0.6	1.1
2300 kWh/(m^2·yr); η = 0.3	1.2	0.9	0.5	0.8

Chatzisideris et al., 2016

Chatzisideris et al. (2016) observed that an LCA study might produce considerably different results for some impact categories if it disregards the disposal stage. The disposal stage can entail benefits due to the recyclability of certain materials.

Equally important to considering the entire PV life cycle, LCA studies must include all environmental impact categories to identify the most problematic ones and avoid burden-shifting from one impact category to another one. Chatzisideris et al. (2016) illustrate this statement with the results of a study from Serrano-Luján. In this study the impact of electricity generated by a CdTe PV system was lower than the impact of electricity from Spain's average electricity mix in 9 impact categories. The results were higher for metal depletion category than the results of Spain's average electricity mix. The reason stems from the use of copper, lead and steel for the CdTe modules and BOS.

Based on normalised results presented in some of the reviewed papers, Chatzisideris et al. (2016) identified toxicity impacts and resource depletion as important impact categories for thin-film PV.

Conclusions on hot spots at module level could only be made by Chatzisideris et al. (2016) for primary energy demand. This is because most of the reviewed papers only made a hot spot analysis for this indicator. Primary energy demand consumed by the production of thin-film modules was mainly the result of electricity demanding processes rather than materials with a high-embedded energy. Across technologies, these are mainly metal deposition processes with vacuum conditions and high temperatures such as ITO sputtering and layer deposition. Only a few studies were found to identify materials with embedded energy as hotspots with the highest contribution to energy demand. These include Al as encapsulation or framing material. In metal-free or ITO-free technologies, main contributors to energy demand are plastics: PET as substrate and encapsulation barriers.

Across thin-film technologies, the contribution of BOS to environmental impacts can be significant, ranging from 3% to 95% depending on the impact category. For CdTe systems cradle to grave, the reported contribution ranges from 40 to 51% for the impact categories climate change, ozone depletion, photochemical ozone formation and acidification. These findings demonstrate the significant influence of BOS components on the environmental performance across impact categories.

Tschumperlin et 2016

Tschümperlin et al. (2016) compared the results obtained with the newly compiled inventories for low power inverters (2.5 kW, 5 kW, 10 kW and 20 kW) to existing inventory of a 2.5 kW inverter dating back to products over 10 years old.

They also analysed the main contributors to each of the seven impact categories modelled using the new inverters inventories. The hot spot is clearly the print board assembly, which is responsible for 59 % of the total result for the impact category climate change; 50% of the human toxicity cancer effects, 55% of the human toxicity non-cancer effects, 52 % of the total PM emissions, 67 % of the total freshwater ecotoxicity contribution and 75 % of the overall impact on resource depletion.

On the other hand, the energy used during production is at most responsible for 1.5% of any of the impact categories. Also, environmental impacts due to packaging, infrastructure, metal processing, transportation of raw materials and end of life treatment are small in all the considered impact categories.

When comparing the old 2.5 kW inverter with the new 2.5 kW inverter, the results are higher for the new inverter across all impact categories except for tow impact categories: human toxicity cancer effects category, where the impacts are equal, and mineral, fossil and renewable resources, in which the old inverter has a higher contribution.

5.7.2 Other environmental or non-environmental impacts of relevance for EU Ecolabel certification and GPP

The aim of this section is to identify environmental impacts which are not explicitly identified through standard LCA tools and PEF, or non-environmental impacts of relevance (e.g. health or social related issues). These impacts are of particular relevance as the basis for the development of potential EU Ecolabel and GPP criteria.

5.7.2.1 Hazardous substances in solar photovoltaic products

This section focuses on substances that may be present in the final product and does not consider substances used in manufacturing as e.g. catalysts, cleaning agents.

The Ecolabel Regulation (EC) 66/2010 contains in Article 6(6) and 6(7) specific requirements that ecolabelled products shall not contain hazardous substances. The implications of these requirements, which are based on definitions laid down in the REACH regulation (EC) No 1907/2006 and in the CLP Regulation (EC) 1272/2008, are briefly explored in the subsequent sections.

5.7.2.1.1 REACH Candidate List substances

Article 6(6) of the Ecolabel Regulation refers to substances which meet the criteria described in Article 57 of the REACH Regulation (EC) No 1907/2006. Article 57 provides the criteria for Substances of Very High Concern that may then be included in the Candidate List. The criteria for being an SVHC are as follows:

- Classified with Hazard Classes 1A and 1B for carcinogenicity, germ cell mutagenicity and reproductive toxicity according to the CLP Regulation;
- Persistent, bioaccumulative and toxic as defined by the criteria in Annex XIII;
- Substances identified on a case by case basis that may raise equivalent levels of concern.

Suppliers of solar photovoltaic modules and inverters are required to comply with the REACH regulation (EC) No 1907/2006. The inclusion of a substance in the Candidate List triggers additional duties for EU manufacturers and importers:

  - Any producer and/or importer of an article or component containing a 'Candidate List' SVHC in a concentration above 0.1 % (w/w) or in quantities in the produced or imported articles above 1 tonne per year has the duty to notify the European Chemical Agency (ECHA).
  - Suppliers must provide the recipient of the article (downstream users) with sufficient information to allow safe use of the article. This information also needs to be provided to consumers within 45 days of a request.

The Candidate List is dynamic, with proposals for SVHC's submitted by Member States being entered onto the list prior to evaluation by ECHA. As of November 2018 the list contains a total of 191 substances[364]. For the purpose of the Ecolabel the whole product as well as subassemblies that are business to business products are to be considered as articles. For example the cells and junction boxes of a crystalline module, the circuit board of the inverter

The IEC 62474 substance declaration list[365] is understood to be used by the solar photovoltaic industry as a tool to pre-screen the Candidate List for relevance. The IEC list is referred to in the criteria of the NSF/ANSI 457 Sustainability Leadership

[364] *ECHA, Candidate List of substances of very high concern for Authorisation, Accessed November 2018, https://echa.europa.eu/candidate-list-table*

[365] *International Electrotechnical Commission (IEC), IEC 62474: Material declaration for products of and for the electrotechnical industry, http://std.iec.ch/iec62474*

Standard for Photovoltaic Modules. The standard has criteria requiring use of IEC 62474 and the disclosure of substances on the Candidate List if they are present in products.

A consortium comprising CEA Tech and Fraunhofer ISE made a preliminary screening of hazardous substances in solar PV products for the EU Ecolabelling Board in 2015. In regard to Candidate List substances they concluded based on screening of the list at the time that only one family of substances and another specific substance were used within the PV industry:

- Phthalates: These type of substances are mainly used as plasticisers in module connector cables, in particular where the sheathing is made of PVC. Phthalates of relevance are DMEP, DIPP, DPP, DnPP and DnHP.
- Cadmium sulphide: This substance forms part of the semi-conductor layer in both CIGS and CdTe technologies. The concentration is understood in both cases to be below 0.1% w/w.
- Disarsenic trioxide: This substance is a fining agent added to solar glass but would be present at below 0.1% w/w.

Subsequent to this screening the substances lead, lead monoxide and diarsenic trioxide have been added to the list and are of relevance to the product group. The inclusion of lead is of high relevance to both modules and inverters being used in solder and metallisation pastes at concentrations that may exceed 0.1%.

Long chain perfluorinated compounds (PFCs) such as PFOA, may be present as impurities (100-200ppm) in the fluoropolymer PVDF, which is used in ~50% of module backsheets produced globally. According to ECHA's restriction report, long chain PFCs are no longer used in the EU for PVDF manufacturing but they are used in China, where most of the PVDF for backsheets is produced.

A search was made of manufacturer REACH Article 57 declarations. LG was found to have a publicly accessible declaration. Their most recent (July 2019) declaration identifies one additional Candidate List substance - Dechlorane Plus (CAS No 13560-89-9) - that they specifically identify as being present in solar PV modules at >0.1% and that it is used in adhesives for module assembly [366].

5.7.2.1.2 Substances classified with CLP hazards

In addition to SVHCs, Article 6(6) of the Ecolabel Regulation refers to substances that *'meet the criteria for classification as toxic, hazardous to the environment, carcinogenic, mutagenic or toxic for reproduction (CMR)'* according to the CLP Regulation (EC) No 1272/2008. For the purposes of ecolabel criteria development the screening threshold for substances classified as such is 0.1% for articles. The hazards to screen are presented in Table 122.

Recognising that progress by manufacturers to substitute or eliminate the use of hazardous substances may vary between products groups, Article 6(7) recognises that in certain circumstances there may be a technical or environmental justification for still using a substance restricted by Article 6(6). In practice therefore, criteria should reflect those products that can demonstrate the state of the art in minimising the presence of hazardous substances.

The hazard screening approach adopted during product criteria development generally focusses on substances that fulfill a necessary function. Following on from initial screening by the CEA Tech/Fraunhofer ISE consortium, the relevance of the substances that provide the function of plasticisers, flame retardants and dirt repellents are briefly reviewed in this in subsequent sub-sections.

Plasticisers

Plasticisers are used primarily in cable sheathing but may also be present in other soft plastics used in the encapsulation of a module. As was already identified in section x.y, a number of low molecular weight phthalate plasticisers have been identified as Substances of Very High Concern because of their classification as being toxic for reproduction and, in some cases, as endocrine disruptors.

Phthalate-free plasticisers and cable sheathing materials have been developed. Material substitutes include thermoplastic elastomers (TPE) and Ethyl Vinyl Acetate (EVA). Safer plasticiser substitutes include TOM and DOTP. Plasticisers derogated in other EU Ecolabel product groups, therefore representing alternatives that at the time of criteria voting were deemed to be acceptable, are listed in Table 123.

[366] *LG Electronics, EU Reach Regulation Compliance https://www.lg.com/global/sustainability/environment/management-of-hazardous-substances*

Table 122 Restricted hazard classifications and their hazard categorisation

Acute toxicity	
Category 1 and 2	**Category 3**
H300 Fatal if swallowed (R28)	H301 Toxic if swallowed (R25)
H310 Fatal in contact with skin (R27)	H311 Toxic in contact with skin (R24)
H330 Fatal if inhaled (R23/26)	H331 Toxic if inhaled (R23)
H304 May be fatal if swallowed and enters airways (R65)	EUH070 Toxic by eye contact (R39/41)
Specific target organ toxicity	
Category 1	**Category 2**
H370 Causes damage to organs (R39/23, R39/24, R39/25, R39/26, R39/27, R39/28)	H371 May cause damage to organs (R68/20, R68/21, R68/22)
H372 Causes damage to organs (R48/25, R48/24, R48/23)	H373 May cause damage to organs (R48/20, R48/21, R48/22)
Respiratory and skin sensitisation	
Category 1A	**Category 1B**
H317: May cause allergic skin reaction (R43)	H317: May cause allergic skin reaction (R43)
H334: May cause allergy or asthma symptoms or breathing difficulties if inhaled (R42)	H334: May cause allergy or asthma symptoms or breathing difficulties if inhaled (R42)
Carcinogenic, mutagenic or toxic for reproduction	
Category 1A and 1B	**Category 2**
H340 May cause genetic defects (R46)	H341 Suspected of causing genetic defects (R68)
H350 May cause cancer (R45)	H351 Suspected of causing cancer (R49)
H350i May cause cancer by inhalation (R49)	
H360F May damage fertility (R60)	H361f Suspected of damaging fertility (R62)
H360D May damage the unborn child (R61)	H361d Suspected of damaging the unborn child (R63)
H360FD May damage fertility. May damage the unborn child (R60, R60/61)	H361fd Suspected of damaging fertility. Suspected of damaging the unborn child (R62/63)
H360Fd May damage fertility. Suspected of damaging the unborn child (R60/63)	H362 May cause harm to breast fed children (R64)
H360Df May damage the unborn child. Suspected of damaging fertility (R61/62)	
Hazardous to the aquatic environment	
Category 1 and 2	**Category 3 and 4**
H400 Very toxic to aquatic life (R50)	H412 Harmful to aquatic life with long-lasting effects (R52/53)
H410 Very toxic to aquatic life with long-lasting effects (R50/53)	H413 May cause long-lasting effects to aquatic life (R53)
H411 Toxic to aquatic life with long-lasting effects (R51/53)	
Hazardous to the ozone layer	
EUH059 Hazardous to the ozone layer (R59)	

Table 123. Plasticiser alternatives that have been derogated for us in other EU Ecolabel product groups

Plasticiser	**CAS No**	**Hazard group**
Derogated for use in external power cords and power packs, external casings and internal cables		
Trioctyl trimetallate (TOM/TOTM)	3319-31-1	Not classified
Dioctyl terephthalate (DOTP)	6422-86-2	Not classified
Hexamoll DINCH	166412-78-8	Not classified
DIDP	68515-49-1	Not classified
DINP	28553-12-0	Not classified.

Flame retardants

Flame retardants are primarily understood to be used in polymer back sheet materials of modules in order to provide fire protection in line with standards such as IEC 61730 and UL 723/790. This is particularly the case for Building Integrated PV products, which must meet more exacting fire protection requirements. More information is needed to verify whether they are used in the junction boxes of modules and in any of the electronic components of inverters, with possible locations including power supply units and printed circuit boards.

However, at a module level, to ensure compliance with IEC 61730-2, a burning brand and flame spreading test are executed. It is understood that all commercially available backsheets when they form part of the modules are able to pass these tests without the use of additional flame retardants. An additional safety concern arises because the fluoro-polymer backsheets can emit corrosive and harmful fluorinated gases.

In relation to back sheet materials themselves if they are required to meet a fire safety test the use of flame retardants or not is understood to be dependent on the chosen polymer. Their use is not necessary in the case that the back sheet material has a high melting point, such as in the case of fluorpolymers (e.g. PVF), or may be necessary in lesser quantities where the thickness of the material creates a barrier (e.g. PET). For other types of polymer they will need to be considered.

Flame retardants derogated in other EU Ecolabel product groups and therefore representing alternatives that at the time of criteria voting were deemed to be acceptable, are listed in Table 124 and Table 125. These flame retardants are potentially relevant for internal electrical components of an inverter and for a module junction box. The types of flame retardant currently used in back sheet materials require further identification with stakeholder input. It is understood that the use of inorganic flame retardants may have implications for the properties of a polymer back sheet.

Table 124. Flame retardants alternatives for circuitry that have been derogated for us in other EU Ecolabel product groups

Flame retardant	**CAS No**	**Hazard group**
Derogated for use in Printed wiring boards, power supply units, internal connectors and sockets.		
Dihydrooxaphosphaphenanthrene (DOPO) CAS No	35948-25-5	Group 3: H411, H412
Fyrol PMP (Aryl Alkylphosphinate)	63747-58-0	Group 3: H413
Magnesium hydroxide (MDH) *with zinc synergist*	1309-42-8	Group 3: H413
Ammonium polyphosphate	68333-79-9	Group 3: H413
Aluminium hydroxide (ATH) *with zinc synergist*	21645-51-2	Group 3: H413
Bisphenol A Bis (diphenyl Phosphate)	5945-33-5	Not classified

In terms of cables, PINFA identify the most significant alternatives to PVC material or brominate chemistries as metal hydroxides, including aluminium hydroxide (ATH), aluminium oxide hydroxide (AOH) and magnesium hydrovide (MDH). Intumescent systems based on phosphate chemistry are also identified as having been adopted by industry.

The substitutes available will depend on the chosen material for the cable sheath. Metal phosphinates are detailed as solutions for Thermoplastic Elastomers (TPE's), co-polyester elastomers and thermoplastic urethanes. The addition of nitrogen synergists such as melamine cyanate and melamine polyphosponate can be used to improve performance to fire protection standard IL94 V0.

The benefits of these alternative Flame Retardant systems are understood to include a substantial reduction in smoke when compared to halogenated materials or retardants. Their disadvantage is understood to be the high concentrations and filler material required.

Table 125. Flame retardants alternatives for cables that have been derogated for us in other EU Ecolabel product groups

Flame retardant	**CAS No**	**Hazard group**
Flame retardants *derogated for use in external power cables and power packs*		
Aluminium hydroxide (ATH) *with zinc synergist*	21645-51-2	Not classified
Magnesium hydroxide (MDH) *with zinc synergist*	1309-42-8	Group 3: H413
Bisphenol A Bis (diphenyl Phosphate)	5945-33-5	Not classified
Ammonium polyphosphonate	68333-79-9	Group 3: H413

Water and dirt repellents

The application of repellent coatings to module glass can reduce the accumulation of dust and dirt on the surface, thereby reducing performance losses[367]. Although such coatings are declared to have a long life-span based on environmental and accelerated life testing parameters – for example, 1,000 bi-monthly cleaning cycles – their possible degradation and migration into the environment may warrant further consideration.

An initial screening suggests that repellent properties are combined with Anti Reflective coatings. Chemistries which have been used as AR coatings include zinc oxide and silicon dioxide. It is understood that titanium dioxide and zinc dioxide are applied as anti-soiling coatings, together with morphological texturing of the glass surface to aid run-off. Fluorinated organic compounds are also understood to be used, but they are generally applied in order to renew or maintain the anti-soiling properties, having therefore a shorter lifetime.

The substitution of repellents in other EU Ecolabel product groups has focussed on the long chain length fluorinated repellents PFOS and PFOA, both of which raised concerns due to their persistency in the environment. They are as a result now the subject of restrictions under REACH. It is not clear the extent to which these chemistries are applied to module glass. According to research by the Danish EPA looking at textiles less persistent alternatives such as silicon or paraffin based repellents may still be classified as hazards so alternative chemistries must be reviewed carefully[368]. It is understood that the fluorinated compounds used to renew or maintain anti-soiling properties can be substituted by silicone repellents.

Textured solar glass additives

The glass used to manufacture solar modules must have a high visible light transmission in order to maximise the solar irradiation that passes through the glass and that is subsequently absorbed by the photovoltaic cells. Antimony compounds are used to remove bubbles of oxygen and oxidise residual iron that can reduce the light transmission of glass that is used to manufacture crystalline modules. Thin film modules use a different type of (float) glass that does not require the same fining agents. Antimony compounds may be present at a concentration of up to 0.8%. This means that the use of antimony containing glass would require a derogation according to the EU Ecolabel Regulation.

Two antimony compounds are understood to be used in solar glass manufacturing for crystalline modules - diantimony trioxide, which is of high concern to workers at production sites because of its classification with H373 and H351, and sodium antimonite which is classified with H411 [369]. Some manufacturers such as Borosil and f-Solar already manufacturer a low iron glass which eliminates the use of antimony altogether whilst achieving very high levels of light transmission.

[367] *Voicu et al, Anti-soiling coatings for PV applications, Presentation made by DSM at PV Module Technology & Applications Forum 2018, 29th January 2018.*

[368] *The Danish Environmental Protection Agency, Alternatives to perfluoroalkyl and polyfluoro-alkyl substances (PFAS) in textiles, Survey of chemical substances in consumer products No. 137, 2015.*

[369] *ECHA (2008) European Union Risk Assessment Report – diantimony trioxide*

The processes used by Borosil and f-Solar to manufacture the solar grade glass result in a highly transparent product (>93.5% uncoated). This advantage will be reflected in a power or energy rating of a module according to IEC 61853-1/3 because the transmittance and absorption of solar radiation by the module will be enhanced. As a result the output power under standard test conditions and the resulting energy yield will be higher compared to modules with front glass that has a lower transmission.

Whilst the presence of antimony requires evaluation because it is classified according to the CLP Regulation leaching tests of glass panels and ground waste glass made according to the EN 16637-2 and EN 12457-4 test conditions suggest that there is very low migration of antimony from glass during the use and end of life phases [370]. The results of these tests were below limit of detection for a PV glass panel (0.005 μg/cm^3, <0.005 ppm) and were 0.38 mg/kg (0.38 ppm) for migration from the granulate.

Concerns have been raised in some countries such as the USA and India about the risks that may arise from the disposal of solar glass containing antimony. Checking of the relevant thresholds in Annex III of Directive 2008/98/EC indicates that the presence of antimony would not result in the classification of such waste glass as hazardous. End of life recovery processes for solar PV modules will increasingly achieve a very high recovery and recycling rate for solar glass grades (>95%) and in the future the development of recovery processes is likely to allow for glass panels to be recovered in their entirety for re-use/recycling.

In relation to end of life glass treatment, feedback from PV Cycle (the largest EU producer responsibility scheme) and the German UBA, who are in the process of developing solar PV module waste criteria [371], indicates that the antimony content of this glass has to date not created a barrier to recycling processes. End markets include the flat glass industry and container glass industry and residual mixed shredded waste is also handled. The German UBA do not currently propose to establish controls or thresholds for antimony content in glass [372].

There are some end markets for which antimony content thresholds have been set. Road marking glass beads are an end market for recycled glass. Because the glass medium is much finer and is dispersed into the environment contamination thresholds have been set because imported waste glass was found to have much higher antimony content. EN 1423 establishes a reporting threshold of <200ppm.

5.7.2.1.3 Substances restricted by the RoHS Regulation

Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast), referred to as the RoHS Directive, lays down rules on the restriction of the use of hazardous substances in electrical and electronic equipment (EEE). These relate to the following substances, to which maximum concentration values in products apply:

- Lead (0,1 %)
- Mercury (0,1 %)
- Cadmium (0,01 %)
- Hexavalent chromium (0,1 %)
- Polybrominated biphenyls (PBB) (0,1 %)
- Polybrominated diphenyl ethers (PBDE) (0,1 %)
- Bis(2-ethylhexyl) phthalate (DEHP) (0,1 %)
- Butyl benzyl phthalate (BBP) (0,1 %)
- Dibutyl phthalate (DBP) (0,1 %)
- Diisobutyl phthalate (DIBP) (0,1 %)

In terms of the product scope considered by this study, photovoltaic modules (referred to below as panels) are specifically excluded according to the following definition:

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[370] *Glass for Europe (2015) The status of Flat Soda Lime Silicate Glass and its raw materials under REACH*

[371] *UBA, Behandlung von Elektroaltgeräten (EAG) unter Ressourcen- und Schadstoffaspekten, 31/2018*

[372] *Communication with JRC (2019)*

‘photovoltaic panels intended to be used in a system that is designed, assembled and installed by professionals for permanent use at a defined location to produce energy from solar light for public, commercial, industrial and residential applications;’

Despite this exclusion it is understood that manufacturers in the sector differentiate themselves by claiming the absence of substances restricted under RoHS - such as lead, cadmium and phthalates.

In this section the potential to minimise the use of lead and cadmium is therefore briefly reviewed against the background of current usage.

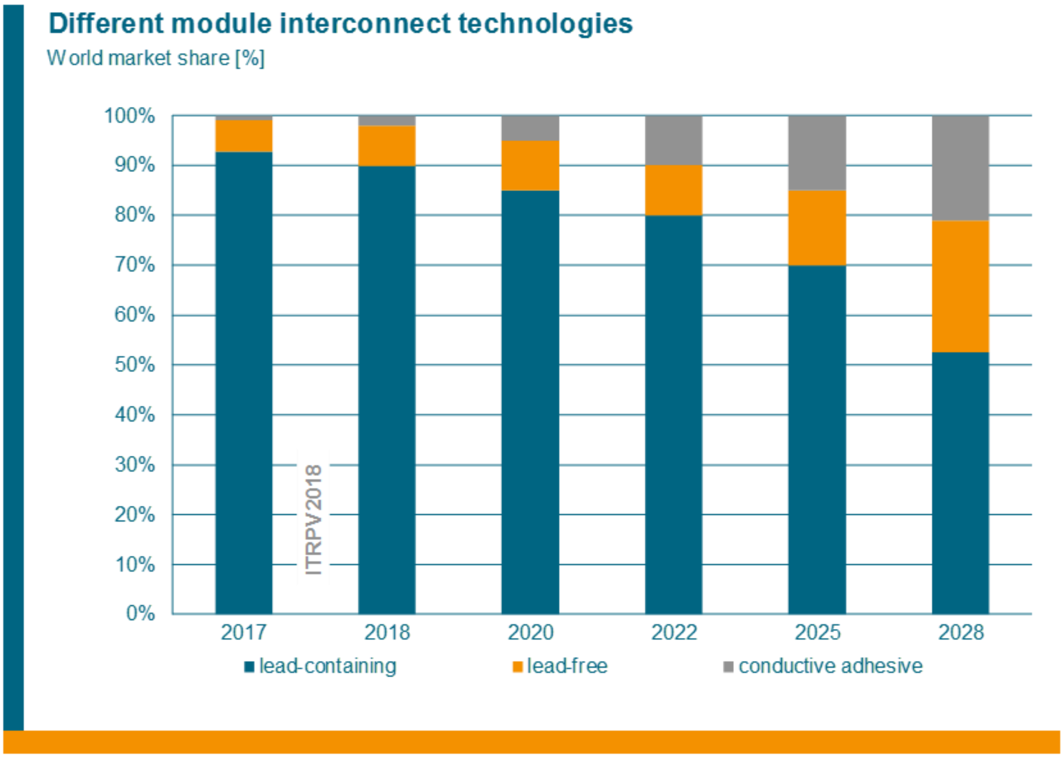
Lead

Lead is present at <0.003 wt.% in the metallization paste of wafer-based and thin film solar cells and is used to enable a contact formation. It is also present in the tin-lead alloy coating of the copper ribbons used to string together crystalline silicon cells in modules. The thickness of this coating depends on the number of ribbons and their thickness. The weight per module has been estimated to be in the range of 0.05% - 0.25% wt. indicating that it may be present at a concentration greater than the EU Ecolabel screening threshold of >0.1%. Following the REACH candidate listing of lead in June 2018, any module which contains more than 0.1% of lead would need to carry the necessary information.

The CEA Tech and Fraunhofer ISE screening study claimed that there was sufficient evidence at the time that lead-free soldering (using SnAgCu alloys) and silver pastes were feasible alternatives[373]. The presence in the market of RoHS compliant modules with declared lead concentrations <0.1 wt.% and lead-free modules was identified.

The commercialisation of lead-free module specifications by manufacturers Sunpower, Panasonic and Mitsubishi was also cited. It is to be cross-checked whether a shift to solders with a higher silver content results in any burden shifting between product stage environmental impacts.

Figure 124. Expected market share of different module interconnection material. International Technology. Roadmap for Photovoltaic (ITRPV)



Cadmium

The thin film technologies CdTe and CIGS both contain cadmium in their semi-conductor layers. CdTe modules contain cadmium telluride and may contain cadmium sulphide, resulting in a total cadmium content of around 0.05 wt.%, although it is to be noted that end of life recovery processes allow for up to 95% of this material to be recycled in a close loop (First solar process). CIGS modules may also contain cadmium sulphide but data could not be found on the concentration. It is understood

[373] *P. Schmitt*, P. Kaiser, C. Savio, M. Tranitz, U. Eitner , Intermetallic Phase Growth and Reliability of Sn-Ag-Soldered Solar Cell Joints, Energy Procedia 27 (2012) 664 – 669*

that both products can be manufactured without cadmium sulphide in their buffer layers. Two CIGS manufacturers - Solar Frontier and Steon - claim that they manufacture modules with 'RoHS compliant' cadmium concentrations of less than 0.01%.

5.7.2.2 Hazardous substances in manufacturing processes

In this sub-section two types of hazards that have been a focus of attention at solar photovoltaic module production sites are briefly reviewed – fluorinated gases with a high Global Warming Potential (GWP) and exposure to silicon tetrachloride.

High GWP (Global Warming Potential) production emissions

Fluorinated gases such as sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) are used in production processes for mass produced thin film products such as televisions and displays and have been identified since several years as being used in thin film photovoltaic production processes 374. Available information suggests that CF4 was used in edge isolation and C_2F_6, SF_6 and/or NF_3 for reactor cleaning after deposition of silicon nitride or film silicon. It was suggested at the time that their use was likely to increase due to a shift from wet to dry processing.

The NSF/ANSI 457 Sustainability Leadership Standard for Photovoltaic Modules includes a specific *requirement* relating to the 'avoidance or reduction of high global warming potential (GWP) gas emissions resulting from photovoltaic module manufacturing' suggesting that these emissions are still of relevance. High GWP gases of relevance are identified as including nitrous oxide (N_2O) and fluorinated greenhouse gases (F-GHGs) and it is noted that these may be used in manufacturing or reactor cleaning operations. The requirement can be met by ensuring that such gases are not emitted or that *'specifically designed abatement systems are installed, operated, and maintained'.*

Exposure to silicon tetrachloride by-product

Silicon-Tetrachloride[375] is a byproduct of crystalline silicon production[376] for the production of silane and trichlorosilane. It is highly toxic, to humans, animals and plants, and has to be converted to solid waste before disposal to landfill. Reports from China also suggest that rapid expansion of production has led to the pollution of rivers [377]. However, it is understood that there is now an economic impetus to recover this by-product. This is because it can be used as a raw material for further polysilicon production and also to manufacturer fibre optics [378]. Further information is required on the abatement strategies adopted by the sector.

5.7.2.2.1 Use of Critical Raw Materials

Critical Raw Materials are defined by the European Commission as 'raw materials of high importance to the economy of the EU and whose supply is associated with high risk'. Task 1 identified the following CRMs as having potential relevance to the solar photovoltaic product group - cobalt, borate, indium, gallium, silicon metal and tantalum. The increased use of other materials assessed for their criticality, such as tellurium could also contribute to a change in their status in the future [379].

Further work on CRM management and the circular economy has identified indium, gallium and silicon metal as being of particular relevance to the solar photovoltaic product group (see Figure 125 for end-use shares). A high potential (95%) for economically feasible recycling was identified, although this also depends on the achievement of high recovery rates for modules and technically is only currently demonstrated by commercial-scale recovery plant for CdTe module technology.

The CIS and CIGS thin film cell design are of particular relevance given that indium and gallium are fundamental to their semi-conductor designs. The potential for the recycling of silicon wafers was discussed in Task 4 and faces economic and technical barriers.

[374] Wild-Schoten, M.J. et al, Fluorinated greenhouse gases in photovoltaic module manufacturing: potential emissions and abatement strategies, 22nd European Photovoltaic Solar Energy Conference, Milano, Italy, 3-7 September 2007

[375] https://pubchem.ncbi.nlm.nih.gov/compound/Tetrachlorosilane#section=2D-Structure

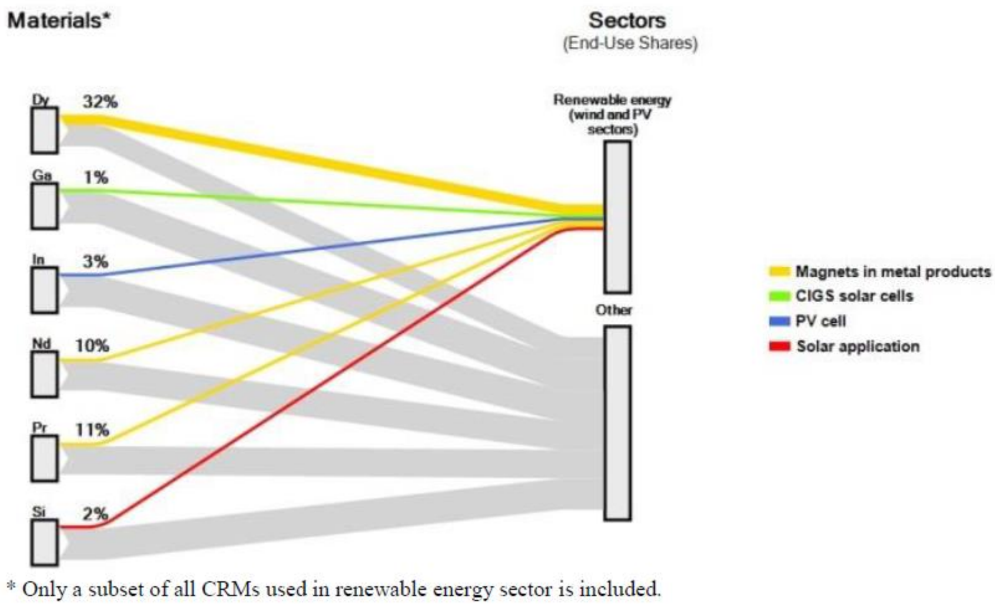
[376] Dustin Mulvaney et al., 2009, 'Toward a Just and Sustainable Solar Energy Industry - A Silicon Valley Toxics Coalition White Paper'

[377] Yanh.H, Huang.X and J.R.Thompson, *Tackle pollution from solar panels*, Nature, 2014/05/28/online

[378] Ye Wan *et al, The preparation and detection of high purity silicon tetrachloride with optical fibres level*, 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* 207 012018

[379] Bustamante.M.L, Gaustad. G and E.Alonso, Comparative Analysis of Supply Risk-Mitigation Strategies for Critical Byproduct Minerals: A Case Study of Tellurium, Environ. Sci. Technol. 2018, 52, 11–21

Figure 125. Share of CRMs used in wind and solar PV cell production



Source: European Commission (2018)

5.7.2.3 Social and ethical issues

Use of minerals from conflict zones

Solar photovoltaic products may contain a number of scarce mineral resources such as tin and tantalum which have been identified as being obtained from conflict areas. The Commission has defined conflict areas as:

> '*areas in a state of armed conflict, fragile post-conflict as well as areas witnessing weak or non-existing governance and security, such as failed states, and widespread and systematic violations of international law, including human rights abuses*.'

Mining in the Great Lakes region of Africa, a conflict area, is recognised as a major source of minerals and according to sources under dangerous conditions, and without sufficient maintenance of health and safety standards and in some cases by children.

Initiatives by the electronics industry to address this issue were stimulated by the US Dodd-Frank Act which requires disclosure of the source of metals. Corporate initiatives generally focus on improving working conditions as opposed to the black listing locations. Verification has tended to be linked to participation in a range of projects that have been established in conflict areas. The Responsible Minerals Assurance Process (RMAP) and the Conflict Free Sourcing Initiative (CFSI) also provide verification routes that focus on specific points in the supply chain for minerals.

Example projects on the ground include those working to establish traceability systems at a general level - such as the Public-Private Alliance for a responsible minerals trade and Solutions for Hope - and those focussed on specific minerals, such as the Conflict-free tin initiative, the Tin Source Initiative and the Tantalum Initiative.

6 Task 6: Assessment of BAT, design options and improvement potential

6.1 General introduction

This task aims at identifying the design options of the photovoltaic product group, their monetary consequences in terms of Life Cycle Cost for the user, their economic and possible social impacts, and pinpointing the solution with the Least Life Cycle Costs (LLCC) and the Best Available Technology (BAT).

The assessment of monetary Life Cycle Costs is relevant to indicate whether design solutions might impact the total user's expenditure over the total product life (purchase, operating, end-of-life costs, etc.). The distance between the LLCC and the BAT indicates — in a case a LLCC solution is set as a minimum target— the remaining space for product-differentiation (competition).

The BAT indicates a target in the shorter term that would probably be more subject to promotion measures than to restrictive action. The BNAT indicates possibilities in the longer term and helps to define the exact scope and definition of possible measures. Any intermediate options between the LLCC and the BAT have to be described, and their impacts assessed.

The scope of the photovoltaic product group was determined in Task 1 and the market segments that have been analysed are the following:

- Residential: up to 10 kW
- Commercial: from 10 to 100 kW
- Utility: above 100 kW

6.1.1 Identification of design options and assessment of their impacts

Available design options will be identified by investigating and assessing the environmental impact and LCC of each suggested design option against each Base-Case (using the MEErP EcoReport 2014):

- The design option should not have a significant variation in the functionality, the quality and in the primary or secondary performance parameters compared to the Base-Case and in the product-specific inputs. In fact the improvements in eco-design parameters may be realised by achieving improvements in quality.
- The design option must have a significant potential for improvement regarding at least one of the following ecodesign parameters and without deteriorating others:
  - the consumption of energy, water and other resources,
  - use of hazardous substances,
  - emissions to air, water or soil,
  - weight and volume of the product,
  - use of recycled material,
  - quantity and nature of consumables needed for proper use and maintenance,
  - ease for reuse and recycling,
  - extension of lifetime or amounts of waste generated.
- The design option should not entail excessive costs. Impacts on the manufacturer must be investigated regarding redesign, testing, investment and/or production costs, including economy of scale, sector-specific margins and market structure, and required time periods for market entrance of the design option and market decline of the current product. The assessment of the monetary impact for categories of users includes the estimation of the possible price increase due to implementation of the design option, either by looking at prices of the product on the market and/ or by applying a production cost model with sector-specific margins.

For each of the identified design options, it shall be described:

- if Member State, Community or Third Country legislation and/or standards are available regarding the design option;
- how market forces may address the design option;
- how large the disparity is in the environmental performance of the product available on the market with equivalent functionality compared to the design option.

The analysis carried out in task 5.2 also has the intention of identifying environmental 'hotspots'., If these hotspots differ from the findings of Ecoreport tool they may then also be taken into account, if relevant, in the analysis under tasks 6 and 7, provided that the life cycle cost is properly assessed.

6.1.2 Summary of how the functional unit for LCA and LCOE results has been calculated

The functional unit used for the calculation of environmental impacts and levelised cost of energy is '1 kWh of electricity generated' taking into account the total electricity generated during a notional 30 year lifetime. The environmental impacts are expressed per kWh of electricity generated. The lead impact category according to the conclusions in Task 5 is the Cumulative Energy Demand (CED), also referred to as primary energy consumption.At module level, the primary energy results do not include the electricity generated by the module. Instead the primary energy is a function of the lifetime energy yield. To get the results per kWh produced, environmental impacts are first calculated per m^2 of module and per inverter. Then the area of modules and amount of inverters needed to generate 1 kWh electricity is calculated using module and inverter efficiencies and derate factors. Area and amount necessary per kWh are then multiplied with the environmental impact per m^2 of module

PV system yield over years is calculated in line with the transitional method under development by JRC unit C2. However, in this part of the study more derate factors have been used. The additional derate factors made possible a more detailed differentiation between the package and system options.

The Task 5 report includes an introduction to Life Cycle Costing and Levelised Cost of electricity (LCOE) (section 5.3.1). LCOE is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment (including module and inverter costs), operations and maintenance, cost of fuel and cost of capital. It is commonly applied to evaluate PV system costs[380]. The Levelised cost of electricity (LCOE) is defined for the purpose of these calculations as:

$$\text{LCOE}[€/\text{kWh}] = \frac{\text{net present value of sum of costs of generation over its lifetime}}{sum\ of\ electrical\ energy\ produced\ over\ its\ life\ time}$$

The LCOE calculation of costs per kWh generated aligns with the functional unit defined in Task 1. In this definition the life cycle environmental impacts of the PV system or component are normalized to 1 kWh of electricity produced by the system/component.

The LCOE results present the cost of supplying each kWh to the grid. It does not present revenue streams for PV owners. Revenues for PV owners depend on the market/subsidy prices.

[380] *https://setis.ec.europa.eu/sites/default/files/reports/Cost-Maps-for-Unsubsidised-Photovoltaic-Electricity.pdf*

Table 126. Overview of design options for photovoltaic modules (the options selected for further analyses are highlighted in grey).

Design options	**Description**	**Rationale for the selection of design options for further analyses**
Option 1: Optimised PERC Si 2020	Optimized PERC modules as of today (2020): - Mono crystalline PERC - white EVA - more busbars (6) - better glass (AR properties) - factory quality control measures - thinner wafer Note: See further details in Table 4.	Expected to become the 2020 mainstream module product which can substitute the base case of Task 5
Option 2: BAT PERC 2019	The 2019 best mono Si PERC cells with also thinner wafers	The best PERC (BAT) as found on the market Q2/2019
Option 3: BAT PERCbi 2019 (bifacial)	Bifacial PERC cells with a glass backsheet	Expected to have a higher yield when applied at utility scale and moreover they do not have a halogenated back sheet It can also model mono-facial glass on glass modules.
Option 4: CdTe	Thin film CdTe	Showed lower carbon footprint and GER in the LCA review in Task 5
Option 5: CIGS	Thin film CIGS	Showed lower carbon footprint and GER in the LCA review in Task 5
Option 6: SHJ	Silicon heterojunction	Silicon heterojunction (SHJ) cells offer high efficiencies, yield and several advantages in the production process compared to conventional crystalline silicon solar cells (Louwen et al, 2015381) SHJ could minimise the use of silicon raw material that has an important GWP/Primary energy impact.
Option 7: BAT PERC 2025	BAT PERC 2019 with further improvements in the BOM, including: – kerf loss recycling,	Could reduce energy intensive Metallurgical grade Silicon wafer manufacturing due to recycling within the manufacturing process, also some other bill of material

[381] *Louwen A., van Sark W.G.J.H.M., Schropp R.E.I., Turkenburg W.C., Faaij A.P.C. 2015. Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs. Progress in photovoltaics: research and application. 23:1406-1428. Doi: 10.1002/pip.2540*

	– halogen free backsheet, – factory quality inspections, – reduced glass thickness (2mm), – reduced wafer thickness (120 µm) and kerf losses (50 µm). – Low factory defect rate (all other options 1,5%, here 0%)	improvements are added.)
Option 8: BNAT PERCbi 2025 incl. Wafer recycling	PERC bifacial cells (PERC 2019) + BNAT option for wafer recycling *Recycle wafers for new cells (BNAT):* this is an ambitious recycling route. It will require additional process steps such as etching to recover wafers but is considered technically feasible. Amongst others it will also require to remove the backsheet. Likely this can only be applied in a closed loop circular economy model where modules return to their original manufacturer for recycling [382].	*Partially modelled:* Could reduce energy intensive Metallurgical grade Silicon wafer manufacturing due to the extended lifetime of cells as a component of modules (*e.g. via cell or wafer reuse/remanufacturing or recycling).*
Option 9: Interdigitated Back-contact (IBC)	Compared to solar cells with two contact sides, back-contact solar cells have both contact polarities on the rear side which significantly reduces shading losses from contacts (task 4 report), such improvements relies on interdigitated Back Contact (IBC) Technology, some manufacturers have already placed these products on the market and they can provide the highest commercial modules efficiencies.	*Not possible to model:* The benefits of the higher module effiency can easily be modelled but there is no reliable quantitative data available to model the impacts from this increased manufacturing complexity and because of propietory processes it was not possible to obtain time representative data for modelling purposes. Therefore this option is not further modelled
Option 10: BNAT Perovskite	Perovskite based thin film PV is not yet in production, but this technology has made remarkable progress in the past few years. Because of its potential of very low-cost production, and its suitable bandgap for tandem formation with crystalline silicon, it could be (or pave the way for) a significant and disruptive technology PV energy generation (task 4 report)	Not possible to model: BNAT and a lack of sufficient and suitable LCA data to model.
Option 11: BNAT Perovskite/Si-tandem	The start-up Oxford PV showed that the tandem configuration has the potential to outperform single junction Si PV with efficiencies over 22%. They have acquired a production facility in Germany targeting tandem pilot production by 2019-2020 (task 4 report).	*Not possible to model*: BNAT and a lack of sufficient and suitable LCA data to model.
Option 12: BNAT kerfless silicon	Kerfless wafer production which eliminates the need for the slicing of silicon blocks or ingots to obtain the wafer substrate.	It is anticipated to reduce the energy intensive wafer manufacturing step.

[382] *Note that also weaker options for cell recycling exist, e.g. refurbishing second hand modules with less invasive steps such as inspection, glass cleaning and coating, replace the bypass diode, etc. These can extend the insitu cell lifetime beyond the 30 years.*

Table 127. Overview of design options for inverters (the options selected for further analyses are highlighted in grey).

Design options	**Description**	**Rationale for the selection of design options for further analyses**
Residential		
Option 1: more efficient	This design option represents the potential for improvement on the Euro efficiency of the base case	The focus of Ecodesign and Energy label is on the energy efficiency during the use phase
Option 2: longer lifetime	This design option represents the potential for extension of the design lifetime of the base case	Reducing the number of inverter replacements during the PV system lifetime will minimise environmental impacts and improve material efficiency
Option 3: repair (repaired)	This design option represents the extent to which a product is designed for repair along its lifetime	Repairing and replacing components to achieve a longer design life will minimise the environmental impacts and improve material efficiency
Option 4: monitor/smart	This design option represents the potential for monitoring to diagnose and react to faults related to firmware or hardware. It can help additionally the consumer to adjust their demand to increase self-consumption	Early fault detection and reaction can reduce downtime and maximise energy efficiency during the use phase
Option 5: Module Level Inverter (MLI)	This design option represents the installation of module level inverters that may increase yield in mismatch conditions	Shifting to inversion at the module level may bring system level benefits, such as maximising energy efficiency during the use phase
Option 6: Hybrid storage worst performer (peak shaving)	These design options represent the installation of inverter with integrated storage to either: - provide peak shaving in feed in (German EEG case). - increase hourly and quarterly self-consumption	A trend has been observed for households to want to increase their self-consumption by integrating battery storage. However, this may introduce losses in the total amount of renewable electricity generated which should be avoided or minimised. There is also the potential to achieve marginal emissions reduction by displacing peak power generating plants in the evening
Option 7: Hybrid storage best performer (load following)		
Commercial		
Option 8: More efficient	This design option represents the potential for improvement on the Euro efficiency of the base case	The focus of Ecodesign and Energy label is on the energy efficiency during the use phase
Option 9: Repair (repaired)	This design option represents the extent to which a product is designed for repair along its lifetime	Repairing and replacing components to achieve a longer design life will minimise the environmental impacts and improve material efficiency
Option 10: Wide band gap inverter (WBG)	This design option represents the installation of inverters which transistors are completely based on new semiconductor materials with a wide band gap	Not possible to model/not selected: Consultation with manufacturers revealed that the benefits and possible trade-offs of this design option are not apparent at this stage
Utility		
Option 11: More efficient	This design option represents the potential for improvement on the system level efficiency of the base case	The focus of Ecodesign and Energy label is on the energy efficiency during the use phase

Option 12: More efficient plus combiner strings	This design option represents the potential for improvement on the Euro efficiency of the base case	Shifting to inversion up the string level may bring system level benefits, such as maximising energy efficiency during the use phase. However, there may be a trade-off in material efficiency
Option 13: Wide band gap inverter (WBG)	This design option represents the installation of inverters which transistors are completely based on new semiconductor materials with a wide band gap	Not selected – consultation of manufacturers revealed that the benefits and possible tradeoffs of this design option are not apparent at this stage.

Table 128. Overview of design options for systems (the options selected for further analyses are highlighted in grey).

Design options	Description	Rationale for the selection of design options for further analyses
Residential		
System Options		
System Option 1: Optimised PERC 2020 + best inverter (SO 1)	This option combines the best module with the best inverter (longer life and monitoring)	An obvious combination of all the best at component level in a system to be compared to a standard design with base case components
System Option 2: Optimised PERC 2020 + best inverter + better design (SO 2)	This system combines the best module with the best inverter (longer life and monitoring) and includes a better design by installer	An obvious combination of all the best at component level in a system to be compared to a standard design with base case components Derating factors are adapted to reflect the better design
System Option 3: Optimised PERC 2020 + best inverter + optimised O&M (SO 3)	This system combines the best module with the best inverter and includes optimized operation and maintenance routine.	This would introduce practices from the large-scale segment including remote monitoring, repair response or early failure detection and cleaning routines.
Package option 1 (PO 1)	Multi Si module and reference inverter	
Package option 2 (PO 2)	Optimised PERC 2020 module and reference inverter	
Package option 3 (PO 3)	BAT PERC 2019 module and reference inverter	
Package option 4 (PO 4)	CIGS module and reference inverter	
Package option 5 (PO 5)	Silicon heterojunction module and reference inverter	
Package option 6 (PO 6)	BAT PERC 2025 module and reference inverter	
Package option 7 (PO 7)	Multi Si module and more efficient inverter	

Package option 8 (PO 8)	Multi Si module and longer life inverter	
Package option 9 (PO 9)	Multi Si Module and inverter with repair	
Package option 10 (PO 10)	Multi Si module and inverter including monitoring	
Package option 11 (PO 11)	Multi Si module and multi-level inverter	
Package option 12 (PO 12)	Multi Si module and inverter including storage (worst case)	
Package option 13 (PO 13)	Multi Si module and inverter including storage (best case)	
Commercial		
System Options		
System Option 1: best combination and design (SO 1)	Improved design, this is a combination of all the best options at component level in a system including bifacial modules (PERCbi 2019) with a more reflective roof surface. This option also assumes higher derating factors due to lower cable, shading and module mismatch losses because of a tailored design	This is an all best combination to be compared to a standard design with base case components. PERC bifacial + higher derating factors due to lower cable losses, shading and module mismatch because of a tailored design
Package option 1 (PO 1)	Multi Si module and reference inverter	
Package option 2 (PO 2)	Optimised PERC 2020 module and reference inverter	
Package option 3 (PO 3)	BAT PERC 2019 module and reference inverter	
Package option 4 (PO 4)	BAT PERCbi 2019 module and reference inverter	
Package option 5 (PO 5)	CdTe module and reference inverter	
Package option 6 (PO 6)	BAT PERC 2025 module and reference inverter	
Package option 7 (PO 7)	BNAT PERCbi 2025 + recycled wafer module and reference inverter	
Package option 8 (PO 8)	Multi Si module and more efficient inverter	
Package option 9 (PO 9)	Multi Si module and inverter with repair	
Utility		

System Options		
System Option 1: best combination and design including single axis tracker (SO 1)	System with single axis tracker, CdTe modules and energy efficient string inverter	Single axis trackers can provide higher yield at the expense of a slewing drive worm gear and motor for a series of modules
Package option 1 (PO 1)	Multi Si module and reference inverter and reference BOS	
Package option 2 (PO 2)	Optimised PERC 2020 module and reference inverter and reference BOS	
Package option 3 (PO 3)	BAT PERC 2019 module and reference inverter and reference BOS	
Package option 4 (PO 4)	BAT PERCbi 2019 module and reference inverter and reference BOS	
Package option 5 (PO 5)	CdTe module and reference inverter and reference BOS	
Package option 6 (PO 6)	BAT PERC 2025 module and reference inverter and reference BOS	
Package option 7 (PO 7)	BNAT PERCbi 2025 + recycled wafer module and reference inverter and reference BOS	
Package option 8 (PO 8)	Multi Si module and more efficient inverter and reference BOS	
Package option 9 (PO 9)	Multi Si module and more efficient string inverter and reference BOS	

6.2 Overview of the selection of single design options

6.2.1 PV modules

6.2.1.1 Assumptions regarding the selected fundamental cell and module design options

Table 129 below provides the assumptions for the selected design options. The modules can be used for residential, commercial and utility scale applications. The design parameters remain identical. Table 129 also provides the estimated additional costs per Wp. A notional lifetime of 30 years has been assumed for all modules, reflecting the point in time where, according to most commercial power guarantees, the performance would drop to below 80-85% of the initial performance as measured under STC.

The Base-Case as defined in Task 5 represents a multi Si BSF module with reference year 2016. The technology of the multi Si base case has been improved since 2016. This has been considered in the Base-Case 'optimised silicon design'. It is assumed that technology will further improve, following the innovations described in the VDMA IRTPV roadmap. BSF will no longer have a relevant market share and will be replaced by mainstream PERC type cells by as early as 2020.

Table 129 contains the performance assumptions for the different module technologies, including the degradation rates that have been used for further modelling. Degradation rates cannot in practice be expressed as a 'single' number, even for the same technology. There are significant possible variations depending on the case, the climate/site conditions, etc. The 0.5%-0.7% range has been selected based on the two most extensive and largely cited studies: Jordan et al (2012)[383] and Ishii et al. (2017)[384].

For bifacial PV, there is not yet enough feedback from the field made publicly available so assumptions have had to be made for this technology options.

For the degradation rate of CIGS, the rate used represents field observed rates and is based on Ishii et al. (2017).

For CdTe the degradation rate is taken from the Series 6 product data sheet (NREL)[385] (0.5%). This long-term rate is complemented by an initial, burn-in degradation of 2%.

The costs specified in Table 129 are applicable to mid 2018. The cost for the last two BAT and BNAT options has a higher degree of uncertainty because they are 'composite' products that do not exist in this form on the market.

[383] *D.C. Jordan and S.R. Kurtz in NREL/JA-5200-51664 (2012)*

[384] *T. Ishii et al. Prog. Photovolt: Res. Appl. 2017; 25:953–967*

[385] First Solar, *Series 6 data sheet*, http://www.firstsolar.com/en-EMEA/-/media/First-Solar/Technical-Documents/Series-6-Datasheets/Series-6-Datasheet.ashx

Table 129. Design option parameters

Acronym	Multi Si – Base Case	Optimised PERC 2020	BAT PERC 2019	BAT PERCbi2019	CdTe	CIGS	SHJ	BAT PERC 2025	BNAT PERCbi 2019+recycled wafer
Module type	Multi crystalline Si	Mono Si PERC (Passivated Emitter and Rear Cell) – optimized design	Passivated Emitter and Rear Cell (PERC), mono Si	PERC + bifacial glass backsheet	Thin film - Cadmium Telluride	Thin film – Copper Indium Gallium Selenide	Silicon heterojunction mono Si cells	BAT PERC 2019 with further improvements in BOM and kerfloss recycling	PERC bifacial + 50% recycled wafer
Performance degradation rate (% per year)	0.7%	0.6%	0.5%	0.5%	0.5% + 2% in first year	1%	1%[1]	0.5%	0.5%
Failure rate modules (%/year)	0.2	0.05	0.05	0.05	0.05	0.05	0.05	0.01	0.05
Cells per module	60	60	60	60	/	/	60	60	60
Module power density (Wp/m^2)	147	175	196	196	180	150	184	196	196
Wafer thickness/Active layer thickness (μm)	200	170	180	180	/	/	150	120	180
Kerf thickness (μm)	100	75	75	75	/	/	75	150	75
Total silicon use (wafer + kerf) in kg per m2	0.638	0.521	0.542	0.5425	/	/	0.478	0.361	0.542
Economic lifetime for the FU (years)	30	30	30	30	30	30	30	30	30
Cost (EUR/Wp) – ref year 2018	0.48	0.52	0.56	0.56	0.48	0.53	0.60	0.62	0.62

6.2.1.2 Assumptions regarding the selected BoM module design options

Two module designs have been introduced as design options that reflect combinations of material and quality improvements that are being achieved or specified in the global market. The expected improvement measures are presented in Table 130 as two design options – the first, an update of the 2016 base case and the second a hypothetical further improvement of this case, albeit still based on the same cell technology.

Table 130. Expected improvement of the multi Si modules (year 2020 and 2025)

Production step	**Selected improvement measures**	
	Optimised PERC Si 2020 (optimised process and materials)	**Further optimisations in BoM (BAT 2025)**
Wafer production	Mono-crystalline with diamond wire sawing with larger wafer size than>156x156 mm^2 170 um wafer thickness and 75 µm of kerf loss	Wafer production with larger wafer size than>156x156 mm^2 and wafer thickness of 120 µm and 50µm of kerf loss with recycling (30% recycled content of kerf)
Semi-conductor preparation e.g. passivation	PERC p-type mono wafer	PERC on p-type mono Si wafer
Cell metallisation	Reduced Ag to 80 mg/cell	Reduced Ag (70 mg/cell) and Pb-free cell metallization paste with < 0.1% module weight
Cell stringing	Full-cells and 5BB interconnection	Half-cell, busbarless cells with copper interconnection with Pb-free soldering
Cell encapsulation	Reduced front glass thickness 3.2 mm	Front glass-non fluorinated backsheet Glass with AR and anti-soiling coating and < 2.5 mm thickness
Module power	281.6 Wp for 60-cell modules	313.6 Wp for 60-cell modules
Degradation rate	0.6%	0.5%
Performance warranty	25 years (modelled for 30 years)	30 years
Factory quality inspection	Infrared + Electroluminescence/ Lock in thermography – <1,5% factory reject rate assumed	Infrared + high-resolution Electroluminescence/Lock in thermography LeTID/Potential Induced Degradation assessment <0,5% factory reject rate assumed

6.2.1.3 Improvement option: thinner wafers

Improved wafer production technologies have resulted in thinner wafers that use less silicon.

The multi Si base case has a wafer thickness of 200 micrometers. This decreases to 120 micrometers in the BAT PERC 2025 option. Wafer thicknesses used in the different intermediate design options are presented in Table 129 which summarises the design option parameters.

6.2.1.4 Improvement option: increased silicon recycling

Two design options contain recycled silicon material. Option 8 (BAT PERC 2025) contains recycled kerf losses from wafer slicing and option 9 (BNAT PERCbi 2025 + recycled wafer) contains reused wafers recovered from old modules.

Two potential recycling routes have been identified for kerf waste from silicon wafer slicing [386] and are considered possible:

1. Recycle as MG Si for Si-steel (BAT). Solar Grade Silicon kerf loss waste is contaminated from the tools used (e.g. SiC), but it remains a useful alloy compound for Si-steel manufacturing to substitute Metallurgical Grade silicon.
2. Recycle as solar grade silicon (BNAT): this is a more ambitious recycling route. Because of the contaminants it is still a challenge and part of research. NorSun has conducted pilot scale tests and will in 2020 introduce such waste into full scale production of silicon blocks. They claim to be able to reprocess 85% of the kerf waste that arises from wafer slicing and can tolerate in the production of new a 30% reprocessed content (claimed for full scale production) [387].

In option 8 (BAT PERC 2025) the second option has been included, being considered as commercially available from 2021 onwards and allowing for 30% recycled kerf waste in new poli-Si block production.

In regard to option 9 and wafer reuse, Tsanakas et al. (2019)[388] recently published a review paper on recycling challenges in the PV sector. This paper mentions to relevant innovations – the first, a module design for recycling by the French manufacturer Apollon, and the second processes to reuse wafers of the type that could be recovered from such a module product at the end of life. The module design of Apollon was also described in Task 4 and is at pilot scale production.

The paper refers to SolarWorld, as having a well-established c-Si recycling program and process, based on a thermal processing method, with which EVA is eliminated through burning, followed by manual separation of metals, silicon and glass. Then, Si cells are re-etched and at the end of such process clean wafers can be re-used. SolarWorld's recovery ratios typically exceed 84% of the module weight, namely 90% of the glass and 95% of the semiconductor materials (Lunardi et al., 2018)[389].

In option 9 an attempt has been made to incorporate wafer reuse into a design option. Data was not possible to obtain from Apollon, despite approaches, due to confidentiality issues. Little data was therefore available and an assumption has instead been made that 50% reused wafers can be tolerated and this reuse would be facilitated by improved future glass-glass module designs, reflecting the approach adopted by Apollon. Life cycle inventory data on possible processing steps were not, however, available. As a consequence these additional processing steps have had to be omitted and the simulation of this option can only be seen as a very limited first attempt to model the potential benefits.

A short description on the data used for life cycle assessment for each of the options is available in paragraph 6.2.1.10.

6.2.1.5 Improvement option: solar glass

Light transmittance of glass can be improved (coatings, iron content, thickness, etc..) in combination with a trend towards manufacturing thinner tempered glass especially for bifacial glass on glass modules. Currently 2 mm for bifacial is possible. Also, when considering the Antimony content it is possible to recycle glass for solar glass, instead of other glass applications.

The assumptions used were as follows:

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[386] Eco-solar project (2018) Eco-solar factory, http://ecosolar.eu.com/wp-content/uploads/2018/11/D6.4-Scientific-Workshop.pdf

[387] Personal communication with Elkem/Norsun

[388] J.A. Tsanakas, A. van der Heide, T. Radavičius, J. Denafas, E. Lemaire, K. Wang, Jef Poortmans, E.Voroshazi. 2019. *Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. Progress in Photovoltaics*.

[389] Lunardi MM, Alvarez-Gaitan JP, Bilbao JI, Corkish R. A Review of Recycling Processes for Photovoltaic Modules. Book

Chapter in Solar Panels and Photovoltaic Materials. Intechopen, 2018; DOI: 10.5772/intechopen.74390.

- Default 3.5 mm and 2x2 mm for bifacial
- Base case (multi Si) is 3.5 mm
- Optimised PERC 2020 is 3.2 mm
- BAT PERC 2025 is 2.5 mm

6.2.1.6 Improvement option: halogen free backsheet

Halogen containing backsheets can be responsible for emissions of air pollutants such as hydrogen fluoride potentially released duringthermal processing of modules[390]. Halogen free backsheets can therefore simplify recycling via thermal and mechanical processing .

In the bifacial design option the polymer backsheet is eliminated and replaced with a glass backsheet. In the BAT PERC 2025 a halogenfree polymer back sheet has been used. The chosen solution is a three layer, polyolefin (HDPE) backsheet.

6.2.1.7 Improvement option: increased manufacturing quality

Evidence from audit programmes suggests that improvements can be obtained by more stringent factory quality control of materials supplied and manufacturing processes. This can both reduce defects, for example those related to cells (poor handling resulting in cracking), tabbing (resulting in mis-alignment of cells) and material purity (e.g. silver purity). This can in turn reduce rejects and the waste in the factory.

This can also contribute to bring modules on the market with narrower efficiency tolerances on bins of rated power that comes out of the factory.

Feedback from factory inspections suggests that there is currently an overall 1.5% reject rate for all modules (no variance provided). For the design option BAT PERC 2025 an improved factory reject rate of 0,5% has been assumed.
Feedback from factory audits suggests that the compound implementation of a series of quality measures can result in between 1-7% uplift in the Wp output from modules upon flash testing. This has been taken into account in the increased efficiency of the design options, with uplifts of 1, 3.5 and 7% used as increments.

A module failure rate of 0,05% has been assumed for all design options except for the BAT PERC 2025 option where an improved failure rate of 0,01% has been assumed.

6.2.1.8 Improvement option: back contact (IBC)

Compared to solar cells with two contact sides, back-contact solar cells have both contact polarities on the rear side which significantly reduces optical losses at the illuminated front side both from cell metallisation and cell-to-cell interconnection (see the task 4 report).

The most promising technology is Interdigitated back contact solar cells (IBC). Their key features are as follows:

- They use a complex diode structure with both positive and negative contacts on the back side.
- They require both n-type(Phosphor) and p-type (Boron) difussion material to used.
- Paste with phophor/boron compound needs to be added before diffusion, e.g. inject printing, silk screen
- They can require various additional production steps and these form part of the intellectual property related to the cell/module products.

Note: The benefits of the higher efficiency can easily be modelled but there is no reliable and up to date quantitative LCI data to model the impacts from the increased manufacturing complexity. Therefore this option has not been possible to model.

6.2.1.9 Improvement option SHJ yield improvement

Silicon heterojunction (SHJ) cells offer high efficiencies and several advantages in the production process compared to conventional crystalline silicon solar cells (Louwen et al, 2015[391]).

[390] *Ardente et al*, Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling, *Waste Management 91 (2019) 156–167*

[391] *Louwen A., van Sark W.G.J.H.M., Schropp R.E.I., Turkenburg W.C., Faaij A.P.C. 2015. Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs. Progress in photovoltaics: research and application. 23:1406-1428. Doi: 10.1002/pip.2540*

SHJ technology could also minimise the use of silicon raw material that has an important GWP/Primary energy impact.

A further benefit of the cell design is a yield improvement because the cells have a lower temperature co-efficient (-0.258 %/°C) and a broader spectral response. This will confer a yield increase in locations with intense solar irradiation and at higher altitudes with clear skies. This improvement has been taken into account in design option 7 (SHJ), which has a conservative adjustment of DR temp of 102% instead of 100%.

6.2.1.10 Life cycle information – Bill of Materials: Modules

6.2.1.10.1 Multi Si (BSF)

Material input for the multi Si module production has been taken from the data collection exercise carried out for the PEF[392]. This is considered to provide the most up to date and representative dataset for the silicon wafer-based cells, as validated by the data quality rating (DQR) contained within the PEF pilot. For this assessment, packaging materials and the end of life treatment of the production waste have been omitted.

Data for the solar cell production has been taken from the ecoinvent 3.4 database. The global dataset has been used. This dataset contained an input of both solar and electronic grade Si. The input of electronic grade Si has been changed into solar grade Si, which better resembles reality.

The PEF data provided the input of photovoltaic cells per m^2, not per kg. The weight of the photovoltaic cells has been calculated based on the wafer thickness. The wafer has a thickness of 200 micrometer. The specific weight cell weight is 0.530 kg/m^2cell (including wafer+kerf losses). The cell area per m^2 module is 93,5% (PEF), which results in a cell weight of 0.496 kg/m^2 module.

The materials which were not available and have been added to the EcoReport tool are: multi Si photovoltaic cell, tin, lead, ethylenvinylacetate, polyvinylfluoride, silicone, solar glass and tempering, tap water, hydrogen fluoride, potassium hydroxide, 1-propanol, isopropanol. The ecoinvent version 3.4 global datasets have been used to model these materials.

Energy use for module manufacturing has been added to the tool as well. The input data have been taken from the PEF life cycle inventory (LCI) file. Data from the EcoReport tool have been used to calculate the environmental impact of the energy use during module manufacturing.

The BOM is available in Annex 6A.

6.2.1.10.2 BAT PERC 2019

The LCI for module production has been taken from the PEF LCI table for Monocrystalline silicon solar modules.

The photovoltaic cell has been taken from the ecoinvent 3.4 database. To this dataset the 'PERC rear passivation layer' process and 'PERC dielectric openings' process has been added based on the LCI information provided in Lunardi et al. (2018). Some minor modifications have been made to the report inventory because some of the inputs or outputs were not available in the ecoinvent database. In addition, electronic grade silicon has been changed into solar grade silicon, like in the multi Si cell. The considered cells are n-type cells.

BOM of PERC 2019. It includes a reduction of silicon use for the wafer (180 micrometer wafer thickness and 75 micrometer kerf losses). The glass thickness is 3.5 mm.

The BOM in EcoReport tool format is available in Annex 6A.

6.2.1.10.3 BAT PERC bifacial 2019

For this design option, we started from the PERC 2019 inventory. The PVF/PET backsheet has been replaced with a glass backsheet. The thickness of the frontsheet has been adapted to 2 mm. The backsheet has the same thickness, being 2 mm. No other changes have been made to the BOM compared to the PERC 2019 design option.

The BOM in EcoReport tool format is available in Annex 6A.

6.2.1.10.4 Optimised PERC 2020

The LCI for module production has been taken from the PEF LCI table for Monocrystalline silicon solar modules.

For the photovoltaic cell again the 'PERC rear passivation layer' process and 'PERC dielectric openings' process have been added based on the LCI information provided in Lunardi et al. (2018). See section 6.2.1.10.2)

[392] *Wyss F., Frischknecht R., de Wild-Scholten M., Stolz P. 2015. PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots*

It includes a reduction of silicon use for the wafer (170 micrometer wafer and 75 micrometer kerf losses). The glass thickness of the backsheet is reduced to 3.2 mm.

The BOM in EcoReport tool format is available in Annex 6A.

6.2.1.10.5 CdTe

The life cycle inventory for the CdTe module production has been taken from PEF. Data for the materials which were not available in the EcoReport Tool have been taken from Ecoinvent 3.4.

The BOM in EcoReport tool format is available in Annex 6A.

6.2.1.10.6 CIGS

The life cycle inventory for the CIGS module production has been taken from PEF. Data for the materials which were not available in the EcoReport Tool have been taken from Ecoinvent 3.4.

The BOM in EcoReport tool format is available in Annex 6A A.

6.2.1.10.7 SHJ

The life cycle inventory for the SHJ module is a combination of data available in ecoinvent and the life cycle inventory published by Louwen et al. (2015)[381]. Data for the materials which were not available in the EcoReport Tool have been taken from Ecoinvent 3.4. The wafer thickness is adapted to 150 µm, the kerf thickness to 75 µm.

The BOM in EcoReport tool format is available in Annex 6A.

6.2.1.10.8 BAT PERC 2025

This option models further expected improvements on the BAT PERC 2019 option related to BOM and manufacturing. To model this design option, the BOM of the PERC module has been used as a starting point (see 6.2.1.10.2). The wafer thickness has been adapted to 120 micrometers. Of the kerf losses, 50 micrometer, 85% are recycled to manufacture new wafers. The input data for the recycling process have been provided by NorSun. Wafers can be manufactured with 30% recycled content. The input of virgin kerf material is 70%.

This option also contains a different backsheet with HDPE, PA and TiO_2 used instead of PVDF and PET.

Composition backsheet in the PERC 2025 option:

- 349 g HDPE/m^2
- 56,5 g/m^2 PA
- 37,8 g/m^2 TiO_2

For the BOM reference is made to the BOM of the PERC module which is available in Annex 6A. Only the solar cell input has been changed compared to the PERC module.

The BOM in EcoReport tool format is available in Annex 6A.

6.2.1.10.9 BNAT PERC bifacial 2025 incl. wafer recycling

This option relates to the new possibilities to reduce environmental impact through recycling of the wafer and/or by achieving an extended cell or wafer life in a new product. Several new recycling and cell reuse routes during production and at the end of life are currently under investigation[393]. A recent study[394] concluded that the '*Assessment of the resource efficiency of PV recycling remains largely unexplored, especially concerning the benefits of increasing recovery rates for different materials in PV waste*'. Accordingly, this option is still denoted as a 'Best Not yet Available' (BNAT) technology. This option also addresses an important topic of Task 4, which was the consumption of ultrapure quartz that is being is considered a critical raw material(CRM) for Si cell manufacturing.

Herein it is worth noting that some proposed recycling schemes aim to recover silicon only as metallurgical grade silicon suitable for the steel industry while others also aim to recover the cells or in part a fraction that can be added to the solar grade silicon manufacturing. Future research in this area is highly recommended. Of course, it is also possible to extend the lifetime of the modules through repair and repurposing.

[393] http://ecosolar.eu.com/wp-content/uploads/2018/11/D6.4-Scientific-Workshop.pdf

[394] https://doi.org/10.1016/j.wasman.2019.04.059

As a relative simplified proxy to model these options, the bifacial module has been used as a starting point and only wafer re-use introduced. Included in this option is therefore the direct re-use of wafers without any additional processing. An assumed conservative estimate that ultimately 50% of the wafers can come from re-use has been used as a proxy for this option.

6.2.2 PV inverters

6.2.2.1 Assumptions regarding the selected design options for residential use

Table 131 below provides the assumptions for the selected design options. The modules can be used for residential applications.

Lifetime assumptions for inverters:

More background on inverter failure is given in Task 3, section 3.3.1.5 and Task 4, section 4.1.4.3. The failure rate of an inverter was defined as the linear average failure rate per year of an inverter relative to its technical lifetime (= 1/MTBFinv).

In electronics the common method applied for reliability prediction of electronic equipment are metrics, methods and data from MIL-HDBK-217, published by the US Department of Defense. It allows to calculate the failure rates [%/y] and the reciprocal value Mean Time Between Failure (MTBF). They are referred as 'MTBF random' failures in Table 131. Note that these computed values in the failure rate bathtub curve (Figure 23, Task 3) relate to the constant failure rate phase only, which excludes premature failures covered under first year warranty. In the Tasks 5 and 6 modelling we assume that premature warranty failures are part of the manufacturing drop out and waste. This does not cover wear out failures or inverters taken out of service due to the economic lifetime of the installation, which are the 'Wear out & economic system life failures' included in Table 131.

Based on literature[395] a 10 years average lifetime was proposed for the base case (see Tasks 2), hence the failure rate of 10 % was established in Task 5 as a minimum reference. This was based on assumptions relating to warranty provisions and indications of a high replacement rate by year 10. However, it is understood that, at least for commercial scale inverters, design lifetimes of manufacturers are now targeted at 20-25 years with accompanying recommendations as to repair and replacement cycles to achieve a longer design lifetime. In the residential sector manufacturers have the objective of making inverters maintenance-free, so as to minimise call-outs.

Clearly as a circular economy improvement option the failure rates of products can be improved using the MIL-HDBK 217 as reference. Task 4 already reported that manufacturers today already offer inverter warranty up to 10 years and input from manufacturers together with the findings from field analysis suggest a constant failure rate of as low as 0,50 % per annum. This is added as a separate improvement option 'longer lifetime'.

Note that 'longer lifetime' is an alternative to repairing low lifetime products, which for residential inverters can be expensive, hence a market shift to longer lifetime products is likely more economic. For larger units service costs aren't a barrier and servicing is common practice.

[395] *See sources cited in Task 3 and 4 but also high amount of inverter failures reported by consumer organisations: https://www.which.co.uk/news/2017/08/top-five-solar-panel-problems/*

Table 131. Design option residential inverters (BC 1)

Acronym	Base Case - Reference	Efficient	Longer life	Repair	Monitoring	MLI (microinverter)	Storage (worst case)	Storage (best case)
Inverter type	String 1 phase reference inverter Transformerless	More efficient inverter	Longer lifetime	Repair/repaired	Monitor/Smart BC1 reference plus monitoring	Module level inverter transformerless	Hybrid storage worst performer	Hybrid storage best performer
Rated power (kVA) AC power	2.5	2.5	2.5	2.5	2.5	2.5 (for all inverters or 10x250 VA)	2.5	2.5
Euro Efficiency η_{conv}[%]	96	98	96	96	96	96	96	96
Wear out & economic system life failures	3.3 % (= 1/30y)	3.3 %	3.3 %	3.3 %	3.3 %	3.3 %	3.3 %	3.3 %
MTBF random failures **(constant failures, e.g. defined in e.g. MIL-HDBK-217)**	6.67% (=1/15 y)	6.67% (=1/15 y)	0.52% (=1/191 y)	6.67% (=1/15 y) (+10 % of BOM replaced)	6.67% (=1/15 y)	6.67% (for a set of 10 inverters or 0.67 % per inverter)	6.67% (=1/15 y)	6.67% (=1/15 y)
Cost (EUR/VA)	0.22	0.25	0.28	0.22	0.25	0.33	0.33	0.33

6.2.2.2 Life cycle information – Bill of Materials: Inverters for Residential use

6.2.2.2.1 More efficient inverter

No change in the BOM compared to the base case (see Task 5 report).

6.2.2.2.2 Longer lifetime inverter

The reference case BOM for 1 inverter has been used as a starting point. The base case inverter is replaced 2 times during the life span of the system. The inverter used in this design option has a failure rate of 3.76% while the reference inverter has a failure rate of 10%.

The BOM in Ecoreport tool format is available in annex 6B.

6.2.2.2.3 Repair

Based on the information contained in Table 4 of the Task 4 report, the main repair events for an inverter are derived. Note that this is related to BC 1 (residential) and BC 2 (commercial) in particular.

The base case inverter is replaced 2 times during the life span of the system. For this design option, it is assumed that inverters are repaired and the damaged components are replaced proportionally to their failure rate and this occurs two times during the 30 year life span of the inverter (after 10 years and after 20 years). The most replaced components during on-site repairs are fuses and circuit boards. However, in the case of other significant failures occurring, then a common practice is that the faulty inverter is taken off site and replaced by refurbished units.

Table 132 provides a proxy LCA estimate for inverter failures that have an impact on Bill-of-Materials. Based on this information the BOM for this design option has been established. The BOM of the base case has been taken from Tschumperlin et al (2016). This BOM contains several proxies and to establish the modelling of this design option further proxies have been added to it (e.g. link between BOM and the failed component), our repair estimate is accordingly.

This estimate excludes software failures. Software failures have no impact on the BOM, only on the derate factor.

Fans are excluded as well, as the best inverter designs are designed without fans.

Table 132. Proxy bill of material estimate to model smaller fanless inverter failures. Source: based on from Table 68 the Task 4 report[396]

Inverter failure area	Percentage of occurrence
Fuse/contactor	56%
Card/board	21%
Matrix/IGBT	10%
Capacitors	5%
Power supply	8%

The bill of materials is adjusted accordingly. A more detailed BOM in EcoReport format is available in annex 6B.

6.2.2.2.4 Monitor/smart ready

The impact of this design option, which would likely require a coms port and circuit board to support LAN communication using Mod/Fieldbus, on the BOM is unknown and therefore the BOM of the reference inverter has been used per similar rated power.

The BOM in Ecoreport tool format is available in annex 6B.

[396] Reference table 4, taks 4 report: T. J. Formica, H. A. Khan, and M. G. Pecht, "*The Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems*," *IEEE Access*, vol. 5, pp. 21336–21343, Sep. 2017.

6.2.2.2.5 Module level inverter

The impact of this design option on the BOM is unknown and therefore the BOM of the reference inverter has been used per similar rated power. A Bill of Materials was not possible to obtain as this information is proprietary to the market leading manufacturer.

The BOM in Ecoreport tool format is available in annex 6B.

6.2.2.2.6 Hybrid storage worst performer

This design option has an impact on the BOM. Based on the weight of commercially available products, the impact has been estimated at +20 %. The BOM of the reference inverter has been used and upscaled.

The external battery is excluded from the BOM as the focus is on the performance of the power conditioning equipment and it is not the intention to set battery performance criteria.

The BOM in Ecoreport tool format is available in annex 6B.

6.2.2.2.7 Hybrid storage best performer

Due to a lack of accurate LCA modelling data apart from efficiency parameters, the same bill of materials as the worst performer storage inverter was assumed. Likely the difference between the two cases is more a cost, design and quality issue.

The BOM in Ecoreport tool format is available in annex B.

6.2.2.3 Assumptions regarding the selected design options for commercial use

This BC 2 has been put together in line with the BC 1 options.

Table 133. Design option inverters for commercial use (BC 2)

Acronym	**Reference**	**Efficient**	**Repair**
Inverter type	3 phase reference inverter Transformerless	More efficient inverter	Repair/repaired
Rated power (kVA) AC	20	20	20
Euro Efficiency η_{conv}[%]	97	98	97
Wear out & economic system life failures	3.3 % (= 1/30y)	3.3 % (= 1/30y)	3.3 % (= 1/30y)
MTBF random failures **(constant failures, e.g. defined in e.g. MIL-HDBK-217**	6.67% (=1/15 y)	6.67% (=1/15 y)	6.67% (=1/15 y) (+10 % of BOM replaced)
Cost (EUR/VA)	0.15	0.18	0.12

6.2.2.4 Life cycle information – Bill of Materials: Inverters for commercial use

6.2.2.4.1 More efficient inverter

The impact of this design option on the BOM is unknown and therefore the BOM of the reference inverter has been used per similar rated power.

The BOM in Ecoreport tool format is available in annex 6B.

6.2.2.4.2 Repair

To model this scenario, the BOM of the reference inverter has been modified in a similar way as in the residential case (see 6.2.2.2.3).

The BOM in Ecoreport tool format is available in annex 6B.

6.2.2.5 Assumptions regarding the selected design options for utility scale

Larger utility scale systems (BC 3) have already the servicing of inverters in the base case. Amongst of the most replaced components are fans and filters of the cooling system (in utility scale systems). Operation and Maintenance (O&M), including the replacement of fans, is modelled in the base case (Task 5) of BC3 (utility scale). In BC 3 we consider therefore inverter O&M as a prerequisite and not an improvement option.

Table 134. Design option inverters for utility scale (BC 3)

Acronym	**Reference**	**Efficient**	**Efficient String**
Inverter type	3 phase reference inverter Transformerless	More efficient inverter	More efficient inverter with string level inverters
Rated power (kVA) AC	1500 kW central inverter	1500 kW central inverter	10 string inverters of 150 kW each
Euro Efficiency η_{conv}[%]	97	98	98
Wear out & economic system life failures	3.3 % (= 1/30y)	3.3 % (= 1/30y)	3.3 % (= 1/30y)
MTBF random failures **(constant failures, e.g. defined in e.g. MIL-HDBK-217)**	6.67% (=1/15 y)	6.67% (=1/15 y)	6.67% (=1/15 y)
Cost (EUR/VA)	0.10	0.12	0.15

6.2.2.6 Life cycle information – Bill of Materials: Inverters for utility scale

6.2.2.6.1 More efficient inverter

The impact of this design option on the BOM is unknown and therefore the BOM of the reference inverter has been used per similar rated power.

The BOM in Ecoreport tool format is available in annex 6B.

6.2.2.6.2 Efficient string inverter

The impact of this design option on the BOM is unknown and therefore the BOM of the reference inverter has been used per similar rated power. More inverter units are required to serve the PV array.

The BOM in Ecoreport tool format is available in annex 6B.

6.2.3 PV Systems

At system level, modules are combined with inverters. Also, the balance of system and mounting systems have been added at system level.

6.2.3.1 Assumptions regarding the selected design options at residential scale

All the design options at residential scale include a reference balance of system, except for some of the design options in which the inverter is different.

Table 135 provides an overview of the considered design options for systems at residential scale.

6.2.3.1.1 Multi Si module and reference inverter (PO 1)
In this design option, a multi Si module has been combined with the reference inverter and a reference BOS.

6.2.3.1.2 Optimised PERC 2020 module and reference inverter (PO 2)
This design option combines the Optimized PERC 2020 module with the reference inverter and reference BOS.

6.2.3.1.3 BAT PERC 2019 module and reference inverter (PO 3)
This design option combines the PERC 2019 module with the reference inverter and a reference BOS.

6.2.3.1.4 CIGS module and reference inverter (PO 4)
This design option combines a CIGS module with a reference inverter and BOS.

6.2.3.1.5 Silicon Heterojunction and reference inverter (PO 5)
This design option combines a silicon heterojunction module with the reference inverter and BOS.

6.2.3.1.6 BAT PERC 2025 module and reference inverter (PO 6)
This design option combines the BAT PERC 2025 module with a reference inverter and BOS.

6.2.3.1.7 Multi Si module and more efficient inverter (PO 7)
This design option makes uses a more efficient inverter. The Euro Efficiency of the inverter is 98%, while 96% was assumed for the reference inverter. This more efficient inverter is combined with the reference multi Si module and a reference BOS.

6.2.3.1.8 Multi Si module and longer life inverter (PO 8)
In this design option the inverter failure rate has been changed from 10% to 0.5%. The inverter with a longer life has been combined with the reference multi Si module and a reference BOS.

6.2.3.1.9 Multi Si module and inverter with repair (PO 9)
This design option makes use of an inverter with an increased repair. The failure rate is 10%, but the failure does not lead to a full replacement of the inverter, rather a repair of the broken component has been assumed. The inverter with increased repair has been combined with the reference Si module and a reference BOS.

6.2.3.1.10 Multi Si module and inverter including monitoring (PO 10)
This design option represents a situation with improved monitoring. Derate soiling factor has been increased to 98% (compared to 96% in the reference case) and derate inverter failure downtime has been increased to 99.9% (compared to 99% in the reference case). The inverter including monitoring has been combined with the reference multi Si module and reference BOS.

6.2.3.1.11 Multi Si module and multi-level inverter (PO 11)
In this design option a multi-level inverter is combined with a multi Si module and reference BOM. The multi-level inverter has a higher Euro Efficiency (97%) compared to the reference inverter (96%). Also, the derate shading is increased to 98% (compared to 90% for the reference inverter). The multi-level inverter is combined with the reference multi Si module and reference BOS.

6.2.3.1.12 Multi Si module and inverter including storage (worst case) (PO 12)
In this design option the Euro Efficiency of the derate module mismatch has been increased from 97% in the reference case to 98.5%. The inverter including storage is combined with a reference multi Si module and reference BOS. The extra system loss storage changes from 5% in the reference case to 30% in this design option including storage. System losses are however not modelled in the Ecoreport tool.

6.2.3.1.13 Multi Si module and inverter including storage (best case) (PO 13)
In this design option the Euro Efficiency of the derate module mismatch has been increased from 97% in the reference case to 98.5%. The inverter including storage is combined with a reference multi Si module and reference BOS. The extra system loss storage changes from 5% in the reference case to 10% in this design option including storage. System losses are however not modelled in the Ecoreport tool.

6.2.3.1.14 Optimized PERC 2020 module and best of best inverters (SO 1)
This design option combines the best performing cost effective module with an inverter design combining the best of all the investigated inverters. The optimised PERC 2020 module combines a low life cycle cost with a lower GER (compared to the multi Si module) and is therefore selected as the best performing module. This option has a derate soiling factor of 96%, the best of best inverter has a Euro Efficiency of 98%, and a derate inverter failure factor of 99.9%. The other derate factors are equal to the reference inverter. A reference BOS is added to this design option.

6.2.3.1.15 Optimized PERC 2020 module, best of best inverters and better design (SO 2)

This design option adds a better design to the pervious design option. The better design is reflected in the higher derate shading factor (96%) and the higher derate cable losses (99.5%) compared to the previous design option (Optimized PERC 2020 + best of best inverter 6.2.3.1.14).

6.2.3.1.16 Optimised PERC 2020+ best inverter + optimised O&M (SO 3)

This system combines the best module with the best inverter and includes optimized operation and maintenance routine. This introduces practices from the large scale segment including remote monitoring, repair response or early failure detection and cleaning routines. This affects the downtime, repair cycles for the modules and inverter and the derate soiling factor.

6.2.3.2 Assumptions regarding the selected design options at commercial scale

All the design options at commercial scale include a reference BOS (except for the inverter which changes in some of the design options).

Table 136 provides an overview of the considered design options for both modules and inverters at commercial scale.

6.2.3.2.1 Multi Si module and reference inverter (Base Case PO 1)

In this design option, a multi Si module has been combined with the reference inverter and a reference BOS.

6.2.3.2.2 Optimized PERC 2020 module and reference inverter (PO 2)

This design option combines the Optimized PERC 2020 module with the reference inverter and reference BOS.

6.2.3.2.3 BAT PERC 2019 module and reference inverter (PO 3)

This design option combines the PERC 2019 module with the reference inverter and a reference BOS.

6.2.3.2.4 BAT PERC bifacial 2019 module and reference inverter (PO 4)

This design option combines the BAT PERC bifacial 2019 module with the reference inverter and reference BOS. The power gain due to the bifacial surface is set at 115%.

6.2.3.2.5 CdTe module and reference inverter (PO 5)

This design option combines a CdTe module with a reference inverter and reference BOS.

6.2.3.2.6 BAT PERC 2025 module and reference inverter (PO 6)

This design option combines the PERC 2025 module with a reference inverter and reference BOS.

6.2.3.2.7 BNAT PERC bifacial 2025 + recycled wafer and reference inverter (PO 7)

This design option combines the *BNAT* PERC 2025 bifacial module with a reference inverter and reference BOS.

6.2.3.2.8 Multi Si module and more efficient inverter (PO 8)
This design option makes use of a more efficient inverter. The Euro Efficiency of the inverter is 98%, while 96% was assumed for the reference inverter. This more efficient inverter is combined with the reference multi Si module and a reference BOS.

6.2.3.2.9 Multi Si module and inverter with repair (PO 9)
This design option makes use of an inverter with an increased repair. The failure rate is 10%, but the failure does not lead to a full replacement of the inverter, rather a repair of the broken component has been assumed. The inverter with increased repair has been combined with the reference Si module and a reference BOS.

6.2.3.2.10 BAT PERC bifacial 2019 and higher derating factors (SO 1)
This design option combines a the BAT PERC bifacial 2019 module with higher derating factors due to lower cable losses, shading and module mismatch because of a tailored design. The Euro Efficiency of the inverter is set at 98%, the derate shading is 98%, the derate module mismatch is 98% and the derate cable losses are 99.5%.

6.2.3.3 Assumptions regarding the selected design options at utility scale

Table 137 provides an overview of the considered design options for both modules and inverters at utility scale.

6.2.3.3.1 Multi Si module and reference inverter and reference BOS (PO 1)

In this design option, a multi Si module has been combined with the reference inverter and a reference BOS.

6.2.3.3.2 Optimised PERC 2020 module and reference inverter and reference BOS (PO 2)

This design option combines the Optimized PERC 2020 module with the reference inverter and reference BOS.

6.2.3.3.3 BAT PERC 2019 module and reference inverter and reference BOS (PO 3)

This design option combines the BAT PERC 2019 module with the reference inverter and a reference BOS.

6.2.3.3.4 BAT PERC bifacial 2019 module and reference inverter and reference BOS (PO 4)

This design option combines the BAT PERC bifacial 2019 module with the reference inverter and reference BOS. The power gain due to the bifacial surface is set at 110%.

6.2.3.3.5 CdTe module and reference inverter and reference BOS (PO 5)
This design option combines a CdTe module with a reference inverter and reference BOS.

6.2.3.3.6 BAT PERC 2025 module with reference inverter and reference BOS (PO 6)

This design option combines the BAT PERC 2025 module with a reference inverter and reference BOS.

6.2.3.3.7 BNAT PERC bifacial 2025 + recycled wafer module with reference inverter and reference BOS (PO 7)

This design option combines the BNAT PERC bifacial 2025 + recycled wafer module with a reference inverter and reference BOS.

6.2.3.3.8 Multi Si module and more efficient inverter and reference BOS (PO 8)
This design option combines the reference multi Si module with a more efficient inverter. The Euro Efficiency of the inverter increases from 97% (reference inverter) to 98%.

6.2.3.3.9 Multi Si module and more efficient string inverter and reference BOS (PO 9)
This design option combines the reference multi Si module with a more efficient string inverter. The Euro Efficiency is 98% and the derate module mismatch is 98%.

6.2.3.3.10 CdTe module, efficient string inverter and tracking (SO 1)
This design option combines a CdTe module with an efficient string inverter and tracking. Due to the use of tracking the radiation hours increase from 1331 hours to 1465 hours (from PVGIS simulation in Frankfurt).

Table 135. Combination of design options for modules and inverters – residential scale systems

System		Base Case - PO 1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	PO 10	PO 11	PO 12	PO 13	SO 1	SO 2	SO 3
Parameters																	
Use phase parameters Task 3 + inverter efficiency of Task 4																	
PR = DRother x DR modelled	%	*74,9%*	*74,9%*	*74,9%*	*74,9%*	*74,9%*	*74,9%*	*76,5%*	*74,9%*	*74,9%*	*77,2%*	*81,6%*	*74,9%*	*74,9%*	*77,2%*	*82,7%*	*84,0%*
DR other	%	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*	*95,1%*
Euro Efficiency ηconv[%]	%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	98,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	98,0%	98,0%	98,0%
DR Module mismatch	%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%
DR shading	%	90,0%	90,0%	90,0%	90,0%	90,0%	90,0%	90,0%	90,0%	90,0%	90,0%	98,0%	90,0%	90,0%	90,0%	96,0%	96,0%
DR temp effect	%	100,0%	100,0%	100,0%	100,0%	102,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
DR soiling	%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	98,0%	96,0%	96,0%	96,0%	96,0%	96,0%	98,0%
DR snow	%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%
DR cable losses	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,5%	99,0%
DR inv failure (downtime)	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,9%	99,9%	99,9%
DR modelled	%	*78,78%*	*78,78%*	*78,78%*	*78,78%*	*78,78%*	*78,78%*	*80,42%*	*78,78%*	*78,78%*	*81,15%*	*85,78%*	*78,78%*	*78,78%*	*81,15%*	*87,00%*	*88,36%*
reference irradiation	hours	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331,00
System yield - Yf (in year 1)		***997***	***997***	***997***	***997***	***997***	***997***	***1018***	***997***	***997***	***1027***	***1086***	***997***	***997***	***1027***	***1101***	***1118***
cleaning and maintenance cycle	#/y	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067
extra system loss storage(ESS) or grid(no ESS)	%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	**30,0%**	**10,0%**	5,0%	5,0%	5,0%
Technology parameters Task 4																	
power gain for bifacial or derating	Wp/m2	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
Rated power/m² or mod. Efficiency	Wp/m2	147	175	196	150	184	196	147	147	147	147	147	147	147	175	175	175
corrected rated power	Wp/m2	147	175	196	150	184	196	147	147	147	147	147	147	147	175	175	175
Performance degradation rate	%	0,70%	0,60%	0,50%	1,00%	1,00%	0,50%	0,70%	0,70%	0,70%	0,70%	0,70%	0,70%	0,70%	0,70%	0,70%	0,70%
Economic System Life (Task 1)	years	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
System yield average over life	hours	***902***	***915***	***928***	***867***	***867***	***928***	***921***	***902***	***902***	***930***	***983***	***902***	***902***	***930***	***997***	***1012***
Failure rate modules	%/year	0,05%	0,05%	0,05%	0,05%	0,05%	0,01%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%
Average module replacement	%/life	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*0,15%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*
Failure rate inverters⊞1/MTBF	%/year	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	3,86%	10,00%	10,00%	10,00%	10,00%	10,00%	3,86%	3,86%	3,86%
Average inverter replacements	%/life	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*115,7%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*115,7%*	*115,7%*	*115,7%*
Installed rated power modules	Wp	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
Rated Power inverter	VA	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Overall output of electricity	kWh	***81215***	***82330***	***83477***	***78062***	***78062***	***83477***	***82907***	***81215***	***81215***	***83661***	***88435***	***81215***	***81215***	***83661***	***89689***	***91098***
total module area	m²	***20,7***	***17,4***	***15,5***	***20,3***	***16,5***	***15,3***	***20,7***	***20,7***	***20,7***	***20,7***	***20,7***	***20,7***	***20,7***	***17,4***	***17,4***	***17,4***
area of single modules	m²	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***
total modules	#	***12,9***	***10,8***	***9,7***	***12,7***	***10,3***	***9,6***	***12,9***	***12,9***	***12,9***	***12,9***	***12,9***	***12,9***	***12,9***	***10,8***	***10,8***	***10,8***
# m2 panel per kWh	**m²/kWh**	***2,55E-04***	***2,11E-04***	***1,86E-04***	***2,60E-04***	***2,12E-04***	***1,84E-04***	***2,50E-04***	***2,55E-04***	***2,55E-04***	***2,48E-04***	***2,34E-04***	***2,55E-04***	***2,55E-04***	***2,07E-04***	***1,93E-04***	***1,90E-04***
# 2.5 kVA inverter (incl repl)/kWh	**units (incl repl)/kWh**	***1,23E-05***	***1,21E-05***	***1,20E-05***	***1,28E-05***	***1,28E-05***	***1,20E-05***	***1,21E-05***	***1,23E-05***	***1,23E-05***	***1,20E-05***	***1,13E-05***	***1,23E-05***	***1,23E-05***	***1,20E-05***	***1,11E-05***	***1,10E-05***
Wafer Thickness	**micrometer**	***2,00E+02***	***1,70E+02***	***1,80E+02***	***not relevant***	***1,50E+02***	***1,20E+02***	***2,00E+02***	***2,00E+02***	***2,00E+02***	***2,00E+02***	***2,00E+02***	***2,00E+02***	***2,00E+02***	***0,00E+00***	***0,00E+00***	***0,00E+00***
Form factor losses silicon	**kg/m2 panel**	***1,85E-01***	***1,51E-01***	***1,58E-01***	***not relevant***	***1,39E-01***	***1,05E-01***	***1,85E-01***	***1,85E-01***	***1,85E-01***	***1,85E-01***	***1,85E-01***	***1,85E-01***	***1,85E-01***	***0,00E+00***	***0,00E+00***	***0,00E+00***
Kerf losses	**micrometer**	***1,00E+02***	***7,50E+01***	***7,50E+01***	***not relevant***	***7,50E+01***	***5,00E+01***	***1,00E+02***	***1,00E+02***	***1,00E+02***	***1,00E+02***	***1,00E+02***	***1,00E+02***	***1,00E+02***	***0,00E+00***	***0,00E+00***	***0,00E+00***
factory defect rate	**%**	***1,5%***	***1,5%***	***1,5%***	***1,5%***	***1,5%***	***0,5%***										

(PO 1): Multi Si module and reference inverter, (PO2): Optimised PERC 202 module and reference inverter; (PO 3): BAT PERC 2019 module and reference inverter; (PO 4): CIGS module and reference inverter; (PO 5): Silicion heterojunction module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): Multi Si module and more efficient inverter; (PO 8): Multi Si module and longer life inverter; (PO 9): Multi Si Module and inverter with repair; (PO 10): Multi Si module and inverter including monitoring; (PO 11): Multi Si module and multi-level inverter; (PO 12): Multi Si module and inverter including storage (worst case); (PO 13): Multi Si module and inverter including storage (best case).

(SO 1): Optimised PERC 2020 + best inverter; (SO 2): Optimised PERC 2020+ best inverter + better design; (SO 3): Optimised PERC 2020+ best inverter + optimised O&M

Table 136. Combination of design options for modules and inverters – commercial scale systems. (SO 1): best combination and design; (PO 1): Multi Si module and reference inverter; (PO 2): Optimised PERC 2020 module and reference inverter; (PO 3):BAT PERC 2019 module and reference inverter; (PO 4):BAT PERC bifacial 2019 module and reference inverter; (PO 5): CdTe module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter; (PO 8):Multi Si module and more efficient inverter; (PO 9): Multi Si module and inverter with repair

System		Base Case - PO 1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
Parameters											
Use phase parameters Task 3 + inverter efficiency of Task 4											
PR = DRother x DR modelled	%	82,5%	82,6%	82,6%	82,6%	82,6%	82,6%	82,6%	83,4%	82,6%	87,8%
DR other	%	98,2%	98,2%	98,2%	98,2%	98,2%	98,2%	98,2%	98,2%	98,2%	98,2%
Euro Efficiency η_{conv}[%]	%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	98,0%	97,0%	98,0%
DR Module mismatch	%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	98,5%
DR shading	%	95,0%	95,0%	95,0%	95,0%	95,0%	95,0%	95,0%	95,0%	95,0%	98,0%
DR temp effect	%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
DR soiling	%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%
DR snow	%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%
DR cable losses	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,5%
DR inv failure (downtime)	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%
DR modelled	%	84,02%	84,10%	84,10%	84,10%	84,10%	84,10%	84,10%	84,97%	84,10%	89,46%
reference irradiation	hours	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331
System yield - Yf (in year 1)		1098	1099	1099	1099	1099	1099	1099	1111	1099	1169
cleaning and maintenance cycle	#/y	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067
extra system loss storage(ESS) or grid(no ESS)	%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%
Technology parameters Task 4											
power gain for bifacial or derating	Wp/m2	100,0%	100,0%	100,0%	115,0%	98,0%	100,0%	115,0%	100,0%	100,0%	115,0%
Rated power/m² or mod. Efficiency	Wp/m2	147	175	196	196	180	196	196	147	147	196
Rated power	Wp/m2	147	175	196	225	176	196	225	147	147	225
Performance degradation rate	%	0,70%	0,60%	0,50%	0,50%	0,50%	0,50%	0,50%	0,70%	0,70%	0,50%
Economic System Life time	years	30	30	30	30	30	30	30	30	30	30
System yield average over life	hours	994	1008	1023	1023	1023	1023	1023	1005	995	1088
Failure rate modules	%/year	0,05%	0,05%	0,05%	0,05%	0,05%	0,01%	0,05%	0,05%	0,05%	0,05%
Average module replacement	%/life	1,50%	1,50%	1,50%	1,50%	1,50%	0,30%	1,50%	1,50%	1,50%	1,50%
Failure rate inverters =1/MTBF	%/year	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%
Average inverter replacements	%/life	300,0%	300,0%	300,0%	300,0%	300,0%	300,0%	300,0%	300,0%	300,0%	300,0%
Capacity modules	Wp	24400	24400	24400	24400	24400	24400	24400	24400	24400	24400
Rated Power inverter	VA	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
Overall output of electricity	kWh	727478	738197	748483	748483	748483	748483	748483	735714	728206	796143
total module area	m²	168,5	141,1	126,4	109,9	140,6	124,9	109,9	168,5	168,5	109,9
area of single modules	m²	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6
total modules	#	105,3	88,2	79,0	68,7	87,8	78,0	68,7	105,3	105,3	68,7
# m2 panel per kWh	**m²/kWh**	2,32E-04	1,91E-04	1,69E-04	1,47E-04	1,88E-04	1,67E-04	1,47E-04	2,29E-04	2,31E-04	1,38E-04
# inverter (incl repl)/kWh	**units (incl repl)/kWh**	1,37E-06	1,35E-06	1,34E-06	1,34E-06	1,34E-06	1,34E-06	1,34E-06	1,36E-06	1,37E-06	1,26E-06
Wafer Thickness	**micrometer**	2,00E+02	1,70E+02	1,80E+02	1,80E+02	not relevant	1,20E+02	1,80E+02	2,00E+02	2,00E+02	0,00E+00
Form factor losses silicon	**kg/m2 panel**	1,85E-01	1,51E-01	1,58E-01	1,58E-01	not relevant	1,05E-01	1,58E-01	1,85E-01	1,85E-01	0,00E+00
Kerf losses	**micrometer**	1,00E+02	7,50E+01	7,50E+01	7,50E+01	not relevant	5,00E+01	7,50E+01	1,00E+02	1,00E+02	0,00E+00
factory defect rate	**%**	1,5%	1,5%	1,5%	1,5%	1,5%	0,5%	1,5%			

Table 137: Combination of design options for modules and inverters – utility scale systems. (SO 1): best combination and design including single axis tracker; (PO 1): Multi Si module and reference inverter and reference BOS; (PO 2): Optimised PERC 2020 module and reference inverter and reference BOS; (PO 3): BAT PERC 2019 module and reference inverter and reference BOS; (PO 4): BAT PERC bifacial 2019 module and reference inverter and reference BOS; (PO 5): CdTe module and reference inverter and reference BOS; (PO6): BAT PERC 2025 module and reference inverter and reference BOS; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter and reference BOS; (PO 8): Multi Si module and more efficient inverter and reference BOS; (PO 9): Multi Si module and more efficient string inverter and reference BOS

System		Base Case - PO 1	PO 2	PO 3	PO4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
Parameters											
Use phase parameters Task 3 + inverter efficiency of Task 4											
PR = DRother x DR modelled	%	***82,5%***	***82,5%***	***82,5%***	***82,5%***	***82,5%***	***82,5%***	***82,5%***	***83,4%***	***84,3%***	***84,3%***
DR other	%	***93,2%***	***93,2%***	***93,2%***	***93,2%***	***93,2%***	***93,2%***	***93,2%***	***93,2%***	***93,2%***	***93,2%***
Euro Efficiency η_{conv}[%]	%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	98,0%	98,0%	98,0%
DR Module mismatch	%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	98,0%	98,0%
DR shading	%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%
DR temp effect	%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
DR soiling	%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%
DR snow	%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%
DR cable losses	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%
DR inv failure (downtime)	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%
DR modelled	%	***88,48%***	***88,57%***	***88,57%***	***88,57%***	***88,57%***	***88,57%***	***88,57%***	***89,48%***	***90,40%***	***90,40%***
Reference irradiation	hours	1331	1331	1331	1331	1331	1331	1331	1331	1331	1465
System yield - Yf (in year 1)		***1098***	***1099***	***1099***	***1099***	***1099***	***1099***	***1099***	***1110***	***1121***	***1234***
cleaning and maintenance cycle	#/y	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067
extra system loss storage(ESS) or grid(no ESS)	%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%
Technology parameters Task 4											
power gain for bifacial or derating	Wp/m2	100,0%	100,0%	100,0%	110,0%	98,0%	100,0%	110,0%	100,0%	100,0%	98,0%
Rated power/m² or mod. Efficiency	Wp/m2	147	175	196	196	180	196	196	147	147	180
Rated power	Wp/m2	147	175	196	216	176	196	216	147	147	176
Performance degradation rate	%	0,70%	0,60%	0,50%	0,50%	0,50%	0,50%	0,50%	0,70%	0,70%	0,50%
Economic System Life time	years	30	30	30	30	30	30	30	30	30	30,00
System yield average over life	hours	***993***	***1008***	***1022***	***1022***	***1022***	***1022***	***1022***	***1005***	***1015***	***1148***
Failure rate modules	%/year	0,05%	0,05%	0,05%	0,05%	0,05%	0,01%	0,05%	0,05%	0,05%	0,05%
Average module replacement	%/life	***1,50%***	***1,50%***	***1,50%***	***1,50%***	***1,50%***	***6,00%***	***1,50%***	***1,50%***	***1,50%***	***1,50%***
Failure rate inverters =1/MTBF	%/year	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%
Average inverter replacements	%/life	***300,0%***	***300,0%***	***300,0%***	***300,0%***	***300,0%***	***300,0%***	***300,0%***	***300,0%***	***300,0%***	***300,0%***
Capacity modules	Wp	1875000	1875000	1875000	1875000	1875000	1875000	1875000	1875000	1875000	1875000
Rated Power inverter	VA	1500000	1500000	1500000	1500000	1500000	1500000	1500000	1500000	1500000	1500000
Overall output of electricity	kWh	***55871867***	***56695080***	***57485081***	***57485081***	***57485081***	***57485081***	***57485081***	***56504370***	***57086890***	***64589581***
total module area	m²	***12946,4***	***10844,6***	***9709,8***	***8827,1***	***10800,7***	***10140,3***	***8827,1***	***12946,4***	***12946,4***	***10800,7***
area of single modules	m²	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***	***1,6***
total modules	#	***8091,5***	***6777,9***	***6068,6***	***5516,9***	***6750,4***	***6337,7***	***5516,9***	***8091,5***	***8091,5***	***6750,4***
# m2 panel per kWh	**m²/kWh**	***2,32E-04***	***1,91E-04***	***1,69E-04***	***1,54E-04***	***1,88E-04***	***1,76E-04***	***1,54E-04***	***2,29E-04***	***2,27E-04***	***1,67E-04***
# inverter (incl repl)/kWh	**units (incl repl)/kWh**	***1,79E-08***	***1,76E-08***	***1,74E-08***	***1,74E-08***	***1,74E-08***	***1,74E-08***	***1,74E-08***	***1,77E-08***	***1,75E-08***	***1,55E-08***
Wafer Thickness	**micrometer**	***2,00E+02***	***1,70E+02***	***1,80E+02***	***1,80E+02***	***not relevant***	***1,20E+02***	***1,80E+02***	***2,00E+02***	***2,00E+02***	***not relevant***
Form factor losses silicon	**kg/m2 panel**	***1,85E-01***	***1,51E-01***	***1,58E-01***	***1,58E-01***	***not relevant***	***1,05E-01***	***1,58E-01***	***1,85E-01***	***1,85E-01***	***not relevant***
Kerf losses	**micrometer**	***1,00E+02***	***7,50E+01***	***7,50E+01***	***7,50E+01***	***not relevant***	***5,00E+01***	***7,50E+01***	***1,00E+02***	***1,00E+02***	***not relevant***
factory defect rate	**%**	***1,5%***	***1,5%***	***1,5%***	***1,5%***	***1,5%***	***0,5%***	***1,5%***			

6.3 Environmental impacts (results from Ecoreport tool)

6.3.1 PV modules

Table 139 shows the relative environmental impacts of the single design options compared to base case PV modules under real life conditions.

Figure 126 shows the results for the primary impact category 'Primary energy' per kWh for the different module types.

Table 138 shows the relative figures of the total primary energy of the base case (=100%) and the single design options for selected environmental impact categories.

Figure 126. Primary energy results in MJ per kWh produced from modules

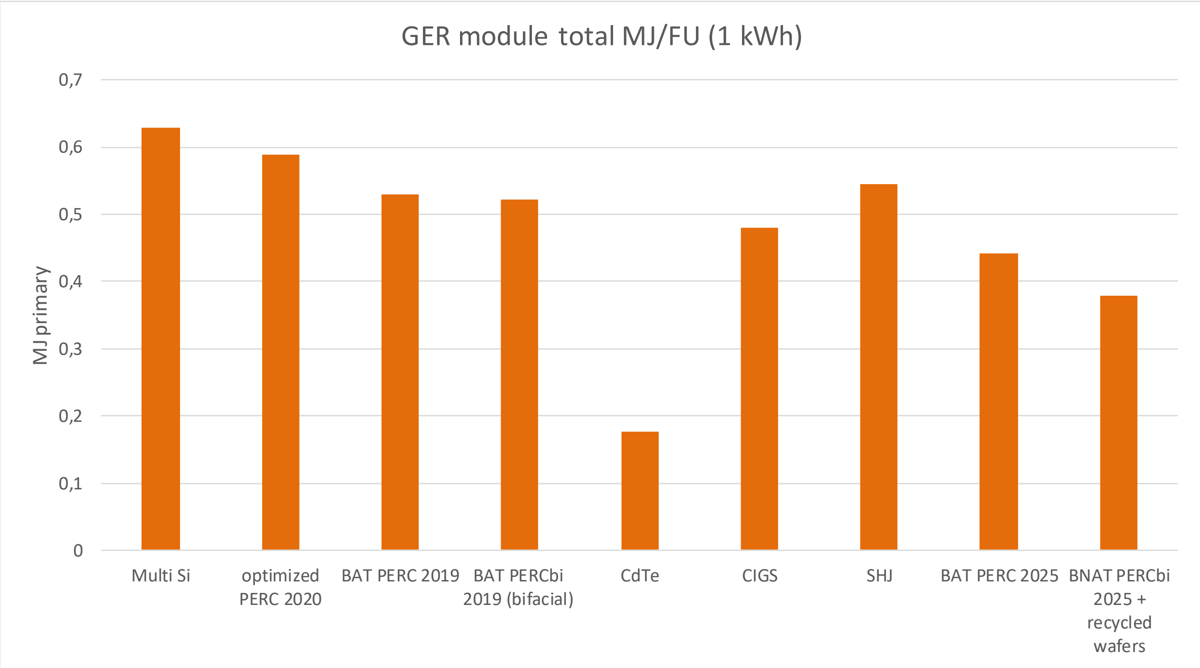


Table 138. Ranking of selected improvement options for PV Modules based on selected environmental indicators

Option	**Total Energy (primary energy)**
CdTe	28%
BNAT PERCbi 2025 + recycled wafer	60%
BAT PERC 2025	70%
CIGS	76%
BAT PERCbi 2019	83%
BAT PERC 2019	84%
SHJ	87%
Optimized PERC 2020	94%
Multi Si Base Case	100%

6.3.1.1 Influence of the electricity mix on the results

The main impact of the multi-Si module comes from the electricity consumed by the production of the solar cell. Therefore, as well the amount of primary energy, the electricity mix or grid factor of the location of cell production can exert an influence on the results.

Table 139. Life cycle impacts of PV module design options with respect to the base case

Indicators (from Ecoreport)	**Base case**	**Optimized PERC 2020**	**BAT PERC 2019**	**BAT PERCbi 2019**	**CdTe**	**CIGS**	**SHJ**	**BAT PERC 2025**	**BNAT PERCbi 2025 + recycled wafer**
Total Energy (GER)	**100%**	**94%**	**84%**	**83%**	**28%**	**76%**	**87%**	**70%**	**60%**
Water	**100%**	**131%**	**118%**	**117%**	**10%**	**24%**	**65%**	**166%**	**95%**
Waste, non-haz./ landfill	**100%**	**115%**	**104%**	**104%**	**14%**	**27%**	**109%**	**82%**	**69%**
Waste, hazardous/ incinerated	**100%**	**38%**	**34%**	**33%**	**5%**	**8%**	**38%**	**33%**	**18%**
Greenhouse Gases in GWP100	**100%**	**96%**	**87%**	**86%**	**28%**	**76%**	**90%**	**72%**	**63%**
Acidification, emissions	**100%**	**95%**	**86%**	**85%**	**28%**	**64%**	**93%**	**76%**	**64%**
Volatile Organic Compounds (VOC)	**100%**	**83%**	**74%**	**74%**	**8%**	**13%**	**85%**	**70%**	**69%**
Persistent Organic Pollutants (POP)	**100%**	**94%**	**84%**	**84%**	**17%**	**45%**	**102%**	**67%**	**61%**
Heavy Metals to air	**100%**	**91%**	**81%**	**81%**	**19%**	**33%**	**112%**	**84%**	**56%**
PAHs	**100%**	**79%**	**71%**	**71%**	**5%**	**66%**	**79%**	**63%**	**57%**
Particulate Matter (PM, dust)	**100%**	**89%**	**79%**	**79%**	**60%**	**81%**	**87%**	**73%**	**70%**
Heavy Metals to water	**100%**	**83%**	**74%**	**74%**	**4%**	**26%**	**111%**	**58%**	**54%**
Eutrophication	**100%**	**102%**	**92%**	**92%**	**13%**	**45%**	**121%**	**66%**	**67%**

To evaluate this influence, the Base Case multi-Si cell has been used. To calculate the environmental impact of this cell, the global ecoinvent data record on the production of a multi Si cell with a global market electricity mix, represents the market for solar cell production.

To account for a variation in the production location, the electricity mixes along all processes of the production of the multi Si solar cell have been changed into the Swedish electricity mix, which is known as a clean electricity mix in Europe, and the EU average electricity mix. Electricity has only been changed in the following levels of the production chain of the solar cell, which were identified as being relevant:

- Cell assembly
- Wafer production
    - Silicon carbide production
    - Silicon solar grade production

All other records (e.g. metallization pastes) remained unchanged, but were also less relevant in the environmental profile of the multi Si cell. Burning of natural gas as an energy source remained unchanged as well.

Figure 127 compares the environmental impact of a multi Si cell produced using energy mixes representing the global market multi Si cell production and the adapted records using the Swedish and the EU average electricity mix.

Figure 128 shows the results at module level. The electricity mix has been changed for the cell only, as described above. The cell is then used in the multi-Si module.

The comparison is made in each case in percentage terms relative to the energy mix with the greatest impact in each category – which, with the exception of water, is the global market multi Si cell.

Figure 127. Comparison of environmental impact photovoltaic cell using global market mix (blue) the EU mix (orange) and using the Swedish mix (grey)

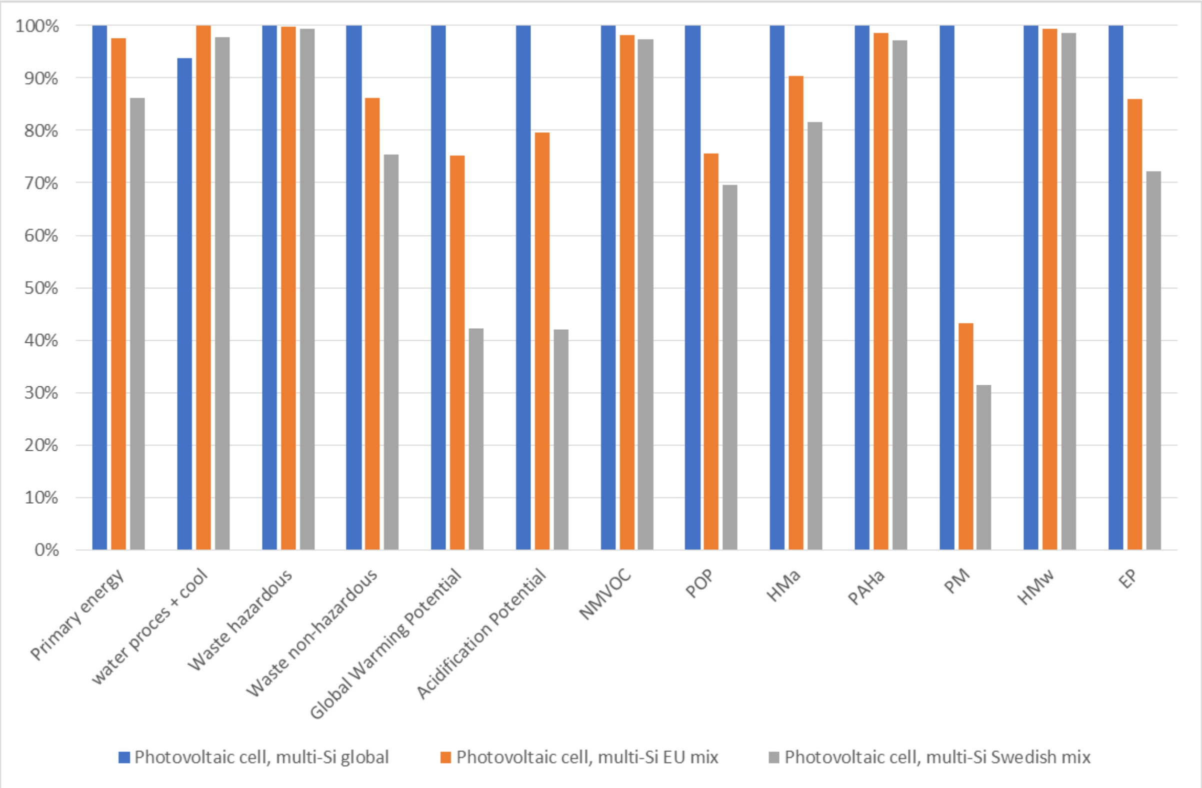
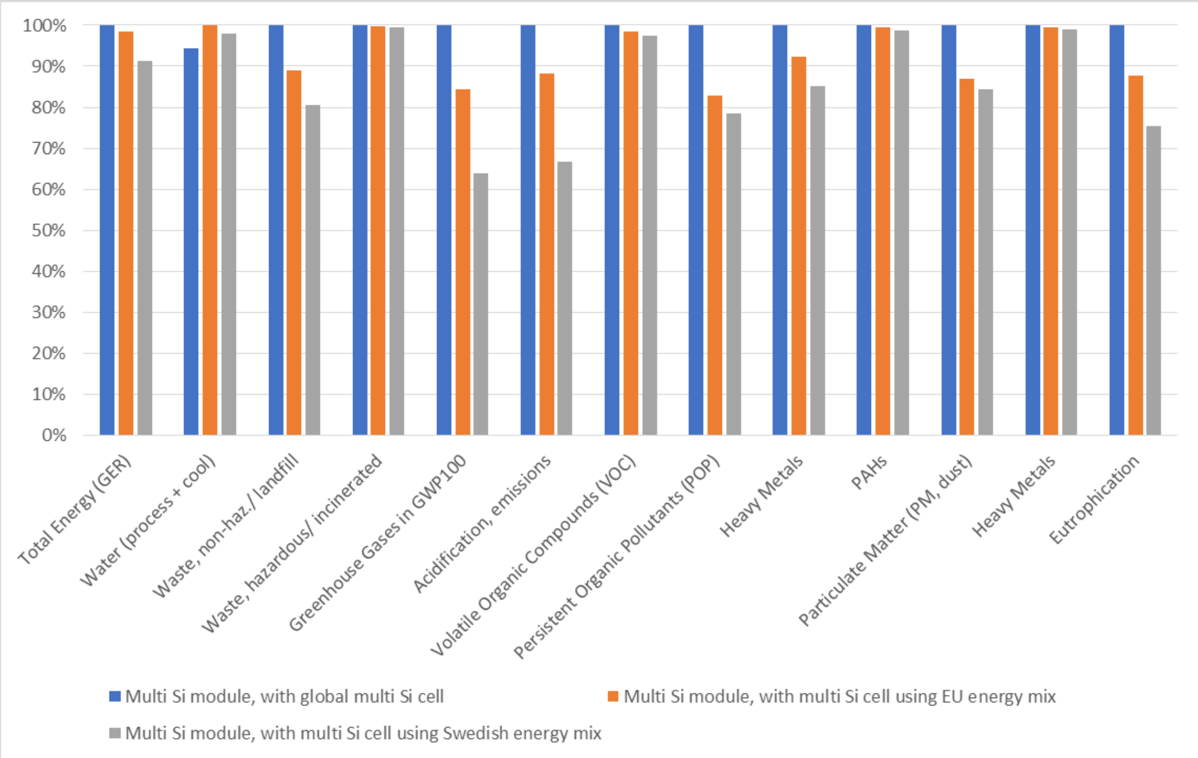


Figure 128. Comparison of the environmental impact of a multi Si module, using a cell produced according to the global market (blue) and a cell produced with the Swedish electricity mix (orange)



6.3.1.2 Influence of changes in metallisation and solder paste to the results

The improved PERC module design (PERC 2025) is likely to contain lead free metallisation and solder paste.

The lead free alternative for metallisation paste contains Bismuth. It was not possible to model a lead free metallisation paste containing bismuth with ecoinvent datasets. Bismuth is not available in this database. The EF (Environmental Footprint) compliant datasets contain a lead free metallisation paste with bismuth. The EF datasets are aggregated datasets and it is not possible to extract from these datasets the contribution of bismuth. One can also not directly compare results made with ecoinvent datasets versus results with EF datasets. Background data might differ substantially (e.g. energy/electricity mixes, assumptions for transport etc.). For this reason an alternative approach had to be devised.

Below the PERC 2020 module is compared with the PERC 2025 module. The PERC 2020 module includes lead containing metallisation paste and also lead in the solder. In this module the ecoinvent dataset for metallization paste is replaced with the EF dataset for lead containing metallisation paste. This will allow for a direct comparison to be made with the PERC 2025 module containing a lead free metallisation paste and lead free solder. The data source for the lead free metallization is the EF database.

In the tables below, the impact of the lead free metallisation paste is contained in the impact of the photovoltaic cell. The impact of the solder is shown separately in the categories 'interconnection – Tin', 'interconnection – lead' and 'interconnection – Copper'.

6.3.1.2.1 PERC 2020 – with ecoinvent lead containing metallisation paste and also lead in solder

Solder with lead, is directly modelled in Ecoreport tool with Ecoreport tool datasets. Metallisation paste is as in ecoinvent (per m^2 cell):

Metallization paste, back side {GLO} market for | Cut-off, U	0,004931 kg	Changed into EF dataset in next step
Metallization paste, back side, aluminium {GLO}| market for | Cut-off, U	0,07191 kg	Does not contain lead, not changed to EF dataset
Metallization paste, front side {GLO}| market for | Cut-off, U	0,0073964 kg	Changed to EF dataset in next step

Table 140. Result for lead-free metalisation and solder paste (in absolute values per kWh)

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	9,21E-02	4,99E-01	1,06E+00	1,58E-02	3,53E+00	3,18E-02	1,43E-01	4,55E-02	1,05E-02	6,78E-02	2,86E-02	7,71E-02	6,45E-02	2,78E+01
interconnection - Tin	2,72E-03	8,71E-04	7,68E-04	8,59E-07	3,43E-03	5,82E-05	1,25E-03	5,34E-05	1,06E-05	6,97E-05	1,55E-05	6,71E-04	6,35E-06	2,56E-02
interconnection - Lead	1,53E-04	3,32E-06	3,15E-06	3,01E-09	8,19E-05	3,25E-07	7,42E-06	2,47E-07	7,25E-06	8,24E-06	1,30E-07	6,61E-07	4,88E-06	7,91E-04
interconnection - Copper	2,17E-02	2,53E-03	0,00E+00	5,25E-06	2,64E-04	1,35E-04	6,34E-03	2,09E-07	8,13E-05	1,20E-03	1,17E-04	6,17E-05	2,04E-03	3,35E-03
encapsulation - ethylvinylacetate	1,84E-01	1,72E-02	1,07E-02	6,37E-06	4,87E-02	5,25E-04	2,04E-03	4,60E-04	9,02E-05	1,32E-03	1,43E-04	6,43E-04	6,75E-05	6,17E-01
backsheet - PVF	2,36E-02	4,79E-03	3,43E-03	6,36E-06	2,21E-02	3,82E-04	1,50E-03	5,47E-05	9,61E-05	7,95E-04	6,95E-05	6,92E-04	5,42E-05	1,73E-01
backsheet - PET	7,29E-02	5,75E-03	5,32E-04	1,17E-04	6,72E-03	2,27E-04	2,51E-03	9,48E-05	0,00E+00	1,65E-04	1,06E-04	3,65E-04	1,46E-07	2,77E-02
pottant & sealing	2,57E-02	1,57E-03	3,04E-03	1,08E-06	7,17E-03	8,44E-05	3,88E-04	4,63E-05	1,98E-05	1,98E-04	2,57E-04	1,30E-04	3,27E-04	4,17E-02
alu frame	4,49E-01	8,65E-02	0,00E+00	0,00E+00	1,62E-01	4,65E-03	3,02E-02	2,97E-05	2,24E-03	1,63E-03	4,33E-02	7,59E-03	1,57E-02	2,22E-03
solar glass	1,69E+00	2,87E-02	1,41E-02	3,05E-05	2,31E-01	2,18E-03	1,79E-02	6,60E-04	5,60E-04	4,71E-03	5,92E-04	2,10E-03	9,66E-04	1,49E+00
junction box - diode	5,92E-04	4,75E-03	0,00E+00	1,40E-04	5,20E-03	2,99E-04	1,65E-03	4,08E-05	2,89E-05	2,64E-04	8,70E-06	4,31E-05	2,21E-03	1,27E-02
junction box - HDPE	5,02E-03	3,84E-04	1,71E-05	2,73E-05	1,92E-04	9,07E-06	3,06E-05	8,03E-07	0,00E+00	0,00E+00	1,73E-06	4,31E-06	0,00E+00	1,50E-04
junction box - glass fibre	6,22E-02	4,09E-03	3,38E-03	4,39E-04	1,93E-02	2,09E-04	1,81E-03	2,88E-07	0,00E+00	0,00E+00	4,03E-06	5,06E-04	2,94E-03	1,96E-01
Auxilaries	1,09E+00	1,18E-03	2,26E-03	1,35E-06	3,14E-02	6,01E-05	6,12E-04	2,21E-05	2,46E-05	3,67E-04	3,06E-05	1,15E-04	2,18E-05	5,98E-02
Total	**3,71E+00**	**6,57E-01**	**1,10E+00**	**1,66E-02**	**4,06E+00**	**4,06E-02**	**2,10E-01**	**4,69E-02**	**1,37E-02**	**7,85E-02**	**7,32E-02**	**9,00E-02**	**8,89E-02**	**3,04E+01**

Table 141. Relative result for lead-free metalisation and solder paste (in absolute values per kWh)

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	2%	76%	95%	95%	87%	78%	68%	97%	77%	86%	39%	86%	73%	91%
interconnection - Tin	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%
interconnection - Lead	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
interconnection - Copper	1%	0%	0%	0%	0%	0%	3%	0%	1%	2%	0%	0%	2%	0%
encapsulation - ethylvinylacetate	5%	3%	1%	0%	1%	1%	1%	1%	1%	2%	0%	1%	0%	2%
backsheet - PVF	1%	1%	0%	0%	1%	1%	1%	0%	1%	1%	0%	1%	0%	1%
backsheet - PET	2%	1%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%
pottant & sealing	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
alu frame	12%	13%	0%	0%	4%	11%	14%	0%	16%	2%	59%	8%	18%	0%
solar glass	45%	4%	1%	0%	6%	5%	9%	1%	4%	6%	1%	2%	1%	5%
junction box - diode	0%	1%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	2%	0%
junction box - HDPE	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
junction box - glass fibre	2%	1%	2%	3%	0%	1%	1%	0%	0%	0%	0%	1%	3%	1%
Auxilaries	29%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%

6.3.1.2.2 PERC 2020 – with EF lead containing metallization paste and also lead in solder

Solder with lead, directly modelled in ecoreport tool with ecoreport tool datasets -> not changed. The metallisation paste as in ecoinvent 3.4 or EF compliant datasets (per m^2 cell):

Metallization paste, front side| components mixing| production mix, at plant| 83% silver, 12% isopropanol, 5% lead {World} [LCI result]	0,004931 kg	EF dataset
Metallization paste, back side, aluminium {GLO}| market for | Cut-off, U	0,07191 kg	Remained from ecoinvent as it did not contain lead
Metallization paste, front side| components mixing| production mix, at plant| 83% silver, 12% isopropanol, 5% lead {World} [LCI result]	0,0073964 kg	EF dataset

Table 142. Result for lead-free metalisation and solder paste (in absolute values per kWh)

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	9,21E-02	5,00E-01	1,87E+00	1,58E-02	3,49E+00	3,19E-02	1,51E-01	4,49E-02	9,73E-03	8,51E-02	2,84E-02	7,53E-02	4,77E-02	2,41E+01
interconnection - Tin	2,72E-03	8,71E-04	7,68E-04	8,59E-07	3,43E-03	5,82E-05	1,25E-03	5,34E-05	1,06E-05	6,97E-05	1,55E-05	6,71E-04	6,35E-06	2,56E-02
interconnection - Lead	1,53E-04	3,32E-06	3,15E-06	3,01E-09	8,19E-05	3,25E-07	7,42E-06	2,47E-07	7,25E-06	8,24E-06	1,30E-07	6,61E-07	4,88E-06	7,91E-04
interconnection - Copper	2,17E-02	2,53E-03	0,00E+00	5,25E-06	2,64E-04	1,35E-04	6,34E-03	2,09E-07	8,13E-05	1,20E-03	1,17E-04	6,17E-05	2,04E-03	3,35E-03
encapsulation - ethylvinylacetate	1,84E-01	1,72E-02	1,07E-02	6,37E-06	4,87E-02	5,25E-04	2,04E-03	4,60E-04	9,02E-05	1,32E-03	1,43E-04	6,43E-04	6,75E-05	6,17E-01
backsheet - PVF	2,36E-02	4,79E-03	3,43E-03	6,36E-06	2,21E-02	3,82E-04	1,50E-03	5,47E-05	9,61E-05	7,95E-04	6,95E-05	6,92E-04	5,42E-05	1,73E-01
backsheet - PET	7,29E-02	5,75E-03	5,32E-04	1,17E-04	6,72E-03	2,27E-04	2,51E-03	9,48E-05	0,00E+00	1,65E-04	1,06E-04	3,65E-04	1,46E-07	2,77E-02
pottant & sealing	2,57E-02	1,57E-03	3,04E-03	1,08E-06	7,17E-03	8,44E-05	3,88E-04	4,63E-05	1,98E-05	1,98E-04	2,57E-04	1,30E-04	3,27E-04	4,17E-02
alu frame	4,49E-01	8,65E-02	0,00E+00	0,00E+00	1,62E-01	4,65E-03	3,02E-02	2,97E-05	2,24E-03	1,63E-03	4,33E-02	7,59E-03	1,57E-02	2,22E-03
solar glass	1,69E+00	2,87E-02	1,41E-02	3,05E-05	2,31E-01	2,18E-03	1,79E-02	6,60E-04	5,60E-04	4,71E-03	5,92E-04	2,10E-03	9,66E-04	1,49E+00
junction box - diode	5,92E-04	4,75E-03	0,00E+00	1,40E-04	5,20E-03	2,99E-04	1,65E-03	4,08E-05	2,89E-05	2,64E-04	8,70E-06	4,31E-05	2,21E-03	1,27E-02
junction box - HDPE	5,02E-03	3,84E-04	1,71E-05	2,73E-05	1,92E-04	9,07E-06	3,06E-05	8,03E-07	0,00E+00	0,00E+00	1,73E-06	4,31E-06	0,00E+00	1,50E-04
junction box - glass fibre	6,22E-02	4,09E-03	3,38E-03	4,39E-04	1,93E-02	2,09E-04	1,81E-03	2,88E-07	0,00E+00	0,00E+00	4,03E-06	5,06E-04	2,94E-03	1,96E-01
Auxilaries	1,09E+00	1,18E-03	2,26E-03	1,35E-06	3,14E-02	6,01E-05	6,12E-04	2,21E-05	2,46E-05	3,67E-04	3,06E-05	1,15E-04	2,18E-05	5,98E-02
Total	**3,71E+00**	**6,58E-01**	**1,91E+00**	**1,66E-02**	**4,02E+00**	**4,07E-02**	**2,17E-01**	**4,64E-02**	**1,29E-02**	**9,58E-02**	**7,31E-02**	**8,82E-02**	**7,21E-02**	**2,68E+01**

Table 143. Relative results for lead-free metalisation and solder paste (in percentages)

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	2%	76%	97%	95%	87%	78%	69%	97%	75%	89%	39%	85%	66%	90%
interconnection - Tin	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%
interconnection - Lead	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
interconnection - Copper	1%	0%	0%	0%	0%	0%	3%	0%	1%	1%	0%	0%	3%	0%
encapsulation - ethylvinylacetate	5%	3%	1%	0%	1%	1%	1%	1%	1%	1%	0%	1%	0%	2%
backsheet - PVF	1%	1%	0%	0%	1%	1%	1%	0%	1%	1%	0%	1%	0%	1%
backsheet - PET	2%	1%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%
pottant & sealing	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
alu frame	12%	13%	0%	0%	4%	11%	14%	0%	17%	2%	59%	9%	22%	0%
solar glass	45%	4%	1%	0%	6%	5%	8%	1%	4%	5%	1%	2%	1%	6%
junction box - diode	0%	1%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	3%	0%
junction box - HDPE	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
junction box - glass fibre	2%	1%	1%	3%	0%	1%	1%	0%	0%	0%	0%	1%	4%	1%
Auxilaries	29%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%

6.3.1.2.3 BNAT 2025 – with EF lead free solder and lead free metallization

Lead in solder has been changed into copper in the ecoreport tool using the records provided. The metallisation paste as in ecoinvent 3.4 or EF compliant datasets (per m² cell):

Metallization paste, back side| components mixing| production mix, at plant| 67% silver, 25% isopropanol, 8% bismuth {World} [LCI result] [397]	0,004931 kg	EF dataset
Metallization paste, back side, aluminium {GLO}| market for | Cut-off, U	0,07191 kg	Remained from ecoinvent as it did not contain lead
Metallization paste, back side| components mixing| production mix, at plant| 67% silver, 25% isopropanol, 8% bismuth {World} [LCI result] [398]	0,0073964 kg	EF dataset

[397] *Thinkstep AG (2017): LCI datasets for EU Environmental Footprinting (EF) implementation 2017. Metallization paste, front side| components mixing| production mix, at plant| 83% silver, 12% isopropanol, 5% lead, http://lcdn.thinkstep.com/Node, 2017, UUID: 8afeb660-6094-46bc-a9d9-21b49bc63ae3, http://lcdn.thinkstep.com. 2019.*

[398] *Thinkstep AG (2017): LCI datasets for EU Environmental Footprinting (EF) implementation 2017. Metallization paste, back side| components mixing| production mix, at plant| 67% silver, 25% isopropanol, 8% bismuth {World}[LCI result], http://lcdn.thinkstep.com/Node, 2017, UUID: fc503796-57a7-412b-b44e-1143a5f3560b, http://lcdn.thinkstep.com. 2019.*

Table 144. Result for lead-free metallisation and solder paste (in absolute values per kWh)

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	6,09E-02	3,26E-01	1,35E+00	1,35E-02	2,29E+00	2,09E-02	9,97E-02	3,80E-02	6,84E-03	6,34E-02	1,89E-02	4,82E-02	4,07E-02	1,68E+01
interconnection - Tin	2,31E-02	7,40E-03	6,53E-03	7,30E-06	2,91E-02	4,95E-04	1,07E-02	4,54E-04	8,99E-05	5,93E-04	1,32E-04	5,70E-03	5,39E-05	2,18E-01
interconnection - Copper solder	7,15E-04	8,33E-05	0,00E+00	1,73E-07	8,70E-06	4,43E-06	2,09E-04	6,88E-09	2,68E-06	3,93E-05	3,84E-06	2,03E-06	6,72E-05	1,10E-04
interconnection - Copper	1,89E-02	2,20E-03	0,00E+00	4,58E-06	2,30E-04	1,17E-04	5,52E-03	1,82E-07	7,08E-05	1,04E-03	1,02E-04	5,37E-05	1,78E-03	2,92E-03
encapsulation - ethylvinylacetate	1,61E-01	1,50E-02	9,35E-03	5,55E-06	4,24E-02	4,58E-04	1,78E-03	4,00E-04	7,86E-05	1,15E-03	1,24E-04	5,60E-04	5,88E-05	5,38E-01
backsheet - HDPE	6,41E-02	4,91E-03	2,18E-04	3,49E-04	2,46E-03	1,16E-04	3,90E-04	1,03E-05	0,00E+00	0,00E+00	2,20E-05	5,51E-05	0,00E+00	1,91E-03
backsheet - PA	1,04E-02	1,24E-03	1,66E-04	1,97E-04	1,83E-03	8,88E-05	4,05E-04	9,34E-08	0,00E+00	0,00E+00	4,19E-06	5,60E-05	5,09E-04	1,94E-02
backsheet - TiO2	6,94E-03	5,81E-04	1,13E-03	7,41E-07	3,01E-02	3,82E-05	6,16E-04	9,20E-06	1,02E-05	1,21E-04	1,32E-05	3,76E-05	4,16E-04	3,10E-02
pottant & sealing	2,24E-02	1,37E-03	2,65E-03	9,44E-07	6,24E-03	7,35E-05	3,38E-04	4,03E-05	1,73E-05	1,73E-04	2,24E-04	1,13E-04	2,85E-04	3,64E-02
alu frame	3,91E-01	7,53E-02	0,00E+00	0,00E+00	1,41E-01	4,05E-03	2,63E-02	2,58E-05	1,95E-03	1,42E-03	3,78E-02	6,62E-03	1,37E-02	1,94E-03
solar glass	1,15E+00	1,95E-02	9,59E-03	2,07E-05	1,57E-01	1,48E-03	1,22E-02	4,49E-04	3,81E-04	3,20E-03	4,03E-04	1,43E-03	6,57E-04	1,02E+00
junction box - diode	5,16E-04	4,14E-03	0,00E+00	1,22E-04	4,53E-03	2,61E-04	1,44E-03	3,56E-05	2,52E-05	2,30E-04	7,58E-06	3,76E-05	1,93E-03	1,11E-02
junction box - HDPE	4,37E-03	3,35E-04	1,49E-05	2,38E-05	1,68E-04	7,90E-06	2,66E-05	6,99E-07	0,00E+00	0,00E+00	1,50E-06	3,76E-06	0,00E+00	1,30E-04
junction box - glass fibre	5,42E-02	3,57E-03	2,94E-03	3,82E-04	1,69E-02	1,82E-04	1,58E-03	2,51E-07	0,00E+00	0,00E+00	3,51E-06	4,41E-04	2,56E-03	1,71E-01
Auxilaries	9,48E-01	1,03E-03	1,97E-03	1,17E-06	2,73E-02	5,24E-05	5,33E-04	1,92E-05	2,14E-05	3,20E-04	2,66E-05	9,99E-05	1,90E-05	5,21E-02
Total	**2,91E+00**	**4,63E-01**	**1,38E+00**	**1,46E-02**	**2,75E+00**	**2,84E-02**	**1,62E-01**	**3,94E-02**	**9,49E-03**	**7,17E-02**	**5,77E-02**	**6,34E-02**	**6,28E-02**	**1,89E+01**

Table 145. Relative results for lead-free metallisation and solder paste (in percentages)

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	2%	70%	98%	92%	83%	74%	62%	96%	72%	88%	33%	76%	65%	89%
interconnection - Tin	1%	2%	0%	0%	1%	2%	7%	1%	1%	1%	0%	9%	0%	1%
interconnection - Copper solder	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
interconnection - Copper	1%	0%	0%	0%	0%	0%	3%	0%	1%	1%	0%	0%	3%	0%
encapsulation - ethylvinylacetate	6%	3%	1%	0%	2%	2%	1%	1%	1%	2%	0%	1%	0%	3%
backsheet - HDPE	2%	1%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
backsheet - PA	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%
backsheet - TiO2	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	1%	0%
pottant & sealing	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
alu frame	13%	16%	0%	0%	5%	14%	16%	0%	21%	2%	65%	10%	22%	0%
solar glass	39%	4%	1%	0%	6%	5%	8%	1%	4%	4%	1%	2%	1%	5%
junction box - diode	0%	1%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	3%	0%
junction box - HDPE	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
junction box - glass fibre	2%	1%	0%	3%	1%	1%	1%	0%	0%	0%	0%	1%	4%	1%

6.3.2 PV inverters – residential scale

Table 146 shows the relative environmental impacts of the single design options compared to base case PV inverters under real life conditions.

Figure 129 shows the results for the primary impact category 'Primary energy' per kWh for the defined inverters at residential scale.

Table 147 shows the relative figures of the total primary energy of the base case (=100%) and the single design options.

6.3.3 PV inverters – commercial scale

Table 148 shows the relative environmental impacts of the single design options compared to base case PV inverters under real life conditions.

Figure 130 shows the results for the primary impact category 'Primary energy' per kWh for the defined inverters at commercial scale.

Table 146. Life cycle impacts of inverter design options with respect to the base case (inverters, residential scale)

Indicators (from ecoreport)	Base Case REF	Efficient	Longer life	Repair	Monitor.	MLI	Storage -worst	Storage - best
Total Energy (GER)	100%	98%	39%	46%	97%	92%	120%	120%
Water	100%	98%	39%	38%	97%	92%	120%	120%
Waste, non-haz./ landfill	100%	98%	39%	51%	97%	92%	120%	120%
Waste, hazardous/ incinerated	100%	98%	39%	47%	97%	92%	120%	120%
Greenhouse Gases in GWP100	100%	98%	39%	46%	97%	92%	120%	120%
Acidification, emissions	100%	98%	39%	46%	97%	92%	120%	120%
Volatile Organic Compounds (VOC)	100%	98%	39%	54%	97%	92%	120%	120%
Persistent Organic Pollutants (POP)	100%	98%	39%	38%	97%	92%	120%	120%
Heavy Metals to air	100%	98%	39%	54%	97%	92%	120%	120%
PAHs	100%	98%	39%	45%	97%	92%	120%	120%
Particulate Matter (PM, dust)	100%	98%	39%	52%	97%	92%	120%	120%
Heavy Metals to water	100%	98%	39%	42%	97%	92%	120%	120%
Eutrophication	100%	98%	39%	50%	97%	92%	120%	120%

Figure 129. Primary energy results per kWh produced from inverters at residential scale

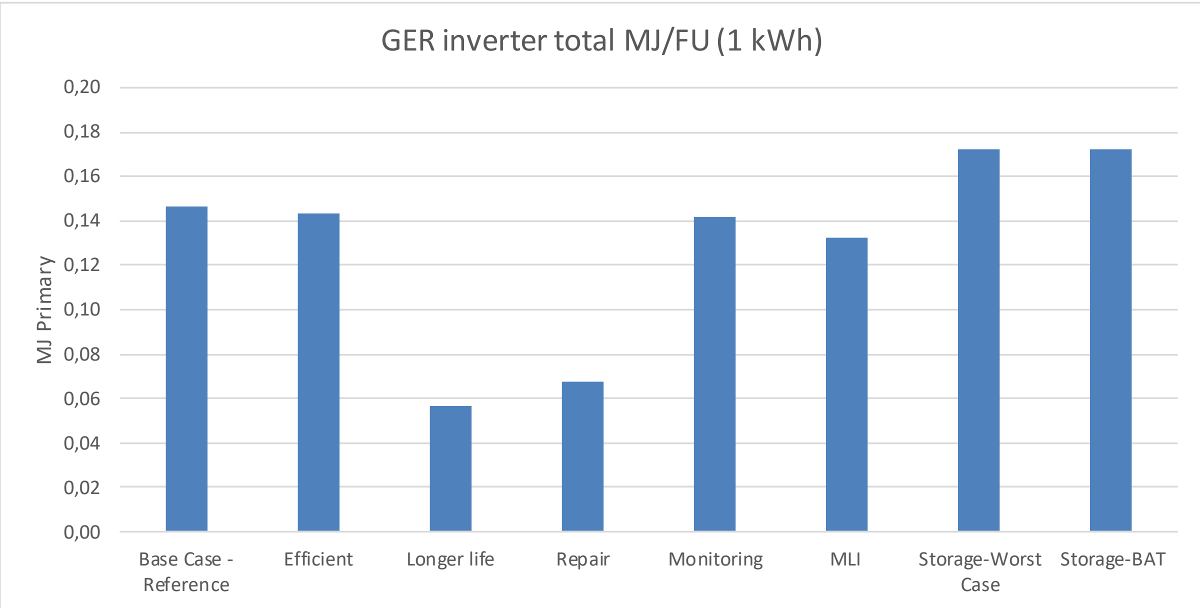


Table 147. Ranking of selected improvement options for inverters based on selected environmental indicators (inverters, residential scale)

Option	Total Energy (primary energy)
Longer life	39%
Repair	46%
MLI (microinverter)	92%
Monitoring	97%
Efficient	98%
Base Case - Reference	100%
Storage - BAT	120%
Storage – worst case	120%

Table 148. Life cycle impacts of inverter design options with respect to the base case (inverters, commercial scale)

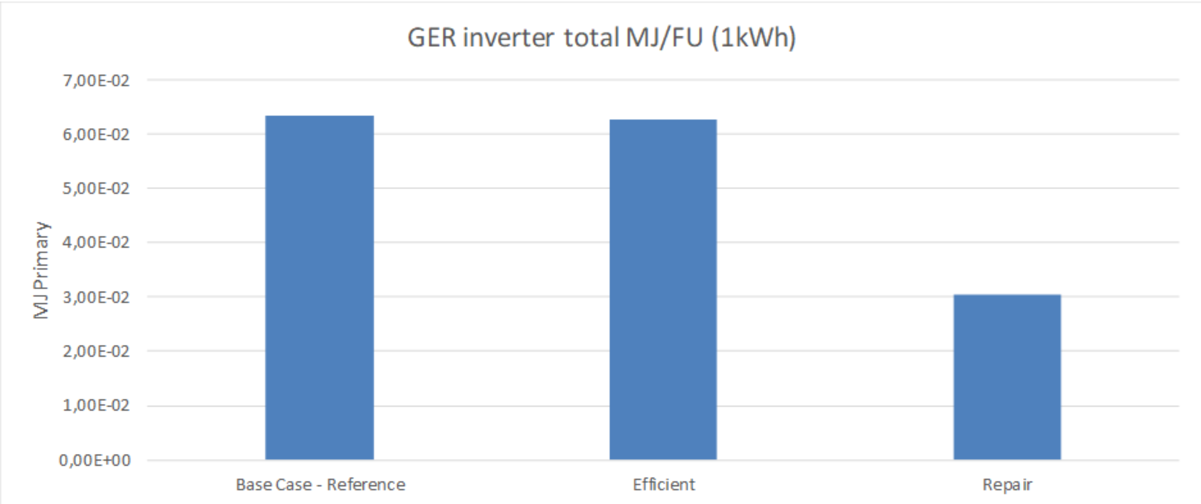
Indicator	Reference	Efficient	Repair
Total Energy (GER)	100%	99%	48%
Water	100%	99%	36%
Waste, non-haz./ landfill	100%	99%	50%
Waste, hazardous/ incinerated	100%	99%	47%
Greenhouse Gases in GWP100	100%	99%	48%
Acidification, emissions	100%	99%	46%
Volatile Organic Compounds (VOC)	100%	99%	55%
Persistent Organic Pollutants (POP)	100%	99%	38%
Heavy Metals to air	100%	99%	53%
PAHs	100%	99%	44%
Particulate Matter (PM, dust)	100%	99%	52%
Heavy Metals to water	100%	99%	43%
Eutrophication	100%	99%	53%

Table 149 shows the relative figures of the total energy of the base case (=100%) and the single design options.

Table 149. Ranking of selected improvement options for inverters based on selected environmental indicators (inverters, commercial scale)

Option	Total Energy (primary energy)
Repair	48%
Efficient	99%
Base Case - Reference	100%

Figure 130. Primary energy results per kWh inverters commercial scale



6.3.4 PV inverters – Utility scale

Table 150 shows the relative environmental impacts of the single design options compared to base case PV inverters under real life conditions.

Figure 131 shows the results for the primary impact category 'Primary energy' per kWh for the defined inverters at utility scale.

Table 151 shows the relative figures of the total primary energy of the base case (=100%) and the single design options.

Table 150. Life cycle impacts of inverter design options with respect to the base case (inverters, utility scale)

Indicator	Reference	Efficient	Efficient + string
Total Energy (GER)	100%	99%	98%
Water	100%	99%	98%
Waste, non-haz./ landfill	100%	99%	98%
Waste, hazardous/ incinerated	100%	99%	98%
Greenhouse Gases in GWP100	100%	99%	98%
Acidification, emissions	100%	99%	98%
Volatile Organic Compounds (VOC)	100%	99%	98%
Persistent Organic Pollutants (POP)	100%	99%	98%
Heavy Metals to air	100%	99%	98%
PAHs	100%	99%	98%
Particulate Matter (PM, dust)	100%	99%	98%
Heavy Metals to water	100%	99%	98%
Eutrophication	100%	99%	98%

Figure 131. Primary energy results per kWh produced from inverters utility scale

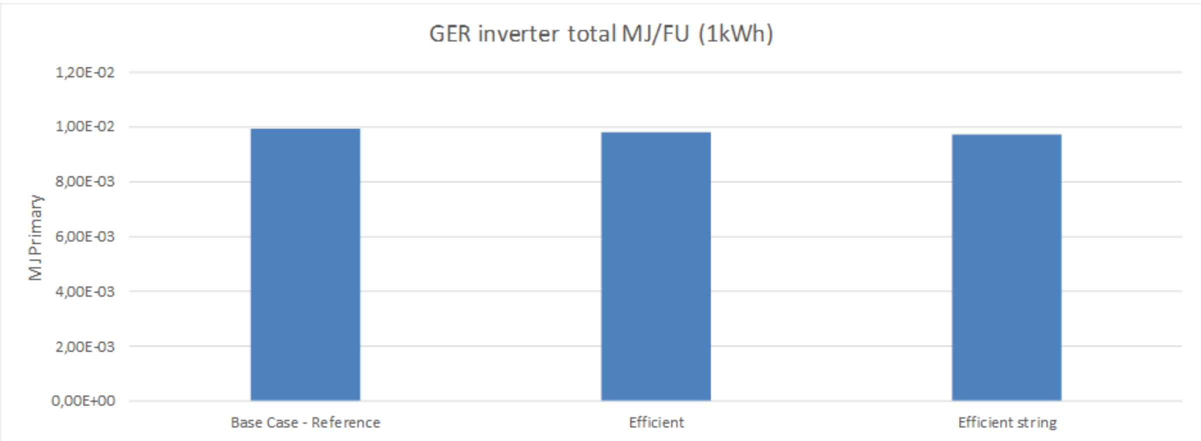


Table 151. Ranking of selected improvement options for inverters based on selected environmental indicators (inverters, utility scale)

Option	Total Energy (primary energy)
Efficient +string	98%
Efficient	99%
Base Case - Reference	100%

6.3.5 PV Systems

In this section the results for systems composed of different module and inverter combinations, together with the Balance of System (BOS) are compiled. In each case the results are presented in both absolute and normalised forms.

6.3.5.1 BC 1 residential scale

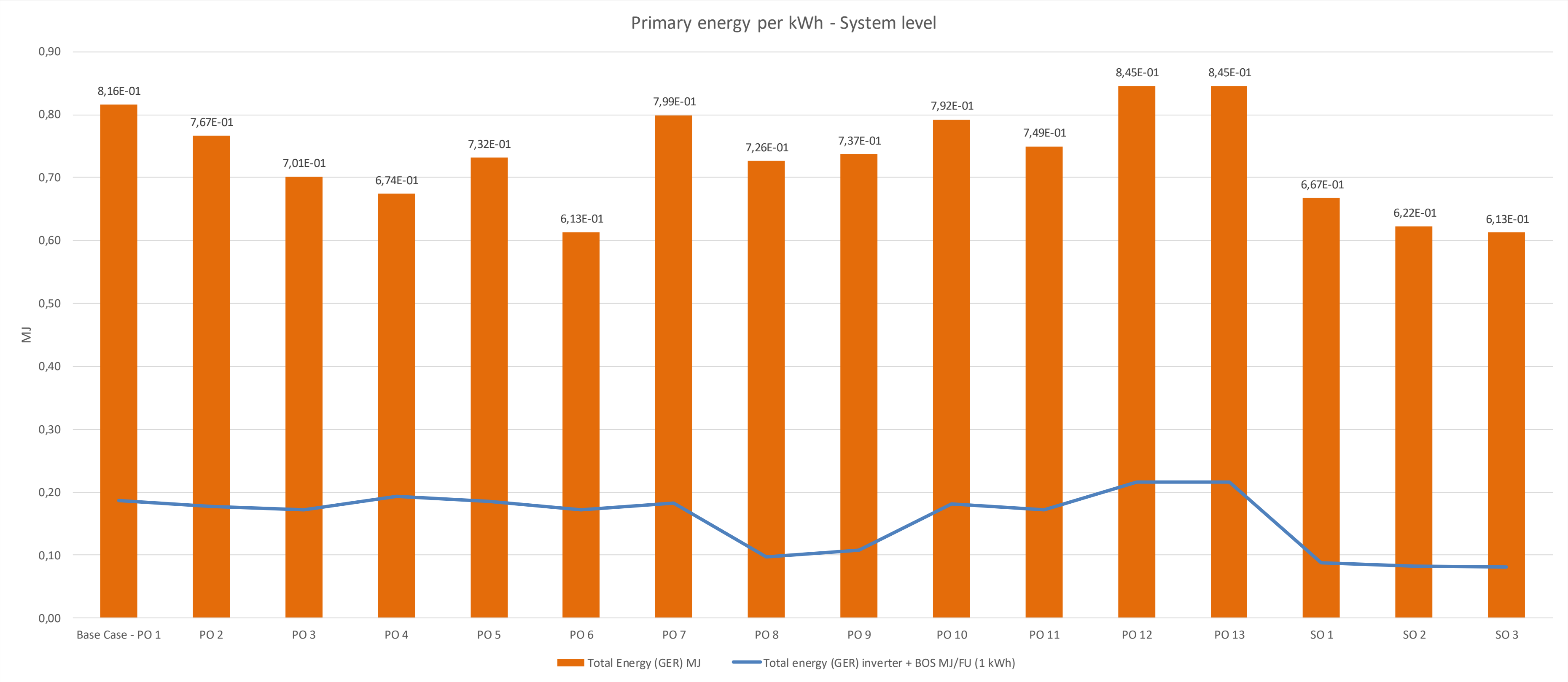
To define the design options, a combination has been made of the reference inverter with the different module options and of the reference module with the different design options for the inverter (package options). In addition, optimised systems making use of the best module and best inverter have been considered as a system option. The best module available for use in a residential scale situation is either the CIGS option or the BAT PERC 2025 module (a hypothetical case). The different options, called package options and system options are discussed in more detail in paragraph 6.2.3.1.

The best inverter combines the benefits of the inverter with a longer life span and the inverter with monitoring functions. In a final design option, the best module and inverter are combined with an optimised design.

Figure 132 shows the results (primary energy) for the defined systems in absolute terms (the orange bars) and as normalised to the functional unit of 1 kWh electricity (the blue line). The optimised systems are the best performing systems, together with the system combining the BAT PERC 2025 module and reference inverter (PO 6).

Table 152 shows from the Ecoreport LCA tool the relative environmental impacts of the design options for the residential scale compared to the base case at residential scale.

Figure 132. Primary energy at system level for different design options at residential scale



(PO 1): Multi Si module and reference inverter, (PO2): Optimised PERC 2020 module and reference inverter; (PO 3): BAT PERC 2019 module and reference inverter; (PO 4): CIGS module and reference inverter; (PO 5): Silicion heterojunction module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): Multi Si module and more efficient inverter; (PO 8): Multi Si module and longer life inverter; (PO 9): Multi Si Module and inverter with repair; (PO 10): Multi Si module and inverter including monitoring; (PO 11): Multi Si module and multi-level inverter; (PO 12): Multi Si module and inverter including storage (worst case); (PO 13): Multi Si module and inverter including storage (best case).

(SO 1): Optimised PERC 2020 + best inverter; (SO 2): Optimised PERC 2020+ best inverter + better design; (SO 3): Optimised PERC 2020+ best inverter + optimised O&M

Table 152. Life cycle impacts of residential package or system options with respect to the base case

Indicators (from Ecoreport)	Base case – PO1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	PO 10	PO 11	PO 12	PO 13	SO 1	SO 2	SO 3
Total Energy (GER)	100%	94%	86%	83%	90%	75%	98%	89%	90%	97%	92%	104%	104%	82%	76%	75%
Water	100%	117%	109%	58%	82%	137%	98%	74%	74%	97%	92%	108%	108%	90%	84%	83%
Waste, non-haz./ landfill	100%	112%	102%	41%	108%	85%	98%	90%	92%	97%	92%	103%	103%	100%	94%	92%
Waste, hazardous/ incinerated	100%	61%	57%	45%	63%	57%	98%	78%	81%	97%	92%	107%	107%	38%	36%	35%
Greenhouse Gases in GWP100	100%	96%	88%	82%	92%	77%	98%	89%	90%	97%	92%	104%	104%	84%	78%	77%
Acidification, emissions	100%	94%	86%	77%	94%	80%	98%	88%	90%	97%	92%	104%	104%	81%	76%	74%
Volatile Organic Compounds (VOC)	100%	84%	75%	19%	86%	71%	98%	96%	97%	97%	92%	101%	101%	79%	74%	73%
Persistent Organic Pollutants (POP)	100%	95%	88%	68%	102%	78%	98%	78%	78%	97%	92%	107%	107%	73%	68%	67%
Heavy Metals to air	100%	93%	87%	62%	108%	88%	98%	78%	83%	97%	92%	107%	107%	70%	65%	64%
PAHs	100%	81%	73%	69%	80%	65%	98%	96%	96%	97%	92%	101%	101%	75%	70%	69%
Particulate Matter (PM, dust)	100%	89%	80%	82%	88%	74%	98%	97%	98%	97%	92%	101%	101%	85%	80%	78%
Heavy Metals to water	100%	88%	81%	51%	109%	70%	98%	81%	82%	97%	92%	106%	106%	68%	63%	62%
Eutrophication	100%	102%	93%	53%	119%	70%	98%	93%	94%	97%	92%	102%	102%	93%	87%	85%

(PO 1): Multi Si module and reference inverter, (PO2): Optimised PERC 2020 module and reference inverter; (PO 3): BAT PERC 2019 module and reference inverter; (PO 4): CIGS module and reference inverter; (PO 5): Silicion heterojunction module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): Multi Si module and more efficient inverter; (PO 8): Multi Si module and longer life inverter; (PO 9): Multi Si Module and inverter with repair; (PO 10): Multi Si module and inverter including monitoring; (PO 11): Multi Si module and multi-level inverter; (PO 12): Multi Si module and inverter including storage (worst case); (PO 13): Multi Si module and inverter including storage (best case).

(SO 1): Optimised PERC 2020 + best inverter; (SO 2): Optimised PERC 2020+ best inverter + better design; (SO 3): Optimised PERC 2020+ best inverter + optimised O&M

6.3.5.2 BC 2 commercial scale

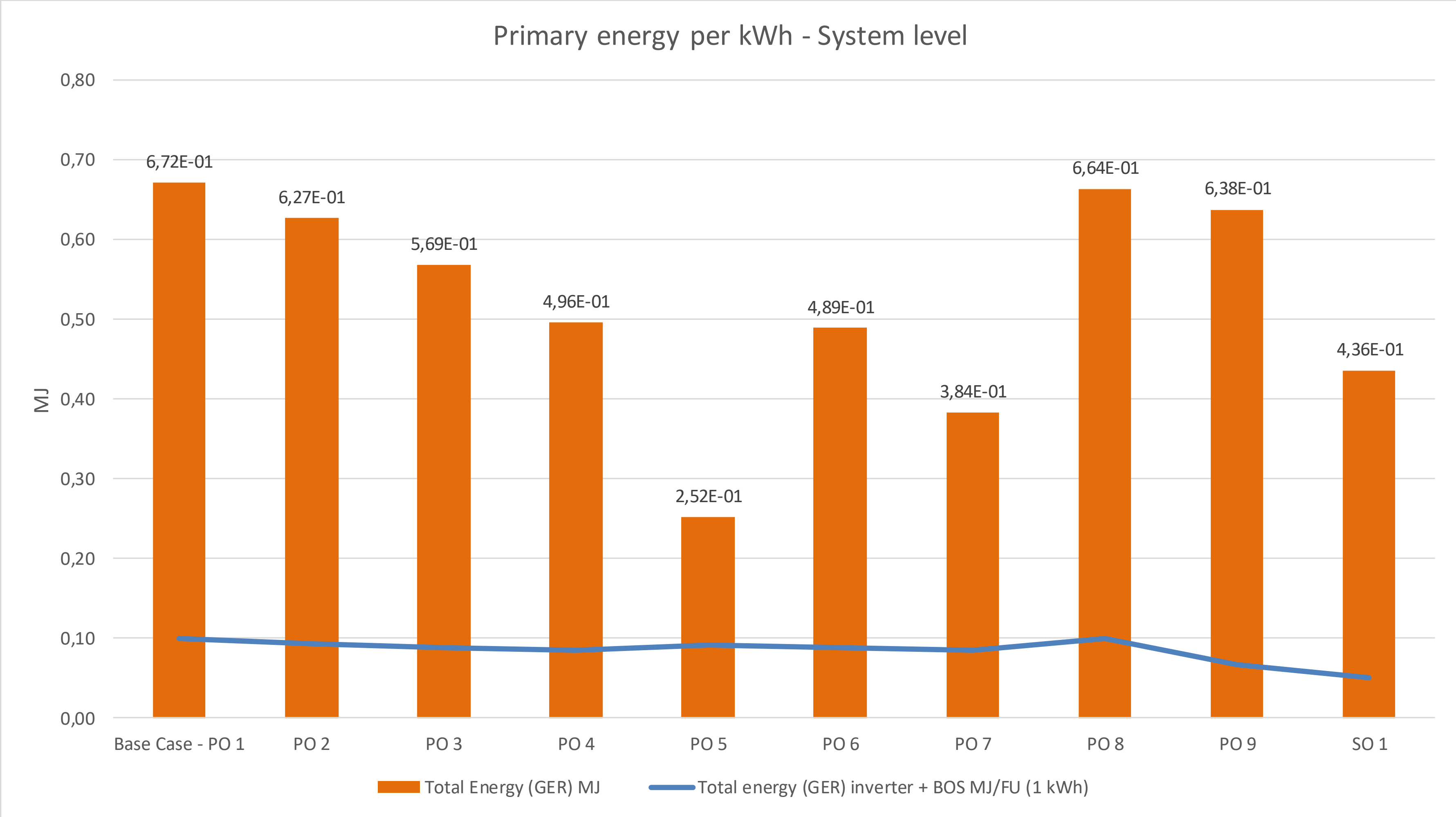
Again, the considered design options are a combination of the reference inverter with the different module options and of the reference module with the different design options for the inverter. In addition, an optimised system has been defined which consist of a PERC bifacial module and the benefits of an inverter with improved repair and high efficiency. The derating factors in this system design are higher due to lower cable losses and a tailored design.

Figure 133 shows the results (primary energy) for the different systems in absolute terms (the orange bars) and as normalised to the functional unit of 1 kWh electricity (the blue line). The system with the lowest contribution to primary energy is a system combining a CdTe module with a reference inverter (PO 5). The optimised system, using a bifacial PERC 2019 module and an optimised inverter has the third lowest contribution.

As an indication, the system combining the BNAT PERC bifacial 2025 + recycled wafers module with the reference inverter has the second lowest contribution. In the modelling of this system a first attempt has been made to take the potential for the recycling of wafers into account. Further investigation of the environmental impact of this system is however necessary before taking any further conclusions.

Table 153 shows from the Ecoreport LCA tool the relative environmental impacts of the design options for the commercial scale compared to the base case at residential scale.

Figure 133. Primary energy at system level for different design options at commercial scale



(SO 1): best combination and design; (PO 1): Multi Si module and reference inverter; (PO 2): Optimised PERC 2020 module and reference inverter; (PO 3):BAT PERC 2019 module and reference inverter; (PO 4):BAT PERC bifacial 2019 module and reference inverter; (PO 5): CdTe module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter; (PO 8):Multi Si module and more efficient inverter; (PO 9): Multi Si module and inverter with repair

Table 153. Life cycle impacts of commercial package or system options with respect to the base case

Indicators (from Ecoreport)	Base case – PO1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
Total Energy (GER)	100%	93%	85%	74%	38%	73%	57%	99%	95%	65%
Water	100%	122%	112%	100%	34%	147%	86%	99%	83%	78%
Waste, non-haz./ landfill	100%	113%	103%	90%	23%	84%	63%	99%	95%	81%
Waste, hazardous/ incinerated	100%	53%	49%	45%	27%	49%	35%	99%	88%	32%
Greenhouse Gases in GWP100	100%	96%	87%	76%	37%	74%	59%	99%	95%	67%
Acidification, emissions	100%	93%	85%	75%	44%	78%	61%	99%	94%	65%
Volatile Organic Compounds (VOC)	100%	84%	75%	65%	10%	71%	61%	99%	98%	60%
Persistent Organic Pollutants (POP)	100%	94%	86%	78%	37%	74%	63%	99%	87%	61%
Heavy Metals to air	100%	92%	84%	76%	41%	86%	61%	99%	90%	62%
PAHs	100%	80%	72%	63%	9%	64%	51%	99%	98%	57%
Particulate Matter (PM, dust)	100%	89%	79%	69%	61%	74%	62%	99%	99%	64%
Heavy Metals to water	100%	86%	78%	70%	22%	65%	57%	99%	89%	56%
Eutrophication	100%	102%	92%	81%	18%	68%	61%	99%	97%	73%

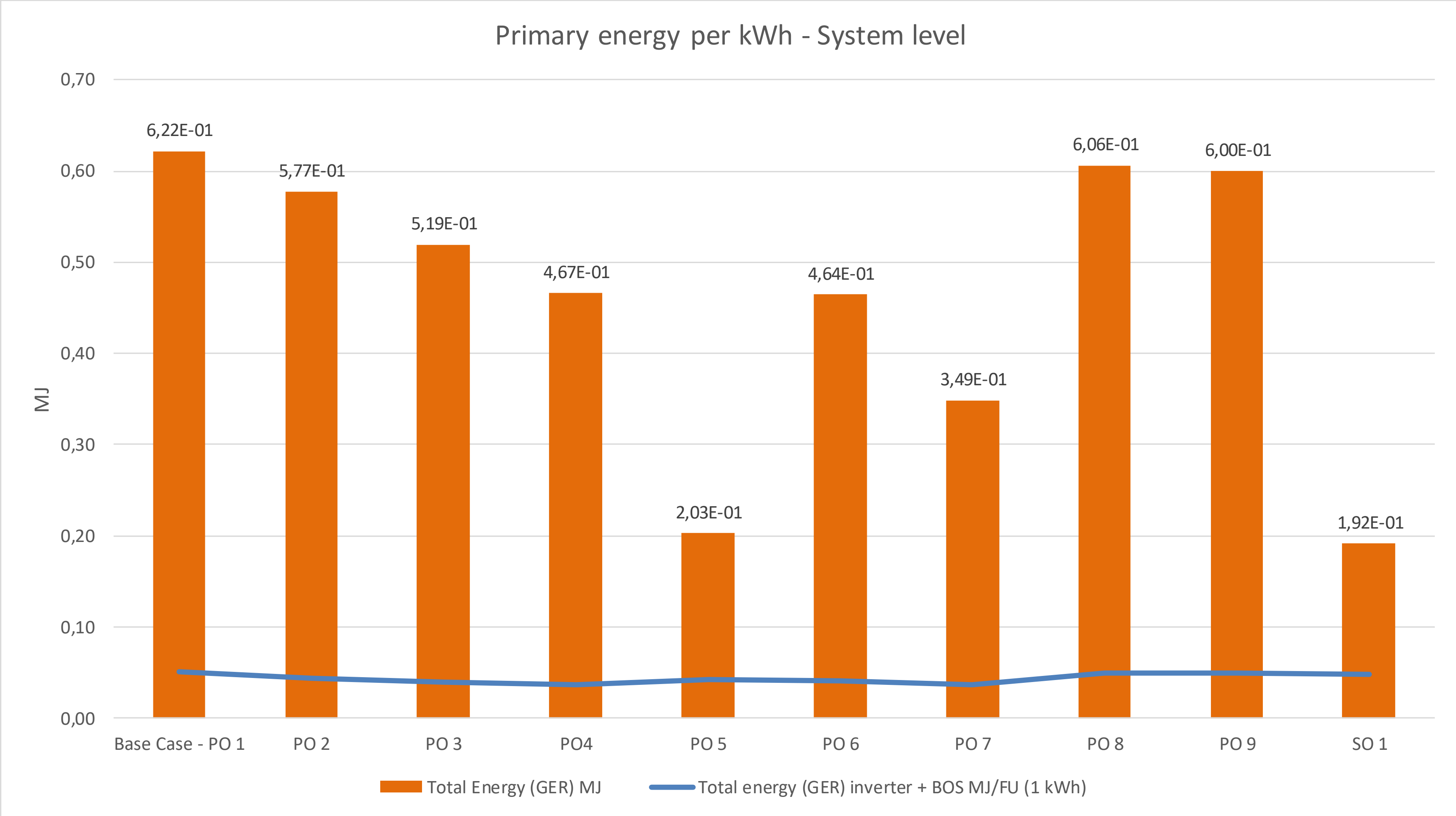
SO 1): best combination and design; (PO 1): Multi Si module and reference inverter; (PO 2): Optimised PERC 2020 module and reference inverter; (PO 3):BAT PERC 2019 module and reference inverter; (PO 4):BAT PERC bifacial 2019 module and reference inverter; (PO 5): CdTe module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter; (PO 8):Multi Si module and more efficient inverter; (PO 9): Multi Si module and inverter with repair

6.3.5.3 BC 3 Utility scale

Also, at utility scale the considered design options are a combination of the reference (central) inverter with the different module options and of the reference module with the different design options for the inverter. In addition, an optimised system has been defined which consists of a CdTe module and an energy efficient inverter. The system makes use of single axis tracking.

Figure 134 shows the results (primary energy) for the different systems in absolute terms (the orange bars) and as normalised to the functional unit of 1 kWh electricity (the blue line). The system with the lowest contribution to primary energy is the optimised system combining a CdTe module with an efficient string inverter and tracking (SO 1). The option combining the CdTe module and reference inverter (PO 5) has the second lowest contribution to primary energy. Table **154** shows from the Ecoreport LCA tool the relative environmental impacts of the design options for utility scale compared to the base case at residential scale.

Figure 134. Primary energy at system level for different design options at utility scale



(SO 1): best combination and design including single axis tracker; (PO 1): Multi Si module and reference inverter and reference BOS; (PO 2): Optimised PERC 2020 module and reference inverter and reference BOS; (PO 3): BAT PERC 2019 module and reference inverter and reference BOS; (PO 4): BAT PERC bifacial 2019 module and reference inverter and reference BOS; (PO 5): CdTe module and reference inverter and reference BOS; (PO6): BAT PERC 2025 module and reference inverter and reference BOS; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter and reference BOS; (PO 8): Multi Si module and more efficient inverter and reference BOS; (PO 9): Multi Si module and more efficient string inverter and reference BOS

Table 154. Life cycle impacts of utility scale package or system options with respect to the base case

Indicators (from Ecoreport)	Base case – PO1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
Total Energy (GER)	100%	93%	84%	75%	33%	75%	56%	98%	97%	31%
Water	100%	122%	112%	104%	33%	155%	89%	98%	97%	31%
Waste, non-haz./ landfill	100%	114%	103%	94%	18%	87%	64%	97%	96%	22%
Waste, hazardous/ incinerated	100%	39%	34%	31%	6%	36%	18%	97%	96%	6%
Greenhouse Gases in GWP100	100%	96%	86%	78%	32%	76%	58%	98%	97%	30%
Acidification, emissions	100%	91%	82%	74%	45%	79%	61%	98%	97%	43%
Volatile Organic Compounds (VOC)	100%	84%	74%	68%	9%	74%	64%	97%	96%	9%
Persistent Organic Pollutants (POP)	100%	93%	85%	78%	32%	75%	62%	98%	97%	49%
Heavy Metals to air	100%	90%	80%	73%	33%	87%	56%	98%	97%	35%
PAHs	100%	79%	71%	64%	7%	67%	52%	97%	96%	8%
Particulate Matter (PM, dust)	100%	89%	79%	72%	61%	78%	64%	97%	96%	56%
Heavy Metals to water	100%	83%	74%	67%	6%	62%	50%	97%	96%	8%
Eutrophication	100%	102%	92%	84%	14%	70%	61%	97%	96%	13%

(SO 1): best combination and design including single axis tracker; (PO 1): Multi Si module and reference inverter and reference BOS; (PO 2): Optimised PERC 2020 module and reference inverter and reference BOS; (PO 3): BAT PERC 2019 module and reference inverter and reference BOS; (PO 4): BAT PERC bifacial 2019 module and reference inverter and reference BOS; (PO 5): CdTe module and reference inverter and reference BOS; (PO6): BAT PERC 2025 module and reference inverter and reference BOS; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter and reference BOS; (PO 8): Multi Si module and more efficient inverter and reference BOS; (PO 9): Multi Si module and more efficient string inverter and reference BOS

6.4 Analysis of BAT and LLCC

The design options identified in the technical, environmental and economic analysis in subtask 6.1 must be ranked regarding the Best Available Technology (BAT) and the Least (minimum) Life Cycle Costs. More specifically, this section includes:

- Ranking of the identified design options by LCC (e.g. option 1, option 2, option 3), considering possible trade-offs between different environmental impacts;
- Estimating the cumulative improvement and cost effect of implementing the ranked options simultaneously (e.g. option 1, option 1+2, option 1+2+3, etc.), also taking into account 'rebound' side effects of the individual design measures;
- Ranking of the cumulative design options, drawing of a LCC-curve (Y-axis= LLCC, X-axis= options) and identifying the Least Life Cycle Cost (LLCC) point and the BAT point.

The improvement potential resulting from the ranking is discussed and informs further discussion in the Task 7 report as to:

- the appropriateness to set minimum requirements at the LLCC point,
- to use the environmental performance of the BAT point or benchmarks set in other countries,
- if manufacturers will make use of this ranking to evaluate alternative design solutions and the achieved environmental performance of the products.

6.4.1 Lead environmental impact category and supplementary parameters

Based on the results of Tasks 4 and 5 and the 14 impact categories that MEErP considers, GWP(CO_2eq) and the related Primary Energy(MJ) could be used as significant parameters that can be optimised.

Primary energy (referred to in Ecoreport as total primary energy) has been chosen as the lead indicator. It excludes the regionalised effects of process energy requirements as far as possible, such as the grid electricity generating mix, as analysed in 6.3.1.1 [399]. It instead ensures a focus on the improvement potential of production processes and material choices.

Other environmental parameters assessed in the MEErP Ecoreport tool are listed below, And can be seen to combine mid-point impact categories and inventory flow indicators:

- Water
- Non hazardous waste
- Hazardous waste
- Acidification
- Volatile Organic Compounds
- Persistent Organic Pollutants
- Heavy Metals
- PAHs (Polycyclic Aromatic Hydrocarbons)
- Particulate Matter

Using a combination of the weightings according to societal costs in the Ecoreport tool and analysis of which impact categories contributions are not strongly linked to electricity generation, the following impact categories could be used as secondary indicators:

Modules:

- PAHs
- Volatile organic compounds
- Heavy metals

[399] Regionalised effects are assumed to be excluded in the materials which are available in the Ecoreport tool. A lot of materials had to be added to the Ecoreport tool to appropriately model the modules and inverters. The environmental impact for those materials was sourced from other databases and includes different types of energy sources and mixes.

Inverters

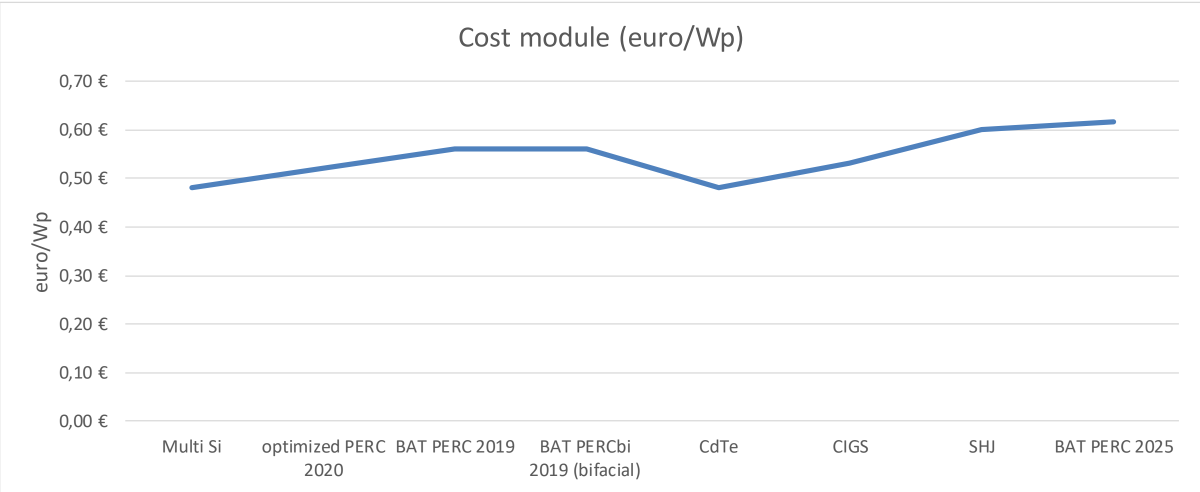
- Photochemical ozone formation
- PAHs
- Heavy metals

6.4.2 LCC of the design options for PV modules

Figure 135 provides the module costs in euro/Wp at residential scale. They represent average costs. To understand the LCOE for different modules the system design option results should be consulted (see 6.4.5). BNAT options have been omitted because of a lack of certainty on their costs.

These costs, particularly for mass market modules such as PERC 2019, can be expected to shift rapidly, with downward pressure from the demand side, for example from capacity auctions, and as further planned economies of scale are implemented from the supply side. For example, the Mono PERC spot price range is, as of later 2019 quoted within a range of 0.19 – 0.35 €/Wp. Some market commentators also segment costs into categories such as high efficiency, mainstream and low cost.

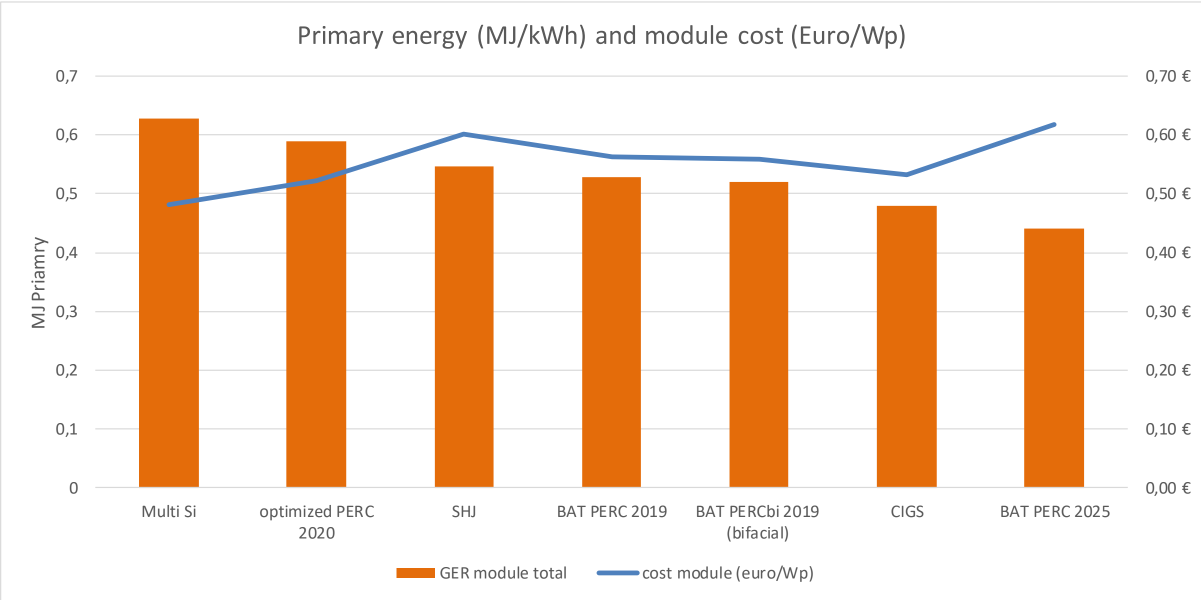
Figure 135. Module costs in euro per Wp



6.4.2.1 Residential scale (BC 1)

The CIGS module is the best (currently) available technology (BAT) from an environmental perspective (when looking at primary energy), taking into account that the 2025 option is a hypothetical case. Although the results may be within the margin of error. The multi Si base case has the lowest cost per Wp. It is to be noted, however, that the CIGS technology has a very low penetration rate in the residential sector (see Task 2). Figure 136 shows the results for the different modules on primary energy (per kWh) and costs (per Wp).

Figure 136. Modules Primary energy (MJ/kWh) and cost (per Wp) at residential scale

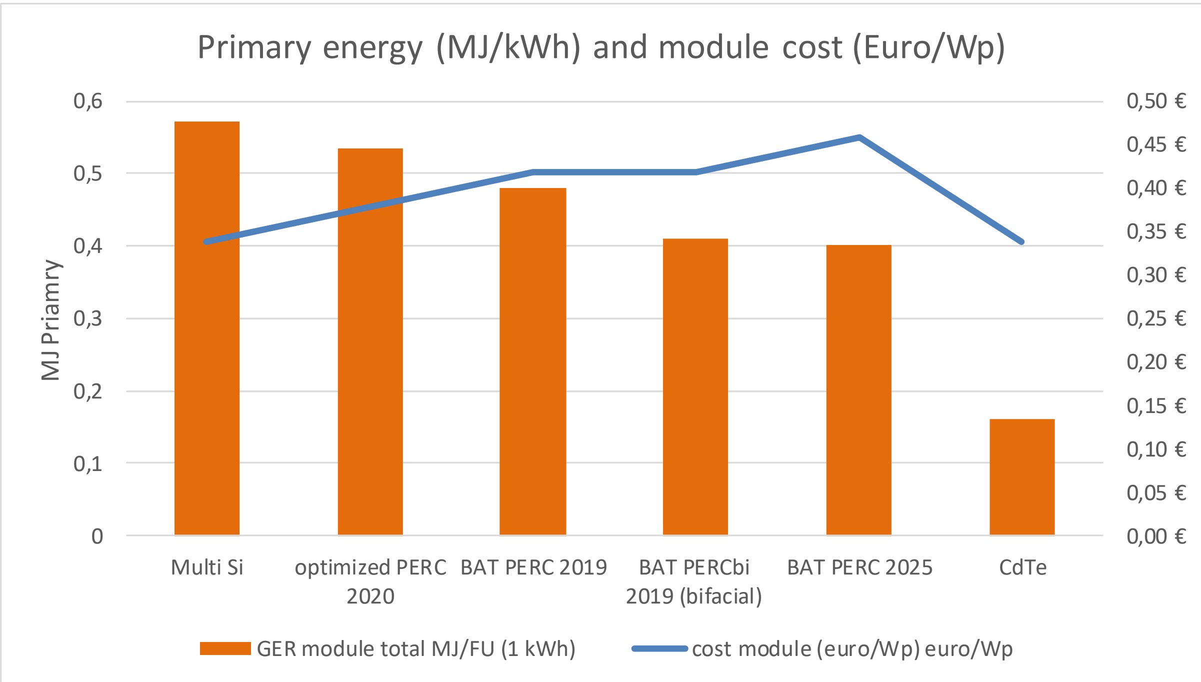


6.4.2.2 Commercial scale (BC 2)

The CdTe module is the best available technology (BAT) from an environmental (when looking at primary energy) and economic point of view (cost per Wp). The multi Si reference module has a comparable cost per Wp to the CdTe module.

Figure 137 shows the results for the different modules on primary energy (per kWh) and costs (per Wp).

Figure 137. Modules Primary energy (MJ/kWh) and cost (per Wp) at commercial scale

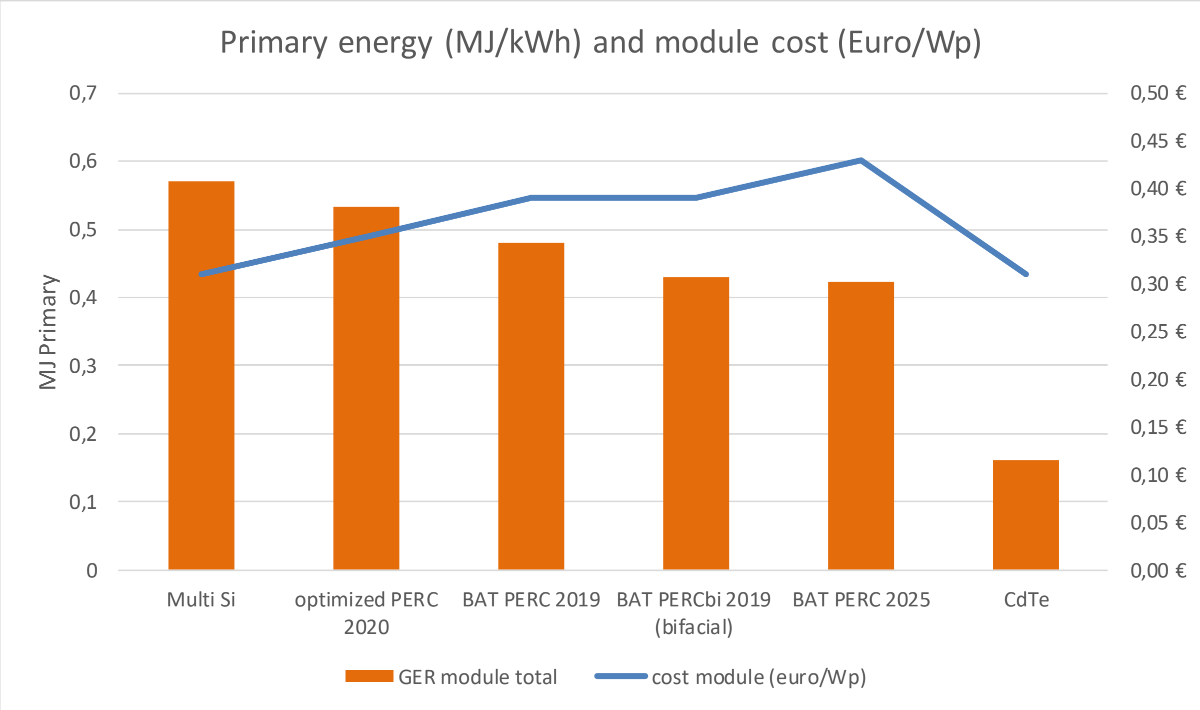


6.4.2.3 Utility scale (BC 3)

The CdTe module is the best available technology (BAT) from an environmental (primary energy) and economic point of view. The multi Si reference module has comparable costs to the CdTe module.

Figure 138 shows the results for the different modules on primary energy (per kWh) and costs (per Wp).

Figure 138. Modules Primary energy (MJ/kWh) and cost (per Wp) at utility scale

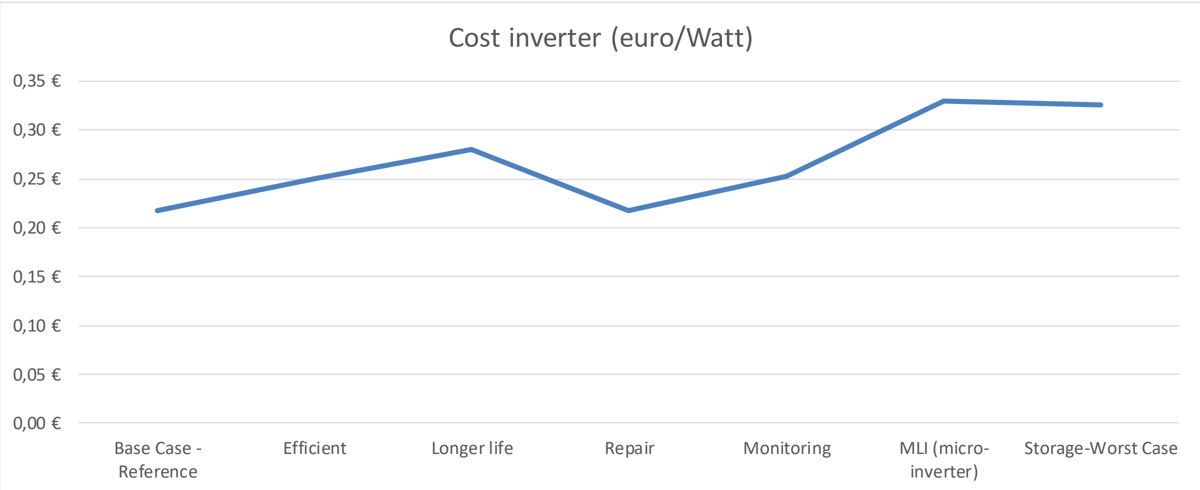


6.4.3 LCC of the design options for the inverters

6.4.3.1 Residential scale (BC 1)

Figure 139 provides the inverter life cycle cost in euro per Watt.

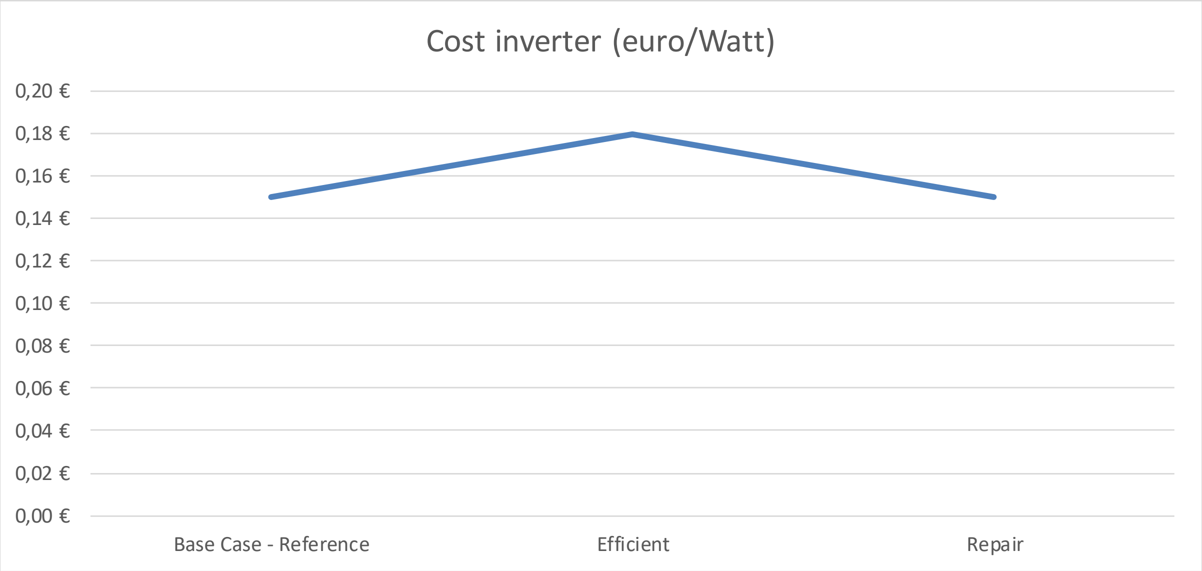
Figure 139. Inverter life cycle cost in Euro per Watt – residential scale



6.4.3.2 Commercial scale (BC 2)

Figure 140 provides the inverter life cycle cost in euro per Watt.

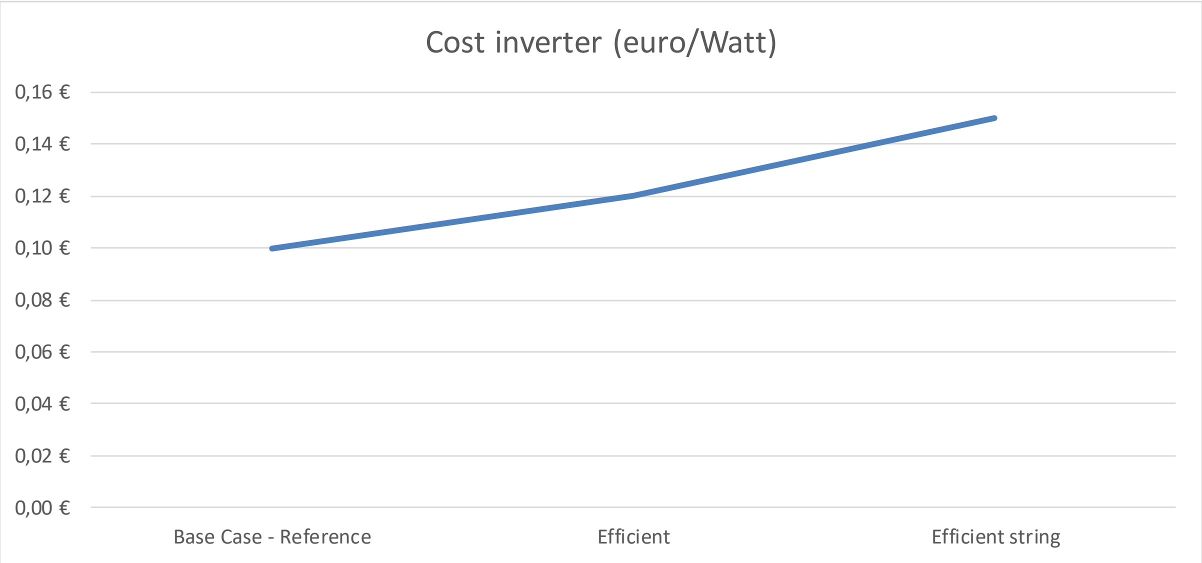
Figure 140. Inverter life cycle cost in Euro per Watt – commercial scale



6.4.3.3 Utility scale (BC 3)

Figure 141 provides the inverter life cycle cost in euro per Watt.

Figure 141. Inverter life cycle cost in Euro per Watt – utility scale



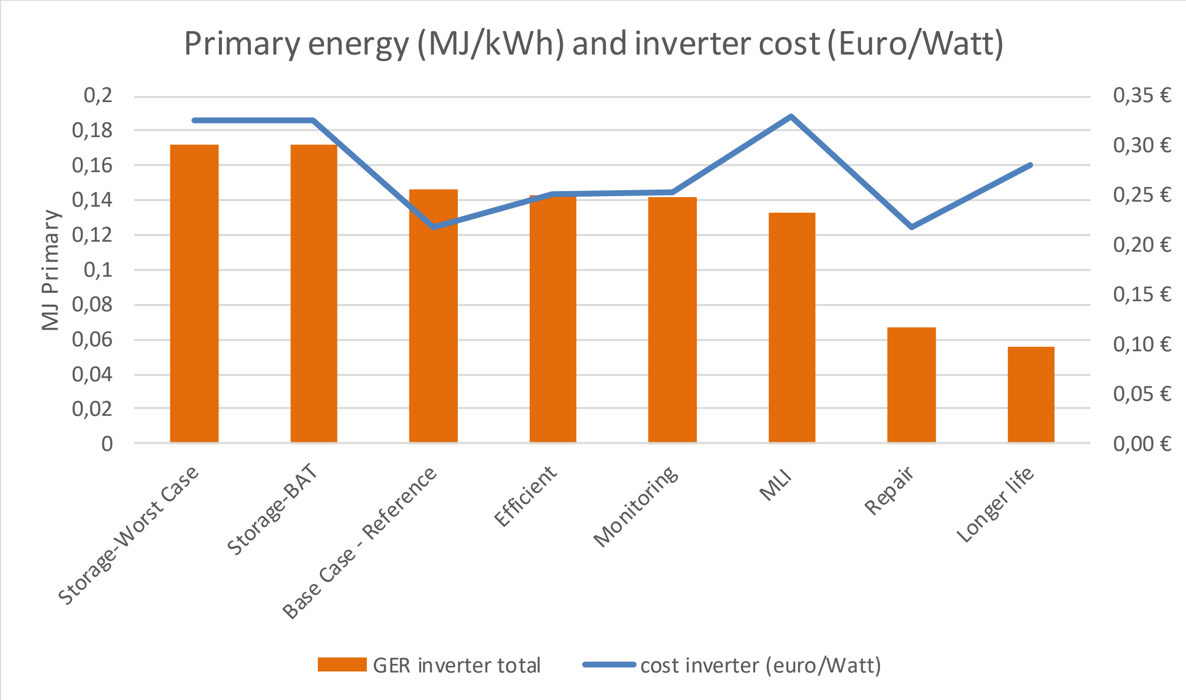
6.4.4 Best available and Least LCC options of inverters

6.4.4.1 Residential scale (BC 1)

The best available technology from an environmental point of view (primary energy only) is the inverter with a longer life span. From an economic point of view, the costs are lower for the reference inverter and repaired inverter. The benefits of the repair option could only be achieved if the ongoing servicing was provided to the household installing the inverter, which it is understood may not always be the case.

Figure 142 shows the results for the different inverters on primary energy (per kWh) and costs (per Watt)

Figure 142. Inverters primary energy and cost – residential scale

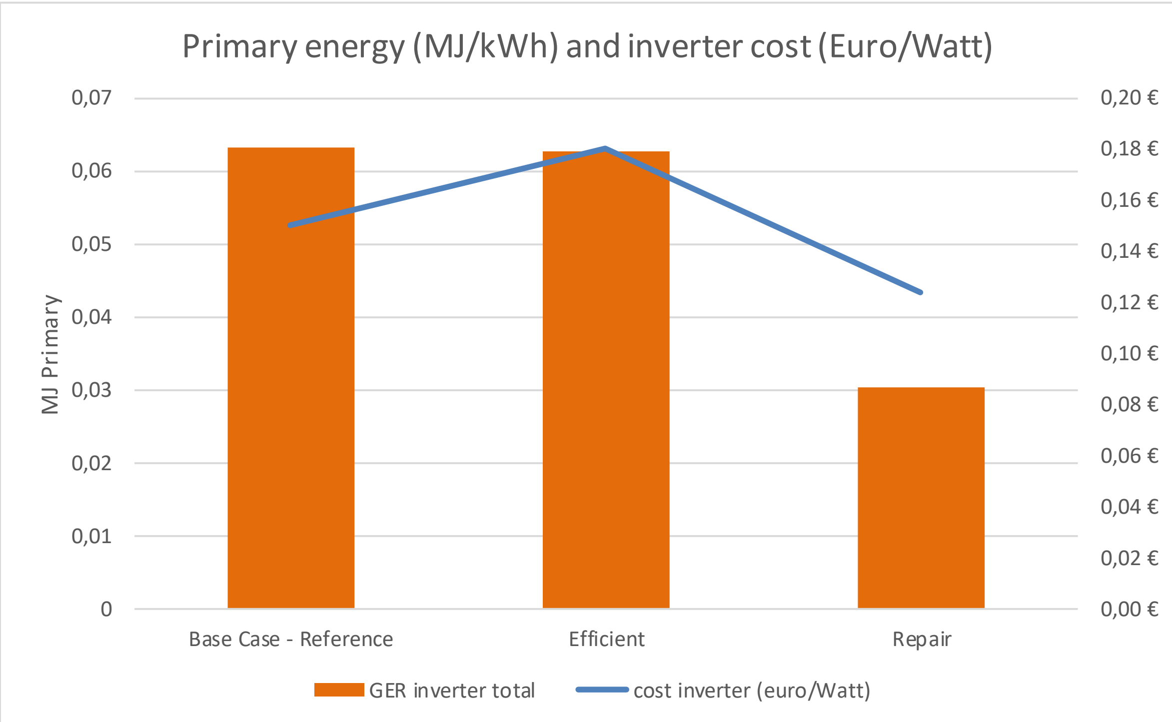


6.4.4.2 Commercial scale (BC 2)

The best available technology from an environmental point of view (primary energy only) is the inverter with repair, also the costs are lowest for this design option.

Figure 143 shows the results for the different inverters on primary energy (per kWh) and costs (per Watt)

Figure 143. Inverters primary energy and cost – commercial scale

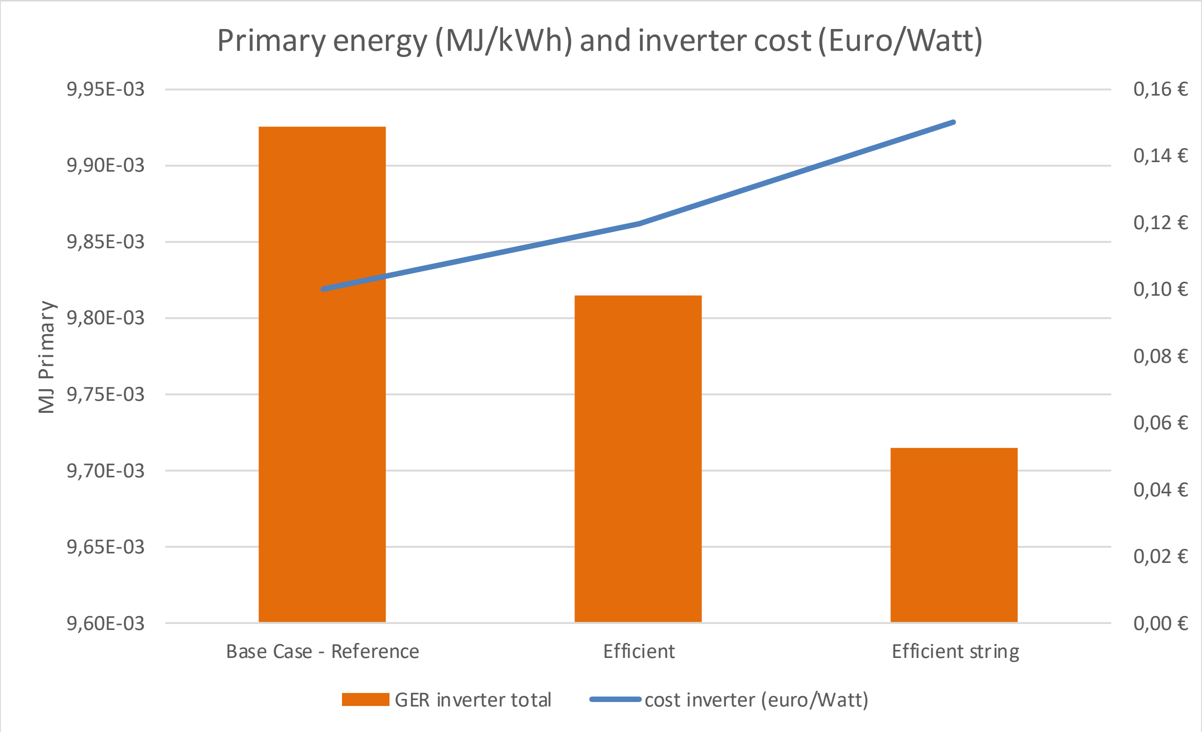


6.4.4.3 Utility scale (BC 3)

The best available technology from an environmental point of view (primary energy only) is the efficient string inverter. However, the difference in primary energy is marginal (note the scale) while the cost is relatively higher. The inverter with the lowest cost per Watt is the reference inverter.

Figure 144 shows the results for the different inverters on primary energy (per kWh) and costs (per Wp)

Figure 144. Inverters primary energy and cost – utility scale



6.4.5 Best available and Least LCC options of PV systems

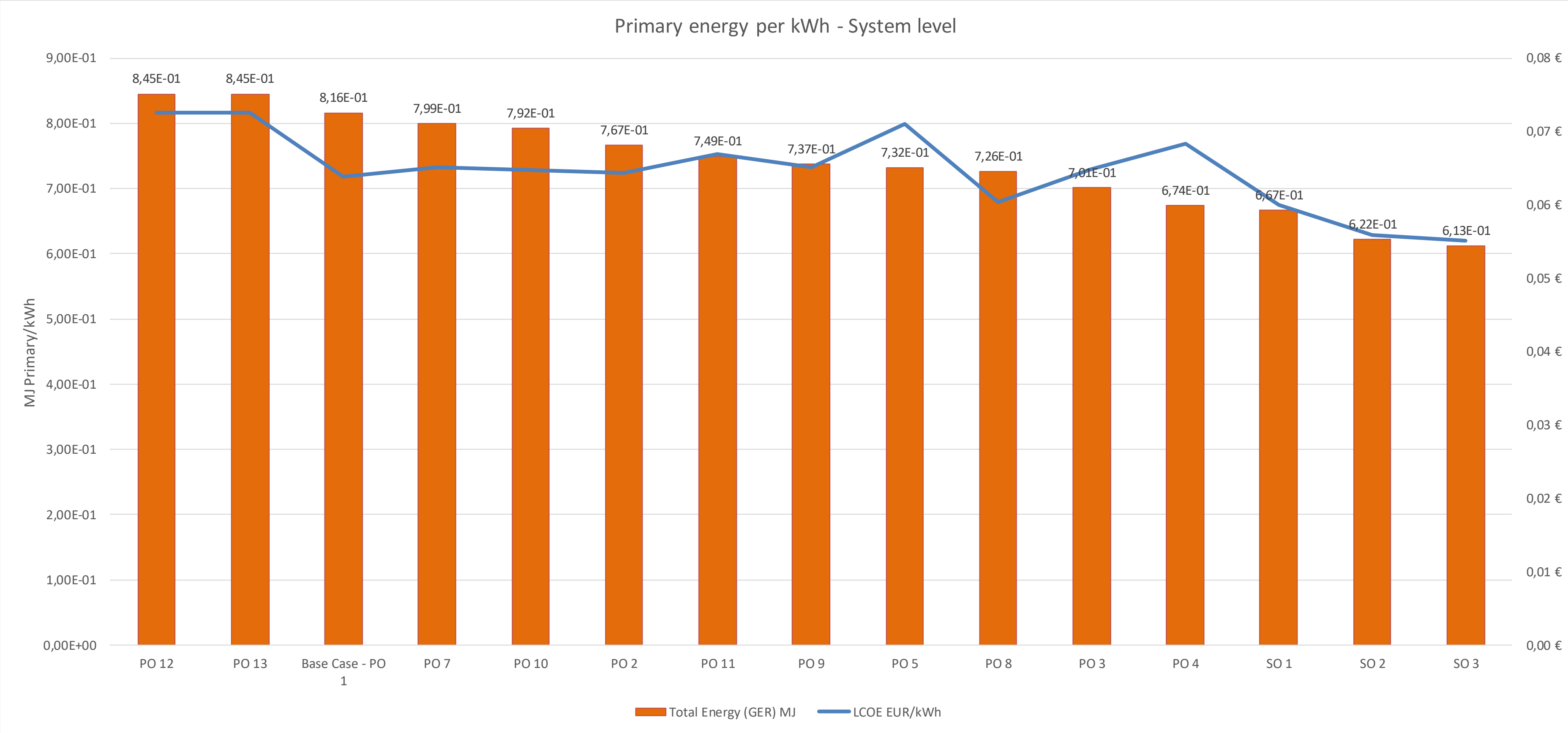
To calculate the life cycle costs at system level the module cost, inverter cost, frame/mounting system cost, cost for cables and connectors, design and installation costs, O&M costs and end-of-life costs (dismantling, scrap value, recycling costs) have been considered. Detailed information is published in Annex C.

6.4.5.1 Residential scale

The best available technology from an environmental point of view (primary energy) and life cycle cost point of view is the Optimised PERC 2020 + best inverter + optimised O&M (SO 3).

Figure 145 shows the primary energy use and LCOE per kWh for the different design options for base case 1, residential scale.

Figure 145. MJ primary energy and LCOE per kWh – residential scale



(PO 1): Multi Si module and reference inverter, (PO2): Optimised PERC 202 module and reference inverter; (PO 3): BAT PERC 2019 module and reference inverter; (PO 4): CIGS module and reference inverter; (PO 5): Silicion heterojunction module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): Multi Si module and more efficient inverter; (PO 8): Multi Si module and longer life inverter; (PO 9): Multi Si Module and inverter with repair; (PO 10): Multi Si module and inverter including monitoring; (PO 11): Multi Si module and multi-level inverter; (PO 12): Multi Si module and inverter including storage (worst case); (PO 13): Multi Si module and inverter including storage (best case).

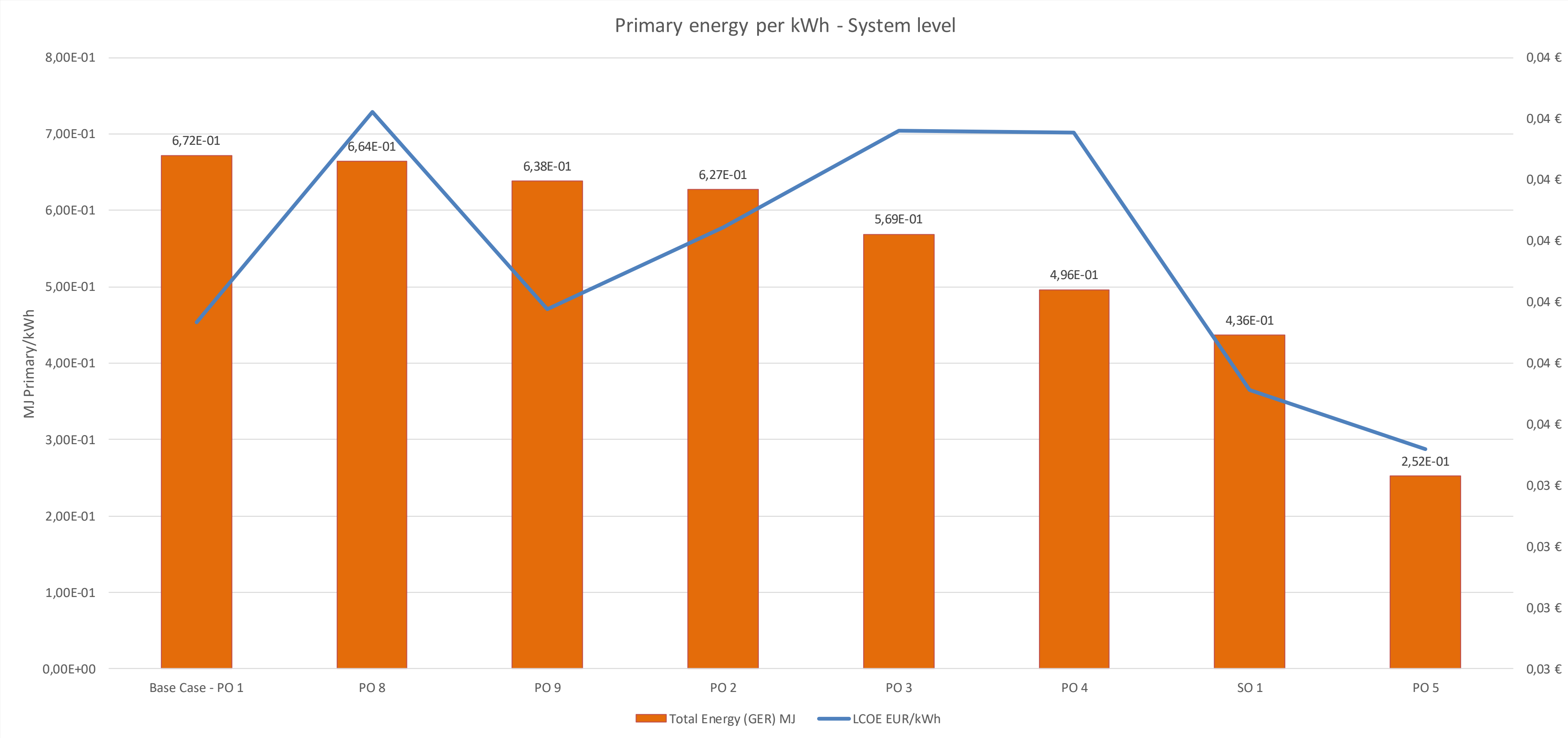
(SO 1): Optimised PERC 2020 + best inverter; (SO 2): Optimised PERC 2020+ best inverter + better design; (SO 3): Optimised PERC 2020+ best inverter + optimised O&M

6.4.5.2 Commercial scale

The best available technology from an environmental (primary energy) and life cycle cost point of view is the CdTe system.

Figure 146 shows the primary energy use and LCOE per kWh for the different design options for base case 2, commercial scale.

Figure 146. MJ primary energy and LCOE per kWh – commercial scale



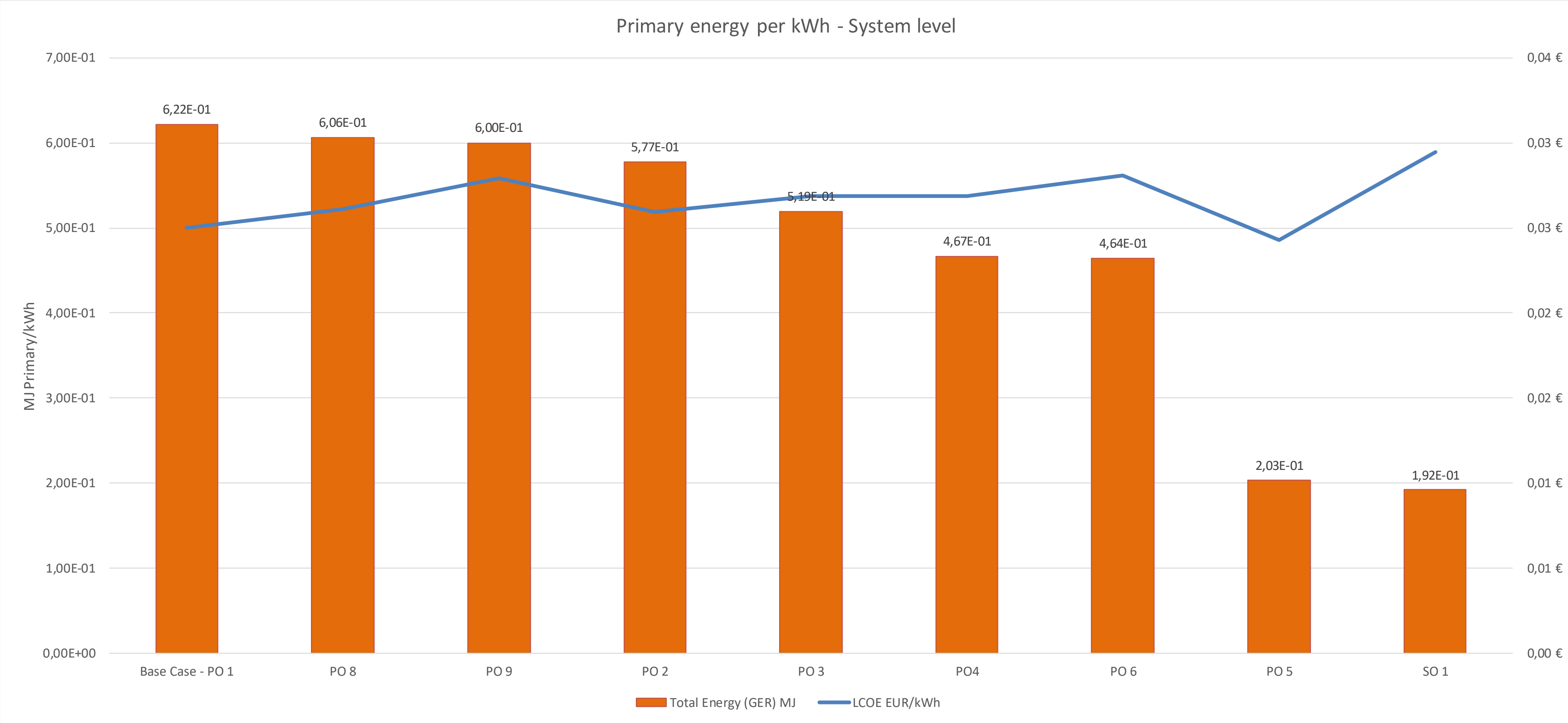
(SO 1): best combination and design; (PO 1): Multi Si module and reference inverter; (PO 2): Optimised PERC 2020 module and reference inverter; (PO 3):BAT PERC 2019 module and reference inverter; (PO 4):BAT PERC bifacial 2019 module and reference inverter; (PO 5): CdTe module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 8):Multi Si module and more efficient inverter; (PO 9): Multi Si module and inverter with repair

6.4.5.3 Utility scale

The best available technology from an environmental point of view (primary energy) are the systems using CdTe modules. Note that the addition of a single axis tracker (SO 1) to the system does not appear to compensate the additional cost (SO 1 versus PO 5). The system 'CdTe + reference inverter + reference BOS' has the lowest LCOE. This illustrates the strong influence of the module selection on the primary energy.

Figure 147 shows the primary energy use and LCOE per kWh for the different design options for base case 3, utility scale.

Figure 147. MJ primary energy and LCOE per kWh – utility scale



(SO 1): best combination and design including single axis tracker; (PO 1): Multi Si module and reference inverter and reference BOS; (PO 2): Optimised PERC 2020 module and reference inverter and reference BOS; (PO 3): BAT PERC 2019 module and reference inverter and reference BOS; (PO 4): BAT PERC bifacial 2019 module and reference inverter and reference BOS; (PO 5): CdTe module and reference inverter and reference BOS; (PO6): BAT PERC 2025 module and reference inverter and reference BOS; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter and reference BOS; (PO 8): Multi Si module and more efficient inverter and reference BOS; (PO 9): Multi Si module and more efficient string inverter and reference BOS.

6.5 Long-term potential (BNAT) & systems analysis

This section deals with the long-term technical potential within the existing product system, including whether there is sufficient scope for product differentiation beyond the BAT and the LLCC options

6.5.1 BNAT analysis for modules

Based on the technology analysis made in Task 4, four 'lead' BNAT candidates can be identified and are presented here in notional descending order of proximity to market:

- TOPCon passivated contact cells: This technology is based on the application of an additional thin oxide passivation layer across the whole front of a silicon wafer. The technology is estimated to increase efficiencies by up to 23%. The first mass market application of this technology is projected to be n-type PERT multi crystalline cells, with over 1.5 GWp of production capacity anticipated to convert [400]. In China application to p-type crystalline cells, albeit more challenging, have already formed part of solutions entered into the Top Runner auction programme [401].
- Silicon wafer material and energy efficiency: The production of silicon wafers by alternative processes that are more efficient in their use of energy and silicon, such as epitaxial growth or 'lift-off' processes, are currently identified as BNAT, although in reality this will represent an optimisation of BAT designs that previously entered the market in the period 1999 – 2014 [402]. This type of wafer could potentially be introduced into multi-silicon module production lines, which in 2016 accounted for around 65% of the crystalline portion of the market, which at the present time is expanded from BSF cells to also now includes some PERx cell variants (PERC/PERL on p-type material). However, this portion is projected to decline to around 10% by 2030, when only multicrystaline PERC/PERL cells may remain, so the scope to bring process efficiency gains into the market may be constrained unless the associated modules are more competitively priced.
- Tandem perovskite cells: Perovskite technology is anticipated to first enter the market at a commercial scale in the form of tandem layered cells. The application of perovskite layers to monocrystalline wafers is currently being planned at commercial scale for 2020/21 by at least one company worldwide. The claimed benefit would be an increase in the overall efficiency of each cell from 20-22% to up to 30%. There is however a question mark over the raw materials required and potential lifetime of the perovskite layer, given the continuing challenges faced in seeking to achieve acceptable levels of stability. Pilot production modules incorporating tandem cells have already been certified to have passed IEC 61215 design approval.
- Back contact silicon heterojunction cells: The integration of the two technologies with some of the highest recorded commercial efficiencies and yields has been the subject of research under the Horizon 2020 programme [403]. The aim has been to achieve 26% cell efficiencies and 22% module efficiencies.

'Drop-in' technology such as kerfless wafer production could be particularly important for the residential market segment where the large scale deployment of the identified BAT (CIGS) is not yet demonstrated due to a small market penetration. This should therefore be taken into consideration in the design of any policy interventions.

A further option has been identified that has passed the prototyping stage and has entered small-scale production so can be considered intermediate to BNAT and BAT:

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[400] *PV Magazine, TOPCon: The next big thing after PERC, October 8th 2018, https://www.pv-magazine.com/2018/10/08/topcon-the-next-big-thing-after-perc/*

[401] *PV Magazine, TOPCon boosts demand for EU equipment, 15th December 2018, https://www.pv-magazine.com/2018/12/15/the-weekend-read-topcon-boosts-demand-for-eu-equipment/*

[402] *Manufacturers includes RWE-Schott, Astropower and Evergreen*

[403] *NextBase project: The next generation baseline for solar modules, https://nextbase-project.eu/*

- Crystalline module redesign for recycling: Currently the majority of module designs present various difficulties at the moment of seeking to dismantle them to recovery materials for recycling. Once the junction box and aluminium frame (if present) have been removed the main difficulty is to separate the encapsulated components as well as the soldered connections and tabbing of the cells. This requires destructive thermal and mechanical processes to be used, which result in low grade, cross contaminated material recovery. Alternative module designs have been developed to pre-commercial stage that have eliminated the polymer encapsulants and laminates as well as the metal soldering that hinder dismantling [404]. Pilot production modules have already been certified to have passed IEC 61215 design approval.

As a conclusion considering all this, further improvements in GER and energy yield can be expected beyond which it has been possible to model in this report.

6.5.2 BNAT analysis for inverters

The main candidates for the Best Not Yet Available Technology (BNAT) are inverter designs based on wider band gap semi-conductors (MOSFET). Whilst some products are entered the commercial scale market segment in 2018 – suggesting that they could eventually be candidates for BAT – their application field is, as yet limited.. Moreover, information is still lacking on the potential benefits and trade-offs in relation to changes in the bill of materials and their performance under higher temperature conditions. Given the significance of thermally induced failures in inverters, this technology could be particularly important in warmer climates if the claimed benefits were to be confirmed.

6.6 Conclusions

This task has sought to identify the design options of the photovoltaic product group with the Least Life Cycle Costs (LLCC) and the Best Available Technology (BAT). The results and conclusions are summarised for the three sub-products under study:

6.6.1 Solar photovoltaic module BAT and LLCC options

For solar PV modules 12 design options were carried forward from the Task 4 analysis, with 8 of them considered to represent technology that is available presently and to therefore be BAT candidates and 4 considered to represent BNAT technologies. The IBC and design for recycling options were not possible to model, either in part or fully, because of problems accessing confidential product data. The modules designs were summarised in Table 126.

Because of the rapid advances in module design, two of the solar PV module designs are composites. They consider changes:

- cell architectures (so as to represent advancement in the market 'base case');
- possible combinations of improvements in the Bill of Materials as well as;
- key performance parameters which are the outcome of changes to these two aspects, such as cell efficiency and degradation.

The composite designs were summarised in Table 130.

Based on the results obtained from the Ecoreport tool for the lead indicator of primary energy (GER), the Best Available Technology (BAT) is, for the residential market segment, the CIGS thin film design and for the commercial and utility segments, the CdTe thin film design.

It is notable that in the residential segment the composite designs based on PERx cell architectures are potentially within the margin of variance for the CIGS design for the GER results – suggesting that composite improvements to designs based on silicon wafers can approach BAT performance. This is particularly the case if BNAT options such as kerfless wafers and design for recycling were to be implemented.

For the secondary environmental indicators selected – namely PAHs, Volatile organic compounds and heavy metals to air and water – the two thin film technologies also achieve the best results for VOCs and heavy metals. However, the composite PERC 2025 and the BNAT options perform marginally better in respect of PAHs emissions and also have the potential to close the gap in the results for the other two impact categories to between 23-57%.

From a life cycle cost perspective, the thin film products also appear to deliver the least life cycle costs. However, in the case of CIGS in the residential market segment, the costs are closely matched and it is recommended to also consider them within the context of the whole PV system costs. Whilst silicon wafer-based design options can also deliver low life cycle costs, the

[404] *Einhaus et al, Recycling and reuse potential of NICE PV-modules (2016)*

results show that this can be at the expense of introducing less environmentally preferable products into the market, suggesting that requirements could be considered in order to ensure that the environmental performance is in parity.

Following comments from stakeholders, a sensitivity analysis of the influence of the electricity grid mix in difference global regions was made. This showed that whilst a variance of up to 10% in GER and up to 15% could be seen in the other three environmental impact categories, a greater variance could be seen if life cycle GWP were to be selected as the lead indicator. A variance of up to 38% can be seen in the results for life cycle GWP, suggesting that this could be considered as a further indicator to screen for the influence of electricity and fuel infrastructure.

6.6.2 Inverter BAT and LLCC options

For inverters 13 design options were carried forward from the Task 4 analysis, with 11 of them considered to represent technology that is available presently and to therefore be BAT candidates and 1 considered to represent a BNAT technology. The inverter designs were summarised in Table 127.

Based on the results obtained from the Ecoreport tool for the lead indicator of primary energy (GER), the Best Available Technology (BAT) options are, for the residential market segment, the longer life and repair options, with both achieving a significant margin of 54-61% improvement upon the base case. In the commercial segment repair comes out as the BAT, showing a 52% improvement. In the utility segment there is very limited margin to identify a BAT based on the design options modelled.

For the secondary environmental indicators selected – namely PAHs, Volatile organic compounds and heavy metals to air and water – the results and improvement potential are of a similar order of magnitude. However, for all impact categories the result for the two storage options modelled is higher than the base case, even without the modelling of the battery, so the benefits of promoting these options as part of a self-consumption strategy require careful consideration within the wider electricity system.

From a life cycle cost perspective, the repair design option appears to deliver the least life cycle costs in both the residential and commercial market segments. In the utility segment the string inverter improvement option incurs higher costs whilst offering very limited margin for environmental improvement.

6.6.3 PV system BAT and LLCC options

For PV systems 13 and 9 design options were carried forward from the Task 4 analysis for the residential and commercial/utility segments respectively. They largely consist of combinations (or 'packages') of the module and inverter technologies already referred to modelled within a system context. However, to these options have been added options that focus on improvements in system performance as a whole. The PV system designs were summarised in Table 128.

Based on the results obtained from the Ecoreport tool for the lead indicator of primary energy (GER), the Best Available Technology (BAT) options are, for the residential market segment:

- Package options which include a long life inverter or an inverter designed for repair, as well as;
- Options that have had the system performance ratio (PR) optimised – either from a design or an operation & maintenance perspective.

For the secondary environmental indicators selected – namely PAHs, Volatile organic compounds and heavy metals to air and water – the results and improvement potential are of a similar order of magnitude. The package option incorporating CIGS modules can also be seen to significant improvement for the VOC and heavy metal impact categories.

In the commercial market segment, the design option incorporating a CdTe module technology is the BAT. Whereas at the utility scale the design options incorporating a tracker and CdTe respectively are closely matched as the BAT.

From a life cycle cost perspective, the result in the residential and commercial market segment mirrors that for the environmental performance. In the residential segment, the results or the two system optimisation options are closely matched. In both the commercial and utility segments, the CdTe represents the least cost option. In the utility segment, the design option incorporating a single axis tracker appears to push up costs to the extent that they are above the other design options.

7 Task 7: Policy scenario analysis

This task looks at suitable policy means to achieve the identified potential improvement. This could include implementing LLCC as a minimum requirement, the environmental performance of BAT or BNAT as a benchmark, using dynamic aspects, legislative or voluntary agreements, standards, labelling or incentives, relating to public procurement or direct and indirect fiscal instruments.

Under this task scenarios will be drawn up quantifying the improvements that can be achieved versus a Business-as-Usual scenario and comparing the outcomes with EU environmental targets, the societal costs if the environmental impact reduction would have to be achieved in another way, etc. The impact on users (purchasing power, societal costs) and industry (employment, profitability, competitiveness, investment level, etc.), will be estimated explicitly describing and taking into account the typical design cycle (platform change) in a product sector.

In addition, an analysis will be made of which significant impacts may have to be measured under possible implementing measures, and what measurement methods would need to be developed or adapted.

This Task should be read in conjunction with the draft JRC Technical Report 'Transitional methods for PV modules, inverters and systems in an Ecodesign Framework'.

7.1 Policy analysis

In this section the policy options to be modelled are identified and analysed considering the outcomes from the previous six tasks. This includes consideration of:

- Stakeholder's positions
- Market and legislative barriers
- The pros and cons of different policy measures
- Existing standards and measurement requirements
- Self-regulation and sectoral benchmarking
- Installation and user information requirements

The options to arise are then further analysed and modelled in the subsequent sections.

7.1.1 Stakeholder positions

A number of distinct stakeholder positions have emerged along the Preparatory Study, both during the two meetings held to date and in subsequent written consultation round. These positions are briefly identified and summarised in this section before being taken into consideration in the identification of policy options:

- Impact on achievement of EU climate and renewable energy targets: solar PV is expected to make a substantial contribution to achieving the EU 2030 targets, implying an expansion of the market after several years of decline following the financial crisis and with the scaling back of major subsidy regimes. At the same time concern has been raised that any intervention in the market could prejudice the deployment of solar PV technology. In particular it is considered that:
  - The major benefit of solar photovoltaic technology is the electricity it generates in the use phase and the associated reduction in environmental impacts from displacement of 'brown' electricity.
  - Even solar PV systems that are not optimised – for example, by focussing on the Performance Ratio as a metric and minimising derate factors – will have a role to play in meeting medium to long range targets.
  - Policy measures should aim at achieving growth 'above business as usual' and they should not be too complex for SMEs.
- Importance of product quality and durability: The proposal in 2015/16 for an EU Ecolabel for modules was based on the premise that the quality of some products being placed on the EU market were of a lower quality and that ongoing work in the sector to establish standards and test routines could form the basis for criteria. Moreover, from a life cycle perspective performance degradation and lifetime are considered the use phase parameters that have biggest influence on the life cycle environmental impacts of solar PV.

- Address Critical Raw Materials (CRM) and hazardous substances: These two aspects have been highlighted by EU Ecolabel consortium members as an additional area of focus for the differentiation of module performance. The presence of hazardous substances restricted by the RoHS Directive are of specific interest as, although modules have an overall exclusion from its requirements, some manufacturers make product claims of compliance or for the absence of certain substances. The presence of certain CRMs and hazardous substances in PV module technologies such as CdTe and CIGS should be carefully considered as growth in their production could have trade-offs and/or present supply risks that would constrain their future contribution to increasing solar PV capacity.
- Transfer of best practices to the residential market segment: Whilst the design and operation of large scale PV systems and commercial PV systems is understood in most cases to be optimised to ensure they are bankable and to minimise risks, this is not necessarily the case in the residential market segments. There is understood to be significant scope to promote the transfer of best practices from the large scale and commercial market segments.
- NSF 457 leadership standard and the PEFCR as the basis for the EU Ecolabel: These two initiatives are understood to have received a high level of engagement by manufacturers. The former is to be adopted by the US Green Electronics Council as a reference standard for the EPEAT label and it is anticipated that criteria for inverters will be added in 2020. Their suitability as the basis for EU Ecolabel criteria, as evaluated in a separate supporting feasibility report, have limitations because the NSF standard largely consists of process-based criteria whereas the EU Ecolabel has to be based on pass/fail performance based criteria. Following on from the Footprint method pilot it is unclear at present what the next step may be in terms of Product Category Rules for photovoltaic modules.
- Opportunity to stimulate EU industry: Any intervention in the market should be used to stimulate the capacity of EU manufacturing to deliver high quality modules and inverters with a lower environmental impact. This arises from wider discussions within the sector about the potential for a renaissance in EU manufacturing, with a focus on knowledge intensive R&D and manufacturing processes, in part as a response to concerns about the quality of some low cost imports.
- The EU Taxonomy on sustainable activities: A regulation on the establishment of a framework to facilitate sustainable investment. is currently undergoing Impact Assessment [405] and accompanying technical screening criteria for economic activities, including renewable electricity generation, are currently under development and are currently proposed as including a requirement to disclose to investors the life cycle CO_2 emissions of solar PV systems. This initiative will have lasting implications for access to and the cost of capital for green investments, as well as due diligence requirements.

7.1.2 Market and legislative barriers and opportunities for measures

7.1.2.1 Macro trends on the global market

According to the insight from the trends given in Task 2, the main EU and global trends are identified and categorised as relating to:

- the structure of global module production and supply will be subject to further rationalisation: the larger manufacturers could push lower cost-quality products from the market, reducing the potential impact of mandatory cut-off measures.
- the type of the financial incentives and market arrangements that will be used by Member States to support further market growth: the phase out of subsidies is leading to a greater importance for the auction of capacity at the larger end of the markets.
- the relationship of utilities with their consumers and their extent of their role in providing solar PV systems: a range of business models could emerge ranging from third party ownership to off-site PV generation projects.
- the extent to which self-consumption models will shape system designs in the future: a number of models including battery storage, AC modules, collective self-consumption could be important in the residential and commercial market segments.
- a diversification in the range of digital and operational support services available to system owners: this could bring a range of benefits including the smart operation of systems and their components, the enabling of better or more responsive O&M as well as greater self-consumption by households and businesses.

The seven main trends identified from four authoritative market analysis reports, together with a qualitative assessment of their time horizon and uncertainty, are summarised in Table 155 below.

[405] Commission legislative proposals on sustainable finance, 24th May 2018, https://ec.europa.eu/info/publications/180524-proposal-sustainable-finance_en#investment

Table 155. Overview of meta trends in the Global photovoltaic market

Market trend	Time horizon	Degree of uncertainty
Continued overcapacity in global module production	Short term	Medium
Digitalisation of PV systems and components	Short term	Low
Phasing out of financial support schemes	Medium term	Low
Increased use of solar auctions to drive down prices	Medium term	Low
An increase in Corporate Power Purchase Agreements for solar energy	Medium term	Low
An increased focus on operation & maintenance services	Medium term	Medium
An increase in the number of utilities that provide solar PV services	Medium term	High
An increase in self-consumption by system owners	Medium term	Medium to high

Sources: developed from IEA PVPS (2017), GTM (2018), PV Market Alliance (2018)

7.1.2.2 Opportunities and barriers in the EU grid connected market

Following those trends an analysis of the market opportunities and legislative barriers that measures on Ecodesign and or Energy label would have on photovoltaics sector is presented below:

High upfront-cost for PV systems, access to and the cost of capital

One of the main barriers of the PV systems is often the high upfront cost relative to the long-term revenue combined with the cost for capital to invest in a PV project. It can also explain why investors sometimes prefer low price and low lifetime products over high price high quality products or ultimately they do not want to invest in PV but prefer more rewarding other options.

Implication: Interventions would need to ensure that cost structure reductions are not reversed or that the impacts remain on niche products. Quality factors may play a role as well in insuring/reducing cost of capital.

Uncertainties in support policies

The PV development has been powered up to now by the deployment of support policies, aiming at reducing the gap between PV's cost of electricity and the price of conventional electricity sources over the last ten years. In many countries the debate on the financing of support schemes is ongoing creating uncertainty for investors.

Commercial and large-scale segments tend to auctions, while the residential sector sees a weaker growth relying on grid parity.

Implication, Weak support could affect effectiveness of measures, diminished demand for higher performance products. There could be opportunities for novel market interventions e.g. reverse auctions

Uncertainties in future energy prices

Apart from the support schemes part of the return on investment will come from the value of the solar produced electricity per KWh. When looking to the market value of electricity it is important to discriminate the wholesale market price from the retail price. Retail prices can be significantly much higher compared to wholesale market price therefore they can provide an important driver for investing in PV systems and in particular for self-consumption.

Implication: Smart technology could facilitate yield maximisation and increased self-consumption to obtain retail prices. However, because the PV investments are long-term investments and design tools/data have variable uncertainty.

Market access and metering schemes for small producers

The way countries deal with the grid access and monitoring of energy locally generated from PV panels is not the same.

Implication: the lack of access arrangements could affect effectiveness of measures, and diminish the demand for higher performance products.

Lack of knowledge or skilled subcontractors

The deployment, repair and maintenance of PV systems requires skilled technicians which should demonstrate some form of certification attesting their qualification. Across Europe these schemes may vary or might even be inexistent in some countries, even though training for PV installers might exist (PVTRIN, 2013[208]). Still, different eligibility requirements and qualifications may exist for the training courses.

Implication: this could affect the potential for performance improvement of design options that rely on overall system design optimisation, particularly in the residential sector.

Repair frameworks may not be supported particularly in residential segment

The complexity or lack of clear consumer distribution channels limits the potential for an on-going relationship between the installer and the customer in order to maintain the performance of the system along its lifetime.

Implication: for system or package label implementation could be affected, also for voluntary instruments.

Opportunities to increase self-consumption

Onto the opportunities that can be created, next to the existing solutions, measures in photovoltaics can create opportunities for batteries and Demand Response Management (DRM). Mainly, in the residential sector, there is a mismatch between PV production and the typical demand which opens up the way to energy storage. There are also emerging arrangements that can facilitate communities of local self-consumption.

Implication: self-consumption could be moreover facilitated by smart requirements and guidelines for auctions/fund establishment (GPP).

Opportunities for public authorities to support residential installations

One approach to elimination of barriers to residential deployment is the concept of a ‘reverse auction’. This concept is currently being demonstrated by the ‘Solar Together London’ initiative of the Mayor of London in the UK. It consists of a two-part group buying process that is managed by the public authority – it starts with the registration of households interested in installing a system on their home then followed by a supplier shortlisting and tender process to select an installation company that can service the registered households.

Implication: exploiting the potential economies of scale, the auction process has as a principle objective a reduction in the unit price of each system. A price reduction of 35% on market rates has been claimed for the first auction round based on installations for approximately 4,000 households.

Opportunities to use auctions to drive quality systems and components

The Chinese “top runner program” referred to in Task 1 is an auction based tender program for projects using high efficiency modules and advanced technologies The programme has directed project developers to adopt the latest technology, increasing module efficiency (e.g. minimum requirements for multi Si modules ≥17% or for mono Si modules ≥17.8%) and reducing LCOE. By the end of 2016 and largely as a result of the programme, the average cell efficiency of mono Si produced in Mainland China had increased to 20.5%.

The French auction process has also been notable for containing award criteria that reward modules with a higher quality and lower estimated production stage CO_2 emissions. The most recent calls for tender include a specific award threshold expressed in kg eq CO_2/kWp.

Implication: for larger systems there is evidence that the incorporation of requirements to tender specifications can be used to drive improvement in quality and performance, whilst at the same time reducing the LCOE.

7.1.3 Identification of policy options

In this section the policy options to be modelled are selected and defined based on a combination of the policy instruments to be considered by the Preparatory Study and the possible requirements that could be set on modules, inverters and/or systems.

7.1.3.1 The potential for self-regulation

The Ecodesign Directive 2009/125/EC states that priority should be given to alternative courses of action such as self-regulation via the establishment of voluntary agreements before contemplating regulatory interventions and in cases:

> *‘…where such action is likely to deliver the policy objectives faster or in a less costly manner than mandatory requirements.’*

The solar photovoltaic industry is well represented by trade organisations such Solar Power Europe. These organisations benefit from the active engagement of leading module and inverter manufacturers.

At the time of drafting this Task report (June 2018), no proposals of voluntary agreements have been tabled by any (industrial) stakeholder. However, in order to inform discussions the current activity of private initiatives in support of the introduction of performance standards that could form the basis for self-regulation is briefly summarised below:

Module performance:

- Existing private schemes or initiatives for addressing quality and /reliability
- – The PV QAT International Photovoltaic Quality Assurance Task Force (PVQAT) initiative serves as a frame platform for the development of new quality and reliability standards.
- – The DNV reliability module reliability scorecard is based on a series of durability tests applied to the products of leading manufacturers,
- – The Photon module and inverter performance test programme provides data on the energy yield, product defects and degradation effects for modules. An efficiency metric is also tested for inverters. It is not understood to be supported by all parts of the industry due to concerns because of economic motivations.
- Labelling of front runners:
- – The NSF/ANSI 457 standard offers a potential starting point for a first multi-criteria set for modules. The Green Electronics Council (GEC) and TUV are currently developing criteria for inverters.
- – The Ecolabel consortium – a combination of French and German test institutes, together with manufacturer interest led in 2015/16 a consortium to propose modules as an EU Ecolabel product group.
- Development of EPD category rules
- - The Product Environmental Footprint (PEF) pilot has now concluded and there is the option to take forward the Product Category Rules that have been developed.

System performance:

A number of project standards and certifications have been developed, primarily driven by the needs of investors for due diligence and to ensure the 'bankability' of proposals:

- DNV system 'Project certification of photovoltaic power plants' – this certification includes system and component quality and performance requirements
- VDE 'Quality Tested mark for Photovoltaic Power Plants' - this certification is designed to provide information to investors.

In addition the accompanying standards review carried out by the JRC has identified that an IECRE conformity assessment scheme for PV systems is currently under development.

Whilst less activity has been possible to identify for inverters, the PV QAT International Photovoltaic Quality Assurance Task Force (PVQAT) initiative is also active in the development of new standards for inverters and it is to be noted that there are a small number of large EU manufacturers who have captured a significant share of the market, estimated in Task 2 to account for more than 50% of EU shipments in 2016. This could potentially facilitate self-regulatory measures, whereas in the case of modules the lead manufacturers are located in third countries outside the EU and Task 2 highlighted that the EU is no longer the most significant market for these manufacturers.

7.1.3.2 The role of the four EU policy instruments

The focus of the Preparatory study is on the feasibility of employing four individual policy instruments, either individually or in combination. Each instrument has distinct characteristics and requirements that must be taken into consideration when deciding whether an intervention in the market is required. They are each briefly summarised in Table 156.

As was identified in section 7.1.2 there could also be the potential to explore other policy instruments that have been successfully applied in other countries to drive improvements in module and system quality and performance – for example, the inclusion of technical requirements in the auction tender specifications in China and France.

Table 156. Product policy instruments.

Policy Instrument	Stringency	Scope	Life cycle stage	Verification
Ecodesign	Mandatory	Products, packages of products	Requirements can be set on tested use stage product performance, although material efficiency requirements relating to other life cycle stages have been implemented as both requirements and information requirements. Annex V of the Directive also allows for a management system for design through manufacturing to be used for conformity assessment.	Market surveillance is carried out at member state level.
Energy label	Mandatory	Products, packages of products	The chosen Energy Efficiency Index (EEI) shall address performance in the use stage. It is not clear if the EEI can be applied to other life cycle stages.	Market surveillance is carried out at member state level.
EU Ecolabel	Voluntary	Can be products or services	Criteria can be set on any life cycle stage and can include manufacturing sites as well as tested product performance.	Member State Competent Bodies verify compliance evidence and award the label.
Green Public Procurement (GPP)	Voluntary	Can be products or services	Criteria can be set on any life cycle stage and can include manufacturing sites as well as tested product performance. The criteria must always link to the subject matter.	Verification is through evidence from tenderers provided during the procurement process.

7.1.3.3 Policy option specification

In this section the detailed proposals for the policy options are specified based on the results of the analysis from Task 6. Unless specified each policy option is modelled in isolation in order to estimate the environmental benefits and societal costs and benefits. For some options there are multiple variants so that the results for different areas of improvement or performance metrics can be compared and contrasted.

Policy option 1: Business as usual (BAU)

The assumptions forming the basis for the Business As Usual (BAU) stock model are summarised in this section. The main references for the model are the sources of market intelligence that were compiled in the Task 2 report. These include data sourced from the Becquerel Institute, the IEA PVPS programme, PV Market Alliance, Solar Power Europe, GTM and VDMA. The European Reference Scenario for 2016 and subsequent modelling variants has also been used as the main basis for the medium to long-term projections[406].

Module stock model BAU assumptions

The module stock for the EU has been estimated for the reference year 2016. The reference module capacity per technology and segment is shown in Table 157. The values have been taken from the ITRPV Roadmap[407], which tracks the module rated power for different cell technologies. For CdTe the power is modelled on the products of the market leader at the time, Series 4 from First Solar. CIGS module power is modelled on the manufacturers that at the time had the largest market shares. High

[406] *European Reference Scenario 2016, https://ec.europa.eu/energy/en/data-analysis/energy-modelling/eu-reference-scenario-2016*

[407] *VDMA (2019) International Technology*

Roadmap for Photovoltaic (ITRPV) – 10TH Edition , http://www.itrpv.net/Reports/Downloads/

efficiency modules' power is modelled on the products of Panasonic (Heterojunction technology) and Sunpower (IBC back contact technology). The following generalised trends also inform the stock estimate:

- Multi-crystalline is less expensive than mono-crystalline on a Wp basis but on an LCOE basis within a system the latter can deliver a better performance by increasing output and reducing BoS costs.
- Until 2015 multi crystalline was dominant at utility-scale but since then prices for mono-crystalline have declined and production has expanded.
- High-efficiency mono-crystalline has been used in all segments even if the residential segment has seen a higher penetration of that technology. But their share is difficult to measure over time.
- Cadmium Telluride has been used almost exclusively for utility-scale applications. Their use in other segments was extremely small.
- Copper Indium Gallium Selenide CI(G)S has been used in all segments, even if there is limited data to translate their application into a segmentation. An indicative share between segments is assumed.
- The share of amorphous silicon technology for residential applications has been very low due to space constraints.
- High efficiency technologies are defined as those achieving efficiencies indicatively greater than 22% with present technology, which may include modules based on heterojunction, back contact and bifacial cell structures. BNAT variations and combinations of these cell technologies are not reflected in the modelling.

Then the number of installed units in EU can be calculated from the technology shares per market segment that were provided in Task 2 (shown in Table 158)

Table 157. Reference size in Wp of modules installed per segment and technology in 2016.

3	Multi-Si	Mono-Si	CdTe	aSi	CIGS	HighEff
Rated power residential	270	285	n/a	n/a	145	245
Rated power commercial	325	340	n/a	n/a	145	375
Rated power utility	325	340	118	n/a	n/a	375

Table 158. Number of installed units (thousands) of modules per technology and segment estimated from the reference size and the stock of modules for the reference year 2016

	Multi-Si	Mono-Si	CdTe	CIGS	HighEff	Total
Residential	2,898	1,580	-	256	283	5,018
Commercial	4,255	2,455	-	434	361	7,505
Utility-scale	3,861	2,047	1,159	-	262	7,329
Total	11,014	6,082	1,159	690	906	19,852

Quality and technical lifetime

The technical lifetime for the module component of a system is expected to differ more and more from the economic lifetime. PV modules conceived decades ago showed that, apart from the degradation of performance due to aging semiconductors, they could often last much more than 30 years. Since then the onset of mass production has raised concerns about manufactured quality and the lifespan of newer designs and bills of materials.

Once the current quality issues that are addressed in several studies (IEA PVPS task 13 for instance) and which are currently the subject of intense interest within the industry are solved, PV modules should be capable of providing electricity for more than 20 years. However, the economic lifetime depends on business choices and it is considered that 25-30 years will become a corresponding intended service lifetime for most PV modules.

Evolution of the module stock through to 2030

The following assumptions have been developed as the starting point for the modelling. The VDMA roadmap has been used as a starting point and then been cross-referenced with a range of other sources as referred to in the Task 2 report. It has not been considered possible to make predictions beyond 2030 for the technology because of a lack of foresight as to how it may develop.

Modelled design options and BAT

- The global market share for PV modules is dominated by crystalline silicon wafer-based cell types for the reference year 2016 accounting for 94% of modules placed on the market with the starting assumption that this percentage remains constant until 2030.
- In terms of the market split between multi and mono crystalline wafer-based technology, this is estimated to shift from multisilicon dominating with a 65% share in 2016 and falling to below 10% by 2030. Only multi-silicon p-type PERC/PERL cells are predicted to remain by 2030 (see also the section below on BNAT).
- The PERx family of silicon wafer-based cell structures [408] has quickly entered the market, starting in 2016 with approximately 20% market share and being projected to account for a market share of greater than 70% by 2030. This is based on an average of 3.5% percentage point growth in market share each year. It is important to note that the bifacial market share should be deducted from the PERx market share as all bifacial products are based on PERx technology.
- Bifacial PERC cell types are projected to grow steadily, reaching approximately 20% market share by 2021, driven largely by large rooftop and utility scale system installations. They could reach 50-60% market share by 2030. This is based on 3.5% percentage point growth in market share each year.
- Heterojunction (HIT/HJT) cells are expected to gain a market share from 2% in 2016 to 10% in 2025 and 15% by 2030.
- The share for back contact cells is not expected to gain significant market share: rising from 3% in 2016 to approximately 10% in 2030.
- The initial market shares for the predominant thin film technologies – namely CdTe and CIGS – were 3.1% and 1.3% in 2016. CdTe is anticipated to make gains from silicon wafer-based technologies in the large-scale PV system market segment and CIGS in residential and commercial market segments. These market gains have not been possible to estimate and it is also possible that the supply risk associated with tellurium, indium and gallium may have a future influence on pricing and growth.

BNAT candidates

Based on the technology analysis made in Task 4, four 'lead' BNAT candidates can be identified and are presented here in notional descending order of proximity to market:

- TOPCon passivated contact cells: This technology is based on the application of an additional thin oxide passivation layer across the whole front of a silicon wafer. The technology is estimated to increase efficiencies by up to 23%. The first mass market application of this technology is projected to be n-type PERT multi crystalline cells, with over 1.5 GWp of production capacity anticipated to convert [409]. In China application to p-type crystalline cells, albeit more challenging, have already formed part of solutions entered into the Top Runner auction programme [410].
- Silicon wafer material and energy efficiency: The production of silicon wafers by alternative processes that are more efficient in their use of energy and silicon, such as epitaxial growth, are currently identified as BNAT, although in reality this will represent an optimisation of BAT designs that previously entered the market in the period 1999 – 2014 [411]. This type of wafer could potentially be introduced into multi-silicon module production lines, which in 2016 accounted for around 65% of the crystalline portion of the market, which at the present time is expanded from BSF cells to also now includes some PERx cell variants (PERC/PERL on p-type material). However, this portion is projected to decline to around 10% by 2030, when only multicrystaline PERC/PERL cells may remain, so the scope to bring process efficiency gains into the market may be constrained unless the associated modules are more competitively priced.
- Tandem perovskite cells: Perovskite technology is anticipated to first enter the market at a commercial scale in the form of tandem layered cells. The application of perovskite layers to monocrystalline wafers is currently being planned at commercial scale for 2020/21 by at least one company worldwide.

  The claimed benefit would be an increase in the overall efficiency of each cell from 20-22% to up to 30%. There is however a question mark over the potential lifetime of the perovskite layer, given the continuing challenges faced in

[408] *This includes PERC, PERL and PERT silicon wafer-based cell structures*

seeking to achieve acceptable levels of stability. Pilot production modules incorporating tandem cells have already been certified to have passed IEC 61215 design approval.

- Back contact silicon heterojunction cells: The integration of the two technologies with some of the highest recorded commercial efficiencies and yields has been the subject of research under the Horizon 2020 programme [412]. The aim has been to achieve 26% cell efficiencies and 22% module efficiencies.

A further option has been identified that has passed the prototyping stage and has entered small-scale production so can be considered intermediate to BNAT and BAT:

- Crystalline module redesign for recycling: Currently the majority of module designs present various difficulties at the moment of seeking to dismantle them to recovery materials for recycling. Once the junction box and aluminium frame (if present) have been removed the main difficulty is to separate the encapsulated components as well as the soldered connections and tabbing of the cells. This requires destructive thermal and mechanical processes to be used, which result in low grade, cross contaminated material recovery. Alternative module designs have been developed to pre-commercial stage that have eliminated the polymer encapsulants and laminates as well as the metal soldering that hinder dismantling [413]. Pilot production modules have already been certified to have passed IEC 61215 design approval.

Inverter stock model BAU assumptions

The inverter stock for the EU has been estimated for the reference year 2016. The reference inverter capacity per technology and segment is shown in Table 159. The values have been taken from the market research by GTM and Becquerel Institute, which tracks the inverter capacities for different technologies.

Then the number of installed units in the EU can be calculated from the technology shares per market segment that were provided in Task 2 (shown in Table 160.

[409] *PV Magazine, TOPCon: The next big thing after PERC, October 8th 2018, https://www.pv-magazine.com/2018/10/08/topcon-the-next-big-thing-after-perc/*

[410] *PV Magazine, TOPCon boosts demand for EU equipment, 15th December 2018, https://www.pv-magazine.com/2018/12/15/the-weekend-read-topcon-boosts-demand-for-eu-equipment/*

[411] *Manufacturers includes RWE-Schott, Astropower and Evergreen*

[412] *NextBase project: The next generation baseline for solar modules, https://nextbase-project.eu/*

[413] *Einhaus et al, Recycling and reuse potential of NICE PV-modules (2016)*

Table 159. Reference size of inverters installed per segment and technology.

	Micro	String 1 phase	String 3 phase	Central
Rated power residential (W)	250	3000	1000.00	n/a
Rated power commercial (kW)	n/a	n/a	25.00	n/a
Rated power utility (kW)	n/a	n/a	n/a	1,500

Table 160. Number of installed units (thousands) of modules per technology and segment estimated for the reference year 2016

	Micro	String 1 phase	String 3 phase	Central
Residential	345,713	365,060	687,517	n/a
Commercial	n/a	n/a	83,338	n/a
Utility- scale	n/a	n/a	n/a	1,056

Evolution of the inverter stock through to 2022

The following assumptions have been developed as the starting point for the modelling. The starting point is the market data and commentary provided by GTM. This has then been cross-referenced with a range of other sources which were referenced in Task 2. With the exception of micro-inverters, it has not been considered possible to make predictions beyond 2022 for the technology because of a lack of foresight as to how the market may develop.

Modelled design options and BAT

- In 2016 the split between single and three-phase in the residential segment was 35:65. All commercial installations are assumed to have used three phase inverters.
- The string 1 phase share is estimated to reduce from 16% to 13% by 2022.
- The string 3 phase share is estimated to maintain a market share of 60% until 2022.
- In the last years, the cost decrease and capacity increase of string inverters (now up to 125 kW) has allowed to them to now be used in utility-scale plants instead of central inverters. No data could be found to estimate the substitution of central inverters/solutions.
- Most utility-scale PV plants are using central inverters which in 2016 accounted for 23% of the market, with a small increase to 26% by 2022 estimated.
- Micro-inverters attached to the module itself are less common but have experienced some market development in the last years. These are almost exclusively used in the residential market. In 2016 they accounted for around 1.3% and this is estimated to grow to 1.6% by 2022. Their share could grow to 10% by 2030.

BAU assumptions of the system stock model

At the system level, and in agreement with the previous sections for the estimation of modules and inverter sales, the system sales have been estimated and equated to the added system capacity (see Table 161.).

Table 161. Number of installed units of systems per segment estimated for the reference year 2016

	Residential	Commercial	Utility
Average capacity (kW)	3	24.4	1875
Total capacity (MW)	1339	2541	2334
Units	446480	104130	1245

Additional assumptions that underpin the model are detailed here:

- Residential PV systems won't be decommissioned unless the roof requires replacing. While loss of performance will happen through, for example, degradation mechanisms, it is not a reason to consider decommissioning. It is assumed that the system lifetime will correspond to that of the modules, which is assumed to be as a minimum the subsidy contract period available in a member state – up to 30 years. It is assumed that some house owners may decide to replace their system with new panels (repowering) but the probability of this occurring cannot easily be estimated. It is therefore assumed that this may occur after a period of 30 years. It could be considered to include in the assumptions a repowering rate for the stock installed from the outset of major subsidy schemes in Germany , Spain, Italy, UK and France.
- For residential systems across all Member States it is assumed that up to 47% of electricity generated is self-consumed and the remaining 53% of electricity is exported to the grid.
- Commercial and industrial systems may be constrained by other factors such as the lifespan of the building itself on the site. However, assumptions that can be made from a PV system perspective are not readily available. A 30-year lifetime shall be taken as an initial assumption, but this may also be influenced by typical building lifespans. For example, industrial buildings may have a shorter service life than that of the PV system.
- Utility-scale systems have mostly been developed based on 13 to 25 years incentives. It can reasonably be considered that they will be either decommissioned or repowered after 20 years on average. It could be possible to refine this assumption by looking at the proportion of PV systems financed in each country under specific incentive schemes.

Evolution of the system stock through to 2023, 2030 and 2050

Forecasts for the future PV system installations are fundamental in order to also develop stock models for modules and inverters, but a broad range of assumptions must be made and adjusted depending on the time horizon. The following assumptions for short, medium and long-term forecasts are presented as the starting point for discussion:

Short term (until 2023)

Short term forecasts are based on bottom-up market analysis, including Member State policies supporting PV and the general trends in PV development. The data from Solar Power Europe has been used as the starting point. Starting from 115 GW in 2017, the installed capacity in 2023 could reach between 196 - 318 GW according to the three scenarios developed.

Medium term (2023-2030)

The EU's re-cast renewable energy directive sets the target for the 2030 share of renewables in gross final energy consumption at 32%. To achieve this, the EU needs to increase its use of renewables in the power sector by a much higher amount and a significant part of this will come from solar systems.

For the period until 2025, a mix has been used of the starting point provided by the Solar Power Europe scenarios and the European Reference Scenario 2016 afterwards. The forecast is heavily dependent on EU policy as the Reference Scenario was remodelled to reflect the more ambitious targets in the EU 2030 energy and climate change policies.. Development of the policy assumptions is explained further in the box below. Residential scenarios developed for a recent study by DG Justice are referred to as they are estimated by member state based on take up rates and the proportion of remaining capacity to 2030 (see Table 162).

Major factors influencing that post 2023 situation relate to the political willingness in Europe to fulfil climate change commitments and the expected PV market developments due to price competitiveness (parity) in most European countries. At an EU level a new binding renewable energy target for the EU for 2030 has been established of at least 32%, with a clause for a possible upwards revision by 2023.

An assumption has been made that the ratio between wind and PV contributing to targets could be higher than 2:1. Also most other renewable technologies won't grow as fast until 2030 given the competitiveness of wind and solar in the electricity sector. The low scenario of Solar Power Europe corresponds well as a starting point with the 2023/4 projection in the EUCO3232.5 model. By applying a linear annual growth rate of 2.9% through to 2030 this could translate into around 323 GW for photovoltaics, slightly higher than the 295 GW and 305 GW in the EU 2016 and EUCO3232.5 scenarios respectively.

Long-term (2030-2050)

The main policy driver is likely to be the decarbonisation of the energy mix in Europe under the more ambitious version of the Reference Scenario 2016, referred to previously as EUCO3232.5. Because of long range uncertainty a greater possible divergence in the outcomes has been assumed.

The same methodology has therefore be applied as described for 2023-30. The Reference Scenario estimates a nuclear production of 737 TWh in 2050, which leaves 3124 TWh to be produced with RES-E electricity, of which a contribution of 429 TWh is predicted for solar PV. By applying a linear annual growth rate of 2.5% referred to in the original EU Reference Scenario for the period 2030-50 a high end capacity projection of 843 GW is the result, compared to the original projection of 428.5 GW.

Table 162. Projected residential solar PV capacity to 2030 for EU and EEA countries

	Residential solar PV capacity in 2015 (MW)	Residential solar PV capacity in 2030 (MW)	Growth rate, 2017-2030 (% pa)	Share of total potential residential solar PV capacity (2030)	solar PV prosumers as a share of all households (2030)
Belgium	1,976.9	3,255	3.5%	29.0%	8.2%
Bulgaria	8.9	40.6	10.2%	1.4%	0.5%
Czech Rep.	95.0	106.3	0.8%	2.6%	0.7%
Denmark	454.1	838.1	4.2%	18.7%	6.8%
Germany	5,240.5	9,137.8	3.8%	39.5%	5.8%
Estonia	1.1	5.6	8.2%	1.7%	0.2%
Ireland	1.1	12.4	15.3%	0.4%	0.2%
Greece	350.0	950.2	4.4%	27.4%	6.7%
Spain	48.6	57.9	1.2%	0.4%	0.1%
France	1,049.0	2,622.7	6.3%	6.6%	2.6%
Croatia	12.1	30.3	6.3%	1.2%	0.5%
Italy	2,640.0	5,614.1	5.1%	22.6%	5.9%
Cyprus	20.6	55.7	6.7%	7.6%	3.1%
Latvia	0.4	5.6	14.9%	1.5%	0.3%
Lithuania	19.7	31.2	3.1%	3.9%	1.1%
Luxembourg	33.6	80.6	6.0%	14.1%	5.0%
Hungary	60.5	282.8	10.0%	5.0%	2.3%
Malta	19.7	23.6	1.3%	13.0%	3.6%
Netherlands	1,086.0	3,684.0	8.1%	26.4%	9.5%
Austria	377.5	684.2	4.3%	16.4%	5.1%
Poland	10.2	151.2	16.5%	1.0%	0.4%
Portugal	147.1	382.9	6.5%	7.5%	4.1%
Romania	13.3	18.7	2.3%	0.3%	0.2%
Slovenia	1.8	13	12.9%	1.1%	0.5%
Slovakia	5.9	40.4	12.5%	1.9%	0.6%
Finland	4.0	24.5	12%	0.7%	0.2%
Sweden	52.0	257.6	9.4%	3.4%	1.1%
UK	2,499.0	3,539.9	2.1%	13.1%	3.5%
Iceland	-	-	-	0.0%	0.0%
Norway	11.3	25.6	5.5%	0.4%	0.3%

Source: DG JUST study "Residential Prosumers in the European Energy Union' (2017)

Policy option 2: Ecodesign requirements on modules and inverters

Description: Requirements would be set that would apply to individual modules and inverter products placed on the EU market.
Rationale: To foster innovation in module and inverter design, with a focus on life cycle yield, circularity and smart readiness, and to prevent imports that are of low quality. An approach focussed on the two key components is considered to be justified because they are business to business components of all PV systems in general in the case of modules without intended end-use. The intervention would therefore cut off products at the point of being placed on the market to distributors, retailers and installer. It does not require consumer visibility. From a market surveillance perspective it is more appropriate to place requirements on these components.
Evidence: o Modules: The BAT and LLCC options identified in Task 6 show that there is scope within the market to improve the overall performance of modules, both in terms of primary energy and cost. Moreover, requirements on the quality and durability of products over time could further contribute to lower environmental impacts. o Inverters: The BAT and LLCC options identified in Task 6 show that whilst potential efficiency gains are more modest a focus on extending the lifetime of inverters and ensuring that they are readily repairable can contribute to significant reductions in their environmental impact.
Expected benefits: o Product efficiency will be driven up overall. o The cost differential is predicted based on spot prices to be less than 20% between the different design options at the low performance end of the market meaning that a cut-off could be introduced without strongly impacting on the total pricing of systems whilst at the same time increasing their yield. o Information requirements could be used to drive a focus on quality and circular aspects that have been demanded by industry, as well as contributing to EU policy actions. o Requirements could for inverters drive a focus on repairability and customer support and promote their role as a digital gateway to system performance monitoring.
Possible drawbacks: o Requirements could create a supply constraint if they take lower cost/lower end products off the market o High performance products can have higher life cycle impacts e.g. SHJ modules. Any increase in the sale of high efficiency modules would only focus on predicted use stage performance – care would therefore need to be taken in how this would be accounted for. o For inverters there is limited differentiation between products using the Euro Efficiency metric. Account would need to be taken of other beneficial operating characteristics such as under mismatch conditions and design to operate at higher temperatures.

Proposed Ecodesign module requirements under Policy Option 2

Two sets of requirements are proposed for PV modules that each address specific aspects of performance:

1. The first set has the objective of removing those module products with the lowest electricity efficiency or yield.
2. The second set has the objective of ensuring that all modules meet minimum requirements for their quality, durability and circularity.

For the purpose of modelling this allows for the distinct improvements of each aspect of performance to be analysed. These two sets may also be combined into one set of requirements and this combination has also been modelled (see section 7.2). Also for both options some minimum information requirements are proposed.

Scope of the product group

In line with the findings reported in the Task 1 report, the product scope is proposed below. BIPV was initially considered for inclusion with the potential to focus on the performance of the cells used. However, this would still not fully address the diversity of products that are also largely specialist B2B and construction products, whereas the focus of Ecodesign is on consumer products in the market.

Proposed Ecodesign product scope

Modules

The scope shall correspond to photovoltaic modules intended for use in photovoltaic systems for grid-connected electricity generation.

Specifically excluded from this scope are:

- Module level power electronics, containing micro-inverters and power optimisers
- Modules with a DC output power of less than 50 Watts under Standard Test Conditions (STC)
- Building Integrated Photovoltaic (BIPV) products that incorporate solar photovoltaic cells
- Modules intended for mobile applications or integration into consumer electronic products.

Inverters

The scope shall correspond to the following inverters that are intended for use in grid connected electricity generation:

- Utility interactive inverters that are designed to operate in stand-alone and parallel modes.
- Inverters with a maximum circuit voltage of 1500 V DC and connections to systems not exceeding 1000 V AC. Hybrid inverters and micro-inverters sold separately fall within this category.
- String inverters falling within category 2 as defined in draft IEC 62093 ('String-level power electronics') and designed to interface multiple series or parallel connected modules and specified for wall, roof, ceiling or rack mounting.
- Central inverters falling within Category 3 as defined in IEC 62093 ('Large-scale power electronics') and designed to interface multiple series or parallel connected modules, but due to its complexity, size and weight are housed in a free-standing electrical enclosure.

Specifically excluded from this scope are:

- Central inverters that are packaged with transformers (sometimes referred to as central solutions) as defined in Commission Regulation (EU) No 548/2014 on Ecodesign requirements for small, medium and large power transformers.

Module option 2.1: Performance requirements on efficiency and lifetime electricity yield

This initial Ecodesign option would introduce a cut-off based on the potential of module products to generate electricity. The results of Tasks 5 and 6 have shown that increased electricity generation is a determinant in reducing the life cycle primary energy per kWh generated. Moreover, from a market perspective the efficiency of the base case module is an average. The standard products of major manufacturers are currently situated in the range of 16-17% and evidence suggests that less efficient products are still being placed on the EU market [414]. These largely comprise products imported into the EU.

For the BAT module product (CIGS) the reported results, which show the selected model having an advantage over crystalline designs because of their lower production primary energy use, can only be achieved by maximising their efficiency and yield.

[414] *The ENF solar directory identified that of the 16.020 multi-crystalline module models >50 Wp listed as being available on the world market, there are 1.741 with an efficiency in the range of 9 - 14%. These include module products supplied to the major PV markets in Germany, Italy, France and Spain.*

If yield is also taken into account then the mono PERC 2020 and optimised mono PERC design options also both demonstrate low production primary energy use and high yield.

Two options have been identified for the performance requirements (see also Table 163):

1. Power rating (IEC 61853-1): A simplified option based on measurement of the efficiency of a module in converting solar radiation into DC electricity under Standard Test Conditions and,
2. Energy rating (IEC 61853-3): A more complex, but more representative option based on applying performance coefficients to the module efficiency under STC, the estimated yield of a module under reference conditions and in a reference climate zone.

Whilst option 1 is a standard metric used for declaration of the power rating of a module by manufacturers, the standardised test method to support option 2 takes into account more performance corrections in the field and could therefore provide a more representative comparison of product performance. It is however a more complex method that is not yet widely reported on in product datasheets since the yield calculation takes into account specific climate zone conditions as well as PV module performance characteristics such as coefficients for spectral response under low light conditions and the loss of performance at high temperatures.

For option 1 a threshold of 14% rising to 16% is proposed based on the performance of the LLCC option (the mono PERC 2020 module) and the best performing models available in the market for the BAT (the CIGS module). The main assumption underpinning this option is that the Base case and low performing modules would be removed progressively form the market, moving largely towards modules with a higher power output. Care, however, would need to be taken in the application of such a requirement to emerging technologies. Cases such as CIS/CIGS thin films show that although a technology may initially not be able to demonstrate high performance they may subsequently improve as a result of progressive investment in Research & Development.

For the energy output (yield) performance two options are presented. The first (option 2) would be an information requirement, given that this performance metric is not yet as widely declared as the module power rating and the accompanying standard was only introduced in 2018. The second (option 3) would be a minimum requirement but no specific threshold can be proposed yet because of a lack of market data. It could be possible to initially set this based on the power density, spectral response and temperature co-efficient of a selected module representative of the BAT (CIGS).

Table 163. Module policy option 2.1: Efficiency and yield requirements

Performance aspect	**Detailed proposed requirements**
Option 1: Module efficiency	Require a minimum module efficiency 16% measured according to IEC 61853-1 under Standard Test Conditions. This threshold could alternatively be tiered starting at 14% and rising to 16%.
Option 2: Module energy yield	An information requirement to declare the module energy output (yield) expressed in kWh/kWp and calculated according to IEC 61853-3 and for a reference climate zone.
Option 3: Module energy yield	Tier 1: Require a minimum module energy output (yield) expressed in kWh/kWp and calculated according to IEC 61853-3 and for a reference climate zone.
	Tier 2: The minimum module energy output (yield) in kWh/kWp to be time averaged over 30 years to reflect the declared linear degradation rate of the product.

Module option 2.2: Performance requirements on quality, durability and circularity

This further Ecodesign option would introduce a more stringent set of quality and durability tests for module products. It would also seek to ensure that modules were possible to disassemble and dismantle in order to facilitate repairing and recycling. The proposed set of requirements are presented in Table 164.

Quality and durability

The optimised monocrystalline PERC module was identified in Task 6 as the LLC option. Contributing to its performance are a number of factory quality tests and material specifications that are understood to be applied to module products in order to reduce failures at the infant, mid-life and wear out phases of a module product, as well as to reduce performance degradation along a product's lifetime. These were selected based on literature reporting the findings from field analysis of the most common factory defects as well as defects to emerge in the field and manufacturers design and testing responses.

Using IEC 61215 [415] as a starting point for conformity assessment of quality and material specifications, a set of factory and durability test requirements have been specified which complement or extend the currently specified test methods. This would have the effect of focussing attention on specific tests as it appears that although for the largest manufacturers of solar modules who account for approximately 65% of the market it is considered a market entry requirement only a small proportion of module *models* that are available on the world market are currently formally certified to IEC 61215 (in the range of 10-20%). It appears that there are a range of smaller manufacturers for whom design type approval and factory quality control is less comprehensive – as evidenced by a high degree of variation in the findings from factory quality audits [416].

Some other aspects, related to IEC 61215, should be noted in this context:

- Experience from factory quality inspection in China strongly suggests that it is not sufficient to require only a design type approval, as later on in the move to full scale manufacturing there may be:
  - changes in material quality,
  - small changes and deviations may occur from the design and
  - there may not be the same precision manufacturing.

  A complementary focus on implementation of a factory quality standard is therefore recommended to ensure that the design quality is replicated at mass production scale. The standard IEC TS 62941 and linked to that the accompanying IECRE Operational Documents for audits (IECRE OD 405 series).

- As analysed in detail in the draft report 'Transitional methods for PV modules, inverters and systems in an Ecodesign Framework', there are various tests of the IEC 61215 sequence which show clear commonalities (until a certain extent, at least), with the EN IEC 61730. EN IEC 61730 is the harmonised standard for compliance of photovoltaic modules/installations with the provisions of the Low Voltage Directive 2014/35/EU, therefore it can be expected that the tests foreseen under this standard are already commonly executed by manufacturers. This should be taken into account, to avoid overburdening/duplications in terms of costs for testing.
- The indicative cost for the full test sequence of (8) modules, as foreseen in IEC 61215, is in the order of (at least) 30000-35000 Euro.
- Industry stakeholders note that a shortcoming of the current standard is that tests are not applied simultaneously to each module sample, thereby representing tests closer to real life conditions.

As a result and based on the analysis in Tasks 4 to 6 a small number of selected tests rather than the whole IEC 61215 test sequence could be used to focus attention on the following performance aspects:

- Micro-cracks: Module quality testing can be specified to include electroluminescence inspections to detect inactive cell areas in the semi-conductor which may have the potential to propagate over time and at different rates depending on climatic conditions [417]. They can be minimised by careful handling practices.
- Degradation mechanisms: These mechanisms are complex but state of the art analysis based on field observation suggests that they are mostly strongly contributed to by:
  - UV exposure over time,
  - progressive water ingress into a module, and
  - high operating (system) voltages.
- The semi-conductor materials also have different degradation mechanisms. Given that a standardised test for the long-term degradation of performance of all technologies is not available it is considered necessary to complement an overall declaration of the module degradation rate (see below) with UV preconditioning test, water ingress and Potential Induced Degradation (PID) tests. Specific concerns have also been documented in relation to possible severe short term degradation of the new generation of PERx modules, although there is evidence of recovery over

[415] IEC, Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1: Test requirements (2016)

[416] Confidential analysis carried out by STS (9.4 GWp production, 39 manufacturers) and EXXERGY (sample of 195.000 modules before and 350.000 modules after quality audit procedure)

[417] 3-7% power loss in standard modules is possible as a result of micro-cracks according to analysis under IEA PVPS Task 13. Although a relatively high defect rate (16%) was reported by STS from large scale Chinese factory inspections in 2013, quality is claimed to have improved since then and in 2018 an average reject rate of 1.5% has been reported.

time [418]. A test for Light and elevated Temperature Induced Degradation (LeTID) would be preferable as a way of screening out the worst performing products but does not currently have a standardised basis. The introduction of a test into IEC 61215 or as separate technical recommendation is currently under discussion

Other factory quality problems identified include on the material side silicon and silver impurities, and in relation to assembly processes badly aligned tabbing [419]. It is also claimed that, linked to these types of defects, the efficiency of modules can be negatively affected. Based on the results from the implementation of factory quality improvements across a range of production aspects, an increase in the Wp rating of modules of between 1% and 7% is claimed.

Performance requirements associated with these tests could be complemented by an overall information requirement to declare the lifetime degradation rate over a notional service life of 30 years. This is an important measure of the long-term performance of a solar module and strongly influences the overall life cycle impacts. However, despite widespread unsupported declarations in marketing literature and on datasheets of rates and, linked to these rates, performance warranties, there is no standardised experimental basis for estimating a rate. The declaration of the degradation rate would therefore need to clearly state whether the rate was unvalidated (based solely on laboratory tests and models, to be specified by the manufacturer) or validated (based on field observations). The latter would need to follow the Transitional Method for minimum field observed degradation data collection as proposed by the JRC:

- The data should cover at least 5 (five) consecutive years.
- The experimental data shall cover all the climatic profiles that are considered in the calculation of the annual energy yield of PV modules.
- The data shall be collected from at least 2 (two) separate geographic locations in each climatic zone.
- It should contain open rack ground-mounted, roof-mounted and building added and or building integrated systems (at least 2 of the four options must be included).
- The assigned degradation rate shall be the average of all collected degradation rates from above.

The collated report on the observed degradation rates shall be made available to the National Authorities responsible for market surveillance for control and verification.

As a consequence of the application of this policy option, it is expected that durability is improved for some key performance aspects. The main assumption for this option is that the Base case and low performing modules would be removed progressively form the market, moving largely towards modules with an optimised performance.

Circularity requirements

In addition to the identified durability requirements, it is important to address two key aspects of circular design, namely disassemblability to facilitate repair and dismantleability to facility recycling.

In respect to disassembly the failure rate for modules was reported in Task 4 to be low, at around 0.5%. The junction box and bypass diodes were identified as a point of attention for ease of repair. There is a trend towards soldered instead of plug-in diodes which may prevent replacement. Stakeholders also noted that the sealing of the junction box to improve the IP rating can prevent access. In the case of access and diode replacement being hindered it should be possible to replace the whole junction box.

In respect to dismantling, a BNAT module designed for recycling has been identified. The main feature of the design is that the components and their means of assembly allows for an easier separation of the components and materials, including ease of access to the cells without breakage. Materials are carefully selected in order to allow for recycling. In the case of current module designs, which are more problematic to achieve a clean separation of materials, materials choices may hinder recovery processes.

It is therefore proposed to have information on the design and material content of modules. The purpose would be to facilitate future end of life recovery of valuable raw materials and to identify appropriate recovery routes, for example in the case of encapsulant and backsheet materials where the presence of fluorinated materials could create a processing hazard. It can be envisaged that with the right incentives, bifacial glass to glass module designs, which are predicted to account for 50-60% of the market by 2030, could evolve to adopt some features of the BNAT module designed for recycling.

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[418] An LeTID test study of 10 commercially available PERx modules for Photon International performed by PI Berlin yielded degradation of some models relative output power by ≥5% and in some of these cases the degradation curve did not appear to have reached saturation. Some degree of recovery has been observed but the extent that can be expected in the short to medium term is not clear.

[419] Personal communicationwith Thomas Sauer, EXXERGY

Table 164. Module policy option 2.2: Quality, durability and circularity requirements

Performance aspect	Detailed proposed requirements
Performance requirements	
Option 1 2.2.1 Comprehensive durability product test sequence	• Each model shall be certified to have passed the comprehensive product test sequence required for qualification under IEC 61215. To ensure conformity this requirement could be further extended to require factory quality controls and auditing according to IEC TS 62941 and IECRE OD 405 series.
Option 2 2.2.2 Specific durability tests	Component degradation - *UV pre-conditioning:* MQT10 of IEC 61215 over four cycles of 60 kWh/m^2 in the two stipulated UV wavelength ranges, followed by visual inspection and a pass/fail based on no detectable browning of the encapsulant/laminate. - *Damp heat:* MQT 13 of IEC 61215 extended to 2500 hours of exposure divided into four separate cycles followed by application of the pass criteria. - *Potential Induced Degradation:* Testing according to IEC 62804 shall result in no more than a 5% power loss after 192 hours at 1000V. Water ingress - *Junction box:* Achievement of an Ingress Protection rating of at least IP67, category 1 according to EN 60529. Cell integrity - The inactive cell area shall be no more than 8% upon optical inspection using electroluminescence imaging[420].
Information requirements	
2.2.4 Lifetime performance degradation	The manufacturer shall declare the average linear degradation rate expected over a notional service lifetime of 30 years. This shall be the same rate that is used as the basis for the power warranty (if offered). The declaration shall be clearly identified as being either: – *Validated:* The manufacturer's claim shall be an average derived from a series of field observations made according to the Transitional Method, in regard to the number, geographical coverage and the time series. – *Unvalidated:* on the manufacturer shall report on the basis for their claimed rate with reference to accelerate life testing methods and modelling..
2.2.5 Repairability	The manufacturer shall report on: – the possibility to access and replace the bypass diodes in the junction box [421],

	– the possibility to replace the whole junction box of the module *Note: the possibility exists to include semi-quantitative criterion if a product specific standard is developed in accordance with the forthcoming horizontal standard for repairability prEN 45554.*
2.2.6 Dismantlability	The manufacturers shall report on: – the possibility to separate and recover the solar cells or semi-conductor material from the module. – Design measures to prevent breakage and a clean separation of the cells and/or to maximize the purity of the recovered semi-conductor material. *Note: the possibility exists to include semi-quantitative criterion if a product specific standard is developed in accordance with the forthcoming horizontal standard for recyclability prEN 45555.*
2.2.7 Material disclosure	The manufacturer shall declare the content in grams of the following materials in the product: – Antimony – Cadmium – Gallium – Indium – Lead – Silicon metal – Silver – Tellurium For the encapsulant and backsheet the manufacturer shall also declare the type of polymers used (including if it is fluorinated or contains fluorinated additives) and the content in grams.

Proposed Ecodesign inverter requirements under Policy Option 2

Two sets of requirements are proposed for PV inverters that each address specific aspects of performance:

1. The first set that has the objective of removing the remaining poor performing products and ensuring that inverters in the residential market segment in particular support smart monitoring of PV systems.
2. The second set that has the objective of ensuring that all inverters meet minimum requirements for their quality and durability.

This allows for these two distinct aspects of performance to be analysed and modelled. These two sets may also be combined into one set of requirements and this combination has also been modelled (see section 7.2).

Inverter option 2.3: Performance requirements on efficiency

This initial Ecodesign option would introduce a cut-off based on the Euro Efficiency of the inverter product. Whilst the results of Task 4 and 6 suggested that there is a limited potential for further improvement based on the Euro Efficiency and Task 2 reported that the digitalisation of inverters has raised their overall efficiency significantly, there is evidence that a small

[421] This is the main option available for the repair of a module in order to minimise yield loss during the lifetime of the product.

number of less efficient products are still being placed on the EU market, some of which have an efficiency as low as 93% [422]. These include both products imported into and manufactured in the EU. The proposed requirements are presented in Table 165.

Additional requirements are proposed to support the *'smart readiness'* of PV systems. The inverter can integrate monitoring features capable of supporting the advanced yield monitoring and fault diagnosis of PV systems. This improvement aims to facilitate system level improvements in the residential segment and is supported by the two best performing PV system design options in Task 6, which rely on monitoring and fault diagnosis to support repair response and maintenance.

Minimum hybrid inverter energy efficiency requirements

In order to facilitate self-consumption, some consumers are choosing to integrate inverters and battery storage. However, the process of charging and discharging power from the battery introduces the potential for significant losses.[423] It is therefore proposed to include an overall hybrid system efficiency requirement.

The measurement of the efficiency is proposed as being based on the method that has been developed by the Effibat project, which has led to the publication of "Effizienzleitfaden 2.0[424]. The standard measures the DC/DC and DC/AC conversion efficiencies at different steps in a system design – covering AC coupled, DC coupled and generator coupled systems. It also addresses standby losses. Although this is a relatively new private standard it may soon be adopted as a DIN (Deutsches Institut für Normung) national standard in Germany. is based on the laboratory testing of the hybrid products of a range of major inverter manufacturers and so could inform a transitional method and, at this stage, form the basis for an information requirement.

Minimum inverter smart readiness

Inverters can play a key role in providing the in-line data required to achieve these improvements but to date smart monitoring capabilities have largely only been integrated into the specifications of large inverters targeted at commercial and large scale systems. According to inverter manufacturers a Class C monitoring capability according to IEC 61724-1 would be sufficient to support both home owner and installer remote monitoring/call out response. This would also reflect current best practice for residential equipment, therefore being suitable for Ecodesign as a minimum functionality.

Linked to this it could be considered to establish a requirement for the data transfer protocol. The focus should be on the system communication protocol rather than the internet protocol. There are a number of common industry protocols for smart metering (Mbus) and for SCADA systems (Modbus, fieldbus, LonWorks, Bacnet). Cable and wireless connected inverters generally use Fieldbus or Modbus and a variant of the latter called Modbus Sunspec. They are both open platforms which originate from industry with a basis in IEC standards, namely IEC 61158 (withdrawn) and IEC 61784. ,. Modbus appears to be the appropriate protocol for residential scale.

[422] *The ENF solar directory identified that of the 4108 on-grid inverter models listed on the world market, there are 458 with a euro efficiency performance in the range of 93 - 96%. These include micro, string and central inverter products supplied to the major PV markets in Germany, Italy and Spain.*

[423] *A base case system model for the Effibat project indicates possible losses of income of about 13%*

[424] *BVES, Effizienzleitfaden für PV-Speichersysteme v. 2.0.1, July 2019, https://www.bves.de/effizienzleitfaden_2/*

Table 165. Inverter policy option 2.3: Efficiency requirements

Performance aspect	**Detailed proposed requirements**
2.3.1 Euro Efficiency requirement *Option 1* Euro efficiency minimum requirement for PV inverters without storage	Require a minimum efficiency at Tier 1 of 94% and Tier 2 at 96% measured according to EN 50530. *Allowances shall be provided for micro-inverters and hybrid inverters to offset for their other benefits.*
Option 2 Euro Efficiency declaration and supporting information requirement	Declaration of the Euro Efficiency measured according to EN 50350. In addition the following supporting information shall be provided: - The efficiency values shall be presented in a tabulated form. - An annual temperature derating factor for the climate zones defined in IEC 61853-4 and calculated relative to 25ºC
2.3.2 Efficiency requirements for PV inverters with possibility to connect storage or with integrated storage	Require a minimum system efficiency of 90% at 25% of nominal power,at minimum MPP voltage with the battery at around 50% state of charge. Measurement to be made according 'Effizienzleitfaden 2.0'.
2.3.3 Smart readiness	Manufacturers shall ensure that the inverter supports class C data monitoring according to IEC 61724-1. The inverter shall have physical and/or wireless connectivity and be capable of communicating with other devices using the Modbus data transfer protocol in accordance with IEC 61158.

Inverter option 2.4: Performance requirements on quality, durability and circularity

This further Ecodesign option would introduce a more stringent set of quality and durability tests for inverter products, as well as addressing the potential for their repair. The results of Task 6 showed that the inverters designed for repair and a longer lifetime were closely matched for the BAT and LLCC options. This is largely because of the anticipated reduction in the failure rate and the number of product replacements. The proposed requirements are presented in Table 166.

Quality and durability

Taking IEC 62093, IEC 60529-1 and in IEC 62109-1 as a starting point for conformity assessment, design qualification tests have been specified for inverters that are intended to located outside. The tests are selected from the IEC 62093 standard and address thermal stress and water ingress, with the main aim being to minimise mid-life failures. These are the two main (outdoor) environmental conditions understood from analysis of inverters in the field to provoke failures. Design qualification according to these tests will contribute towards a more durable inverter product. Whilst the design type approval standard IEC 62093 as a whole could be specified as a main requirement it is not clear the extent to which it is already implemented.

Stakeholders also emphasised that a complementary focus on the implementation of a factory quality standard would ensure that the design quality is replicated at mass production scale. The relevant standard is IEC TS 63157 and an accompanying IECRE Operational Documents for audits is pending development (reserved number OD 411).

Circularity requirements

Based on feedback from manufacturers the approach needs to distinguish between small and large scale inverters, and by market segment. In the residential segment it appears that the practice for products under warranty is to provide on-site

response with substitution of the faulty device. Devices taken off site would then be taken to a repair workshop and may be refurbished. The main common repair that may be carried out on site is the replacement of circuit boards. It appears therefore that a requirement could focus on the ease of replacement of circuit boards and their availability, out of warranty.

For larger string and central inverters, it appears that a more common practice is to provide a documented preventative maintenance and repair cycle for an anticipated design lifetime. This would identify components and include recommended timings for their replacement, thereby allowing owners of the product/model to ensure they follow practices recommended to extend the life of the product.

The materials disclosure included within the Ecodesign proposal 2.2 for modules, which combined hazardous materials and Critical Raw Materials, has been adapted to also include as an information requirement in the 2.4 proposal.

Table 166. Inverter policy option 2.4: Quality, durability and circularity requirements

Performance aspect	**Detailed proposed requirements**
Option 1 2.4.1 Comprehensive durability product test sequence	• Each model shall be certified to have passed the comprehensive product test sequence required for qualification under IEC 62093. • • To ensure conformity this requirement could be further extended to require factory quality controls and auditing according to IEC TS 63157 and the associated IECRE OD [pending a code].
Option 2 2.4.2 Specific durability tests (for outdoor applications)	*Thermal cycling:* For outdoor conditions, the IEC 62093 Test 6.4 subjected to conditions of -40oC to +85oC for 400 cycles followed by the specified functionality test.
	Operating temperature: Capacitors, inductors and transformers used within inverters shall be selected so that under the most severe rated operating conditions, the temperatures do not exceed the temperature limits specified in IEC 62109-1 Table 1 minus 20 °C (10 °C for capacitors)
	Water ingress: Achievement for outdoor conditions an Ingress Protection rating of at least IP65, category 1 according to EN 60529.
Additional information requirements	
2.4.3 Repairability requirements for inverters <30 kW	The manufacturer shall identify which of the circuit boards can be replaced by an on-site repair service.
2.4.4 Repairability requirements for inverters >30 kW	Manufacturers shall provide a preventative maintenance and replacement cycle. This shall include a list of parts that may be replaced and the timing of preventative measures to achieve a declared intended design technical lifetime (as required in IEC TS 63157). *Note: the possibility exists to include semi-quantitative criterion if a product specific standard is developed in accordance with the forthcoming horizontal standard for repairability prEN 45554.*
2.4.5 Material disclosure	The manufacturer shall declare the content in grams of the following materials in the product as a whole and in the replaceable circuit boards: – Cadmium – Gallium – Indium – Lead – Silicon carbide – Silver – Tantalum

Ecodesign option 2.5: Provision of life cycle GER and GWP performance data

This additional overarching Ecodesign option would establish a standardised basis for the collection, analysis and presentation of module and inverter life cycle data and Life Cycle Assessment (LCA) results in the EU. The initial focus would be on two impact categories – primary energy (GER) and Global Warming Potential (GWP). The latter is also sometimes referred to as a carbon footprint or embodied CO_2 emissions. The initial proposal is presented in Table 167.

Manufacturers would be required to provide LCA results obtained in conformity with the standard for construction product Environmental Product Declarations EN 15804 and/or with reference to the PEF Category Rules for photovoltaic modules. This would represent a first step towards ensuring that good quality, verified life cycle performance data was available for all products on the market, and would serve the dual purpose of supporting the building sector and the energy sector. Given that a period of time would be required for manufacturers to prepare declarations a tiered approach could be adopted.

Given that the majority of solar photovoltaic applications are anticipated to be building attached, and that in particular for Nearly Zero Energy Buildings (NZEB) solar PV is the renewable energy technology of choice for building designers [425], it is considered appropriate to align the requirement with the EN standard for construction product Environmental Product Declarations. Whilst in some EU countries the availability of EPD's for construction materials is generally good, the availability of EPDs for technical building systems is poorer, resulting in the need to use default data in building LCAs.

In most cases the results would need to be verified and registered with an EPD scheme [426], such as INES (France), Oekobaudat (Germany) or Environmental Profiles (UK). The process for obtaining such LCA results would consist of a combination of 1) carrying out an LCA according to the relevant Product Category Rules and 2) verifying and registering each model EPD.

Table 167. Ecodesign policy option 2.5: Life cycle data

Performance aspect	**Detailed proposed requirements**
• Information requirement	
2.5.1 Life cycle GER and GWP product declaration	At the latest by [*delayed year of introduction*] and for a representative product from each module series placed on the market, an Environmental Product Declaration (EPD) for, as a minimum, life cycle primary energy (GER) and GWP shall be developed and provided. • For further discussion: options are for the EPD to be in conformity with EN 15804 or the PEFCR and to have been registered with a Type III Product Category Rule operator.
Note: In order for this proposal to be made 'operational' within an Ecodesign implementing regulation, a dedicated check on the legal feasibility of such a requirement in the framework of the Ecodesign Directive should be carried out.	

Policy option 3: Energy labelling requirements for residential PV systems

Description: Requirements would be set that would apply to either the weighted efficiency of a package consisting of a module type and an accompanying inverter type or, alternatively, the calculated energy yield of a whole system design.
Rationale: The aim is to enable consumers to make an informed choice based on the performance of system packages or system designs offered by retailers and installers. It is not considered to be desirable or practical to have component level requirements because they are B2B products. A package approach is proposed as one option, combining the module(s) and the inverter(s) performance information. An

[425] *Check Concerted Action reference*

[426] *Eco Platform, Established EPD programmes, https://www.eco-platform.org/the-eco-epd-programs.html*

extension of this approach to label system designs could also be considered whereby other derate factors are taken into account. The Energy Efficiency Index (EEI) would be based on the derating of the module power rating or CSER with the inverter efficiency. A declaration would be needed for 3 climate zones in order to capture variations in the module performance, for example due to temperature dependency.

The Energy Efficiency Index (EEI) for the system approach is proposed as being based on the module and inverter performance expressed as an overall calculated yield in each of the three climatic zones identified from IEC 61853-4, normalised to the system rating and area. The yield calculation would also take intoaccount the predicted module degradation rate over a fixed lifetime of 30 years.

Evidence:

- Modules: The BAT and LLCC options identified in Task 6 show that there is scope within the market to improve the overall performance of modules, both in terms of lifetime primary energy, use phase yield and cost. Taking into account other factors that can affect long-term energy yield, such as temperature co-efficient, spectral response and performance degradation could further allow for differentiation of product performance.
- Inverters: The BAT and LLCC options identified in Task 6 show that whilst potential euro efficiency gains are more modest further derating losses may be minimised according to the package design and the intended end-use – for example, reduced mismatch losses by using micro-inverters, reduced temperature dependency by using inverters based on new semi-conductor materials.
- Systems: Evidence from selected Member States suggests that the distribution curve of system performance ratios of the stock has the potential to be shifted positively through:
  - better design to take into account of site-specific conditions,
  - learning applied to installation practices
  - reduced losses due to equipment, cabling and maintenance practices.

  A combination of both the repowering of old systems and the optimisation of new system has the potential to contribute.

Expected benefits:

A focus on the point of sale to consumers is expected to increase the visibility of better performing combinations of products or system designs. Clients are particularly interested in yield and performance, hence the focus on these two aspects in selecting the EEI. Moreover, if a Performance Ratio was to be included this could be later monitored after installation.

Calculation of a yield and Performance Ratio is understood to be current practice for designers and installers when estimating system yield and analysing risk mitigation measures. It allows for multiple variables to provide an indication of a system's efficiency. Some countries already have specified PR targets in their subsidy regimes.

Possible drawback:

Labelling is a new concept for PV system packages or system designs. Care would need to be taken with consumer perceptions, as all new solar PV capacity can be considered advantageous and it would be important not to dissuade consumers. The format of the labelling scale would therefore need to be considered, so as not to portray systems with site constraints in a negative light e.g. a residential roof with an east-west orientation.

Verification of the components within packages could prove to be difficult depending on how often they change based on supplier relationships and pricing. It may not be possible to label a system until the design decisions have been made or, in order to offer different performances, a reduced number of parameters may need to be considered in order to simplify the process.

Not all life cycle performance aspects can be covered within an EEI. As a result a focus on maximising use phase yield could lead to trade-offs if high efficiency components which require more primary energy to manufacture them are selected.

NOTE: the present analysis deals with techo-economic aspects. In parallel, a check is ongoing on the legal feasibility of an Energy labelling scheme for PV products/system, in the form of a delegated act in the framework of Regulation 2017/1369[427].

[427] *Regulation (EU) 2017/1369 of the European Parliament and of the Council of 4 July 2017 setting a framework for energy labelling and repealing Directive 2010/30/EU*

Proposed Energy Labelling package and system performance requirements under Policy Option 3

In this policy option the Energy Label could be used to introduce energy classes in order to provide information to retail customers. The results of Tasks 5 and 6 have shown that increased electricity generation for modules, a higher euro efficiency for inverters and a high Performance Ratio for PV systems are key determinants in reducing the life cycle primary energy/kWh generated.

Two options can be considered for the Energy Efficiency Index (EEI) on which the label classes could be based:

1. A package approach: This would combine either the module power rating or the CSER energy rating with a derating based on the Euro Efficiency of the inverter.

A system approach: This would entail the modelling of a PV system design's yield and performance ratio, taking into account more parameters that are specific to the installation, for example, shading, inclination, orientation.The labelling would be the responsibility of those at the point of sale – i.e. installers that have direct contact with retailers and end-retailers of systems.

It has already been noted that, based on initial feedback from a cross section of stakeholders, care would need to be taken with consumer perceptions of such a label and the possible impact on consumer confidence, as all new solar PV capacity can be considered advantageous and it would be important not to dissuade consumers. The format of the labelling scale would therefore need to be considered, so as not to portray systems that are constrained by site conditions in a negative light e.g. a residential roof with an east-west orientation and shading caused by chimneys and parapets.

In regard to specific references within the Energy Labelling regulation to solar technology, there is already a labelling classification that includes the contribution of solar thermal panels to domestic water heating systems as an improvement upon class A, which is the maximium a fossil fuelled system can achieve:

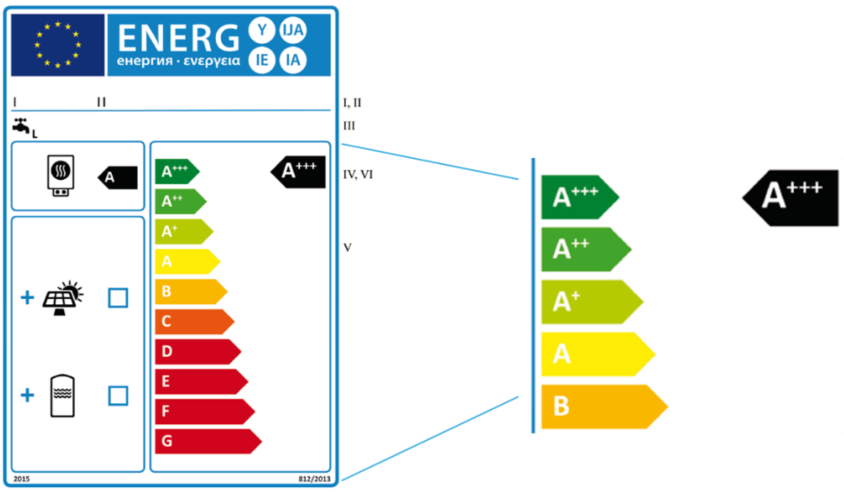
> *(17) Energy labelling of space and water heating products was introduced only recently and the rate of technological progress in those product groups is relatively slow. The current labelling scheme makes a clear distinction between conventional fossil fuel technologies that are at best class A, and technologies that use renewable energy, [...] for which classes A+, A++ and A+++ are reserved.*

In terms of the corresponding colour coding of the classes it could therefore be possible to start from B (orange) so as to indicate a constrained and sub-optimal location and then to label more optimal orientations and system designs A through to A+++ with the coding in different shades of green (seeFigure 148).

Scope of the product group

In line with the findings reported in the Task 1 report and following on the stakeholder consultation on the preliminary evaluation, the product scope is proposed below. BIPV has been included within the scope as it is considered that the CSER for a product can be obtained and, based on feedback from stakeholders, yield information should also be provided for BIPV arrays. The diversity of BIPV products should in this case not pose an issue because only the yield is of concern and not other environmental impacts that may be influenced by the integration design. The issue of operating temperature will require attention within the yield calculation as BIPV products may not be as well ventilated.

Figure 148: Annual. Water heaters label format, incorporating solar water heater scaling



Proposed Energy Label product scope

Modules (as part of a package)

The scope shall correspond to photovoltaic modules selected for use in photovoltaic systems for grid-connected electricity generation. This shall include Building Integrated Photovoltaic (BIPV) products.

Specifically excluded from this scope are:

- Modules with a DC output power of less than 50 Watts under Standard Test Conditions (STC)
- Modules intended for mobile applications or integration into consumer electronic products.

Inverters (as part of a package)

The scope shall correspond to inverters selected for use in photovoltaic systems for grid-connected electricity generation.

Specifically excluded from this scope are:

- Central inverters that are packaged with transformers (sometimes referred to as central solutions) as defined in Commission Regulation (EU) No 548/2014 on Ecodesign requirements for small, medium and large power transformers.

Systems

A photovoltaic system is an assembly of components that comprises the following sub-systems: module array, switches, controls, meters, power conditioning equipment, PV array support structure, and electricity storage components. It also comprises cabling connecting these components.

The scope is limited to grid connected systems installed on residential buildings and with low voltage connections that facilitate self-consumption of the electricity generated by the occupants. This shall include Building Integrated Photovoltaic (BIPV) systems made up of one discrete array consisting of a homogenous PV product.

Residential package energy label option 3.1: Simplified approach based on component efficiency

This first option is simpler to calculate as for both components it is proposed to be based on efficiency standardised rating or efficiency metric. The Energy Efficiency Index (EEI) could be based on the module efficiency (based on the power rating) or yield (energy rating) derated by the euro efficiency. This EEI would server as a proxy for improved yield. See Table 168

Table 168. Energy label policy option 3.1: Efficiency-based EEI

Performance aspect	**Detailed proposed requirements**	**Modelling assumptions**
3.1 Package Efficiency-based approach	The package provider shall combine either: 1. the module power rating measured according to IEC 61853-1 under Standard Test Conditions and expressed as an efficiency, or 2. the module energy rating calculated according to IEC 61853-3 for the reference climate described in IEC 61853-4, with The Euro Efficiency is to be measured according to EN 50530.	The label is modelled to 2030 and that increasing numbers of package combinations achieve ratings of A+ and A++.

In this scenario, a new label class differentiation could be created with five energy classes ranging from B to A+++. Bands of efficiency are then assigned to label classes based on a combination of the performance of the module and inverter models selected to form part of a package offered to consumers. An issue to take into account when establishing the number of label classes are the performance tolerance levels. According to the ENF Solar database the majority of module models had a

tolerance of approximately +/- 5%.[428] Because of this relatively wide possible tolerance the number of label classes would be limited to approximately five.

Table 169 shows an indicative energy label class distribution, together with an indication, per each class, of the typical values of inverter and module efficiency. In practice the energy class of the package would be derived from a derating of the module efficiency by the inverter efficiency, therefore combinations other than those of the table are also possible.

Table 169. Indicative Energy Label class distribution

Label class	**Combined performance**	**Indicative module efficiency**	**% Models**	**Indicative inverter euro efficiency**	**% Models**	**Indicative technology packages**
A+++		*>21.5%*	0%	*Empty*	0%	Tandem perovskite + MOSFET
A++	>19.6 – 21.6%	>19 – 21.5%	4%	>98%	11.6%	SHJ, bifacial + MOSFET
A+	15.3 – 19.6%	>16.5 – 19%	40.6%	>96 – 98%	55.5%	Mono PERC/PERT +String Central
A	12.2 - 15.3%	>14 – 16.5%	43.7%	>94 – 96%	16.4%	BSF, CIGS, CdTe +Micro-inverters
B	8.5% - 12.2%	9-14%	10.9%	<94%	16.3%	BSF, A-Si

Residential system energy label option 3.2: Yield and performance ratio based approach

This option is more complex to calculate but would have the benefit of accommodating a wider range of product performance characteristics, reflecting site specific conditions in the field. It would also allow for system designers to tailor yield estimations to the specific parameters of the installation and to reflect the quality of the electrical design, including the use of low-loss wiring. There would be the potential to later certify the calculated energy rating of the 'as-installed' design, in a similar way to building Energy Performance Certificates (EPCs). Table 170 presents the requirements.

Task 1 identified previous attempts by labels to establish system design and yield criteria. One of the main problems encountered was the need for agreement on a common calculation method which could be used by all actors in the market. Within the frame of the transitional methods under development a simplified tool for modelling and reporting on a system yield is therefore proposed. This would include default values for a number of derate factors within the Performance Ratio of a system. System and site specific values could be entered by designers.

Whilst the main information on the label could be calculated for a reference EU climate, there are distinct variations in performance between module products in different climate zones. For example, some modules have a lower temperature co-efficient and will perform better in a warmer climate. Design choices specific to the site and the electrical configuration would also be taken into account.

For the calculation of the system yield and performance a ratio it is proposed that the following design and derate factors are factored into the yield calculation:

[428] The ENF solar directory identified that of the 34.405 models of PV modules listed as being supplied in the EU, there are 27113 that have a tolerance between +/-5%. This represents 80% of the modules.

- The solar radiation for the location,
- The orientation and inclination of the module array,
- the energy rating (CSER) and yield calculation for the modules, which includes for temperature dependency and spectral response,
- the degradation rate of the modules,
- the Euro efficiency of the inverter(s),
- System losses from:
  - module mismatch,
  - AC and DC wiring,
  - Diodes and connectors
  - Inverter temperature derating
  - Shading,
  - soiling.

For certain input parameters data would be needed from the module and inverter manufacturer, whereas for others either prescribed or site specific values could be used. It is anticipated that this Energy Label option would have the effect of encouraging the selection of modules and inverters to achieve higher yields, as well as system designers and installers to offer to clients design options that are optimised to site conditions and which have lower Performance Ratios.

Table 170. Energy label policy option 3.2: System yield-based EEI

Performance aspect	**Detailed proposed requirements**
3.2 System yield-based approach	The system provider shall follow instructions for the calculation of the overall yield derived from the Performance Ratio for the system design. In addition: – The calculation shall be representative of a notional 30 year service life. – The derate factors to be considered, together with prescribed (default) values, are to be provided in the Implementing Regulation. – The potential to report the PR for a reference location and up to 3 other representative EU climate zones shall be considered. The EEI shall be expressed in units of MWh/kWp.m^2. *Note: useful supporting information would be an average hourly energy output [kWh] profile per month to support calculating a building's energy consumption and to enable accounting for self-consumption.*
3.2.1 Module DC Performance Ratio input variable to the system EEI	The system provider shall calculate and normalise the module yield to kWh/m^2 for the system. The yield shall be derived from the CSER calculated according to IEC 61853-3. In addition: – The module yield shall be adjusted to take into account the declared linear degradation rate over 30 years. – The degradation rate shall be either the prescribed (default) value for the module technology or a field validated rate in accordance with the requirements in the Transitional Method.
3.2.2 Inverter AC input variable to the system EEI	The package provider shall use the inverter Euro Efficiency calculated according to EN 50530.

Various possible locations and configurations for a PV system should be reflected in the label. This is proposed as being achieve by including a yield calculation for the following three climate zones, as defined in IEC 61853-4:

- subtropical arid,
- temperate coastal, and
- temperate continental.

The PV system provider would have the option to choose between the use of prescribed (default) and user defined PV system configuration factors. in the calculated yield along a notional 30 year service lifetime would then be normalised to kWh/kW.m^2

as indicated in the example in Table 171. For more details on the calculation, please see the separate calculator tool which forms part of the supporting Annex on Transitional Methods [429].

Table 171. Draft indicative lifetime PV system AC Energy yield (kWh/kW.m^2)

	PV system configuration		**Energy Label**	
Climates	Default	User defined	**Default**	**User defined**
Subtropical arid	2159	3325	**D**	**B**
Temperate coastal	942	1450	**D**	**B**
Temperate continental	1216	1873	**D**	**B**

Taking into account the consideration of perception and the potential to use the approach applied to solar water heaters, an indicative label scale and the sensitivity by climate zone is shown in Table 172.

Table 172. Draft energy label classes classified by the lifetime energy yield of a PV system in three different climate zones

	Lifetime AC Energy yield (MWh/kW.m^2)		
Energy Label	**Subtropical arid**	**Temperate coastal**	**Temperate continental**
A+++	> 3.61	> 1.58	> 2.04
A++	[3.61 - 2.93)	[1.58 - 1.28)	[2.04 - 1.65)
A+	[2.93 - 2.24)	[1.28 - 0.98)	[1.65 - 1.27)
A	[2.24 - 1.55)	[0.98 - 0.68)	[1.27 - 0.88)
B	< 1.55	< 0.68	<0.88

As for other product categories that are covered under Energy label requirements, a QR matrix barcode could be addedwhich would refer to the European Product Database for Energy Labelling (EPREL), where the main input parameters for selected module and inverters could be gathered.

To date, there are already a few examples of energy labels on packages/systems, in particular on water heaters, space heaters and solid fuel boilers[430]. Guidelines have been prepared in order to clarify the responsibilities of manufacturers, dealers and installers[431]. Comments from stakeholders on this kind of label, gathered in the context of the ongoing review study on the Ecodesign and Energy Labelling measures on space and combination heaters (task 1, in particular[432]), highlighted some areas for potential improvement, summarised as follows:

- potential user groups are not familiar with the label or do not recognise its benefits,
- enforcement (i.e. market surveillance) is considered insufficient,
- installers rarely use this label, which, on the contrary, is mainly used by manufacturers to show the higher rating of the package of heater, temperature control, heat pump and/or solar device.

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[429] *Joint Research Centre, Transitional methods for PV modules, inverters and systems in an Ecodesign Framework, Technical Report, 2019*

[430] *See Commission Delegated Regulation (EU) No 811/2013, Commission Delegated Regulation (EU) No 812/2013 and Commission Delegated Regulation (EU) No 2015/1187*

[431] *https://ec.europa.eu/energy/sites/ener/files/documents/guidelinesspacewaterheaters_final.pdf*

[432] *https://www.ecoboiler-review.eu/downloads/20190326_Boiler%20TASK%201%20draft%20final%20report%20Mar%202019.pdf*

Policy option 4: EU Ecolabel criteria set

Description:

A criteria set would be established that would apply to a combination of a package placed on the EU market and the related system design and installation service offered to consumers.

Rationale:

To foster green innovation in module and inverter design and improve the environmental performance and quality of photovoltaic installations. A dual focus not just on yield improvements, but also on long-term durability, repairability and dismantleability to support recycling and reuse, is considered important because of the projected mass deployment of photovoltaic systems. It is therefore important to signal which aspects of design and operation should be the focus of attention in order to avoid future environmental problems that can be anticipated to arise from management of the stock of modules and inverters.

An approach focussed on the two key components of a system is considered to be justified because they are business to business (B2B) components of all PV systems and so the criteria could support the choice of products with a superior environmental performance at the point of being placed on the market to distributors, retailers and installer. Modules and inverters could therefore be labelled as intermediate products, allowing installers and designers to choose EU Ecolabelled components to offer as part of an EU Ecolabel PV system service 'offer'. Moreover, aspects of the system 'offer' are important in the delivery of a long lasting, high performance system to consumers.

Evidence:

- PV market: Projections for PV deployment continue to be revised upwards and as yet only a small proportion of the market potential has been realised. Long-term issues arising from design quality, performance degradation, short replacement cycles and end of life handling can be addressed through better product design,
- Modules: both the Task 5 LCA review and Task 6 results show that there is margin to reduce the life cycle primary energy use by choosing the best products currently available in the market. Moreover, in locations with lower solar resource there is the need to minimise it in order to have a better energy payback time. A further distinction can be made by referring to life cycle GWP. This allows for the level of decarbonisation of the energy networks where products are manufactured to be differentiated.
- Inverters: the results of Task 6 showed that the most significant opportunity to improve the life cycle performance of inverters is by extending their lifetime and ensuring they are repairable. They can also play an important role in supporting better system performance if they include smart monitoring and, in the case of larger systems, fault diagnosis capabilities.
- Service/system design: a review of literature on minimising LCOE was made in the preliminary report for the EU Ecolabel and GPP. This revealed the importance of the staff training and capabilities in the following aspects when providing a service:
  - surveying and simulating the installation conditions,
  - electrical engineering in solar energy systems, and
  - protocols for the handling and transport of modules.

Expected benefits:

- Benchmarks would be established in the market for products with reduced environmental performance along their life cycle and for the quality of services provided to consumers.
- A focus on the whole life cycle, hazardous substances and circular aspects, including durability, that have been requested by a broad cross section of stakeholders.
- The criteria could, for inverters, drive a focus on repairability and customer support – particularly for the sub-20 kW market segment – and promote their role as a digital gateway to system performance monitoring.

Possible drawbacks:

- If the criteria were not compatible with the EPEAT Photovoltaic Modules and Inverters Product Category criteria there could be duplicated efforts to establish labels with different criteria.
- Whilst there appears to be interest from the sector, there is a risk with a multi criteria set that no one product can comply with all criteria.
- It is not clear that there is a consumer demand for the higher environmental performance of modules, inverters or services, as opposed to a higher yielding and more profitable photovoltaic system.

Proposed EU Ecolabel criteria set under Policy Option 4

Scope of the product group

In line with the findings reported in the Task 1 report and following on the stakeholder consultation on the preliminary evaluation, the product scope and definition are proposed as follows:

Proposed EU Ecolabel product scope

Modules (as part of a package)

The scope shall correspond to photovoltaic modules selected for use in photovoltaic systems for grid-connected electricity generation.

Specifically excluded from this scope are:

- Modules with a DC output power of less than 50 Watts under Standard Test Conditions (STC)
- Building Integrated Photovoltaic (BIPV) products that incorporate solar photovoltaic cells
- Modules intended for mobile applications or integration into consumer electronic products.

Inverters (as part of a package)

The scope shall correspond to inverters selected for use in photovoltaic systems for grid-connected electricity generation.

Specifically excluded from this scope are:

- Central inverters that are packaged with transformers (sometimes referred to as central solutions) as defined in Commission Regulation (EU) No 548/2014 on Ecodesign requirements for small, medium and large power transformers.

Systems

A photovoltaic system is an assembly of components that comprises the following sub-systems: module array, switches, controls, meters, power conditioning equipment, PV array support structure, and electricity storage components. It also comprises cabling connecting these components.

The scope is limited to grid connected systems installed on residential buildings and with low voltage connections that facilitate self-consumption of the electricity generated by the occupants.

Findings of the feasibility evaluation

The background preliminary evaluation of the feasibility of having EU Ecolabel criteria was published in a separate document in support of the Preparatory Study[433]. Section 7 of the preliminary report presented the findings of an LCA hot spot analysis which, together with the other requirements established by the Ecolabel Regulation (EC) 66/2010 including a review of existing standards and ecolabels, was used to identify a set of possible first criteria areas.

A qualitative evaluation, which was made with reference to DG Environment's criteria for establishing new product groups, found there to be feasibility but indicated some areas of uncertainty. A summary as presented to the EU Ecolabel Board is provided in *Table 173*. An important linked issue identified by stakeholders would be the need to complement performance metrics and requirements used in any mandatory policy measures brought forward, with the EU Ecolabel extending or making stricter those requirements.

[433] *Draft options and feasibility evaluation for the EU Ecolabel and GPP, 10/04/19, JRC evaluation report, http://susproc.jrc.ec.europa.eu/solar_photovoltaics/docs/190410_PV_Prep_study_Ecolabel_and_GPP_Preliminary_Consultation_Draft.pdf*

Table 173. Summary findings from the EU Ecolabel preliminary feasibility evaluation

Evaluation criteria	**Finding**	**Observations**
1. Feasibility of definition and scope	To check	Possible focus on kits/packages for residential systems (<5-10 kW) and service offer, but the point of award would need clarification
2. Existence of other ecolabels and schemes	Uncertain	Three standards/labels have criteria that could be reflected in an EU Ecolabel criteria but, to date only one has been awarded to a PV product.
3. Market significance	Uncertain	No specific products can be identified that would achieve all of the identified improvement potential. A points system could allow for flexibility in award.
4. Visibility	Positive	A high profile green product but the degree of visibility for the EU Ecolabel may depend on the point of sale for the PV system or components
5. Potential uptake	To be seen	An industry consortium made a proposal for PV modules in 2015/6. This suggests there are potential verifiers and some manufacturers interested/ready to bring products forward for labelling.
6. Alignment with legislation and standards	Positive	Moderate>strong contributing role was identified in implementing some of the main objectives of energy, construction, electrical equipment and circular economy.
7. Environmental impacts analysis	Variable	There is the potential for performance improvement. There is a lack of performance metrics, performance benchmarks and/or standardised methods for several of the possible criteria areas.

Options for broad criteria areas

Based on this preliminary work, an approach is proposed that is mainly targeted at residential systems of <10 kWp. Taking into account the need for prior verification of products or services by EU Ecolabel Competent Bodies in a selected Member State, two options are proposed for consideration for a multi-criteria set:

1. Package approach: There would be criteria for modules and inverters. The criteria would extend the focus of policy options 2 and 3 on life cycle hot spots, hazardous substances and circular design, introducing more demanding criteria and performance thresholds.
2. Service approach: There would be criteria for the main components of a PV system (i.e. modules and inverters) together with criteria covering aspects of the service provided by system installers. Service aspects could include:
   - the system design factors taken into account, including factors influencing the Performance Ratio
   - the protocols used for the transport/handling of modules;
   - the installation of monitoring capabilities, and
   - the provision of maintenance/aftercare services

It is proposed to combined the benefits of the two approaches. The first would allow for the specifics of the two 'hot spot' components of a residential system to be addressed, whilst the service is considered to represent a more consumer-facing aspect that could create added value for installers using the label.

Findings from Task 6 and the LCA hot spot analysis

The Task 6 results for PV modules have shown that on the lead indicator used, primary energy, the margin for reduction between the best product and the base case, is 31%. For the BAT, CIGS, the margin for reduction is 24%. It is important to note, however, that performance of the mono PERC 2020 and optimised mono PERC deliver a result that is within the margin of error of the BAT, whilst having a higher life cycle electricity yield (see the discussion below relating production and use stages).

It is notable that even with a lower module efficiency and a higher degradation rate the CIGS product still performs better overall when considering the whole life cycle. Secondary indicators were also identified – namely PAH, POP and heavy metals

to air and water – that can be reduced by material efficiency in component and system design. However, the improvement from specific changes in specification – for example, to lead-free solder – have only a limited overall impact because of the inherent trade-offs in substituting them with other materials.

The LCA hot spot analysis carried out in Task 5 highlighted the important influence of the module cells, inverter circuit boards and, in the case of ground mounted systems, mounting structures, on the overall life cycle impacts. They also highlighted the impact of the long-term performance degradation rate on the life cycle primary energy use for some technologies. Indicatively an increase in the degradation rate from 0.5% to 0.7% would lower the energy yield by 7% meaning that environmental impacts would rise proportionally another 7%. Comparing a base case (30y, 0.5% degradation) to a case where lifetime is 30 years and the degradation rate increases to 0.7%), the environmental impacts would be 15 % higher compared to the base case. Criteria to minimise long-term performance degradation should therefore be considered.

The results of the hot spot analysis have also shown that it is important to consider the relationship between the life cycle impacts in the use phase and life cycle benefits of the energy generated by a PV system in the use stage. This relationship is not yet well accounted for or standardised in the LCA studies reviewed or in LCA standards such as the PEFCR or EN 15804. A number of methods exist to express this relationship, either on a relative basis (Energy Payback Time) or absolute basis (Energy Return on Investment) [434].

The ratio of the production phase primary energy investment and the electricity generated in the use phase can vary considerably between locations, and thereafter between products and systems. For multi-silicon module-based systems this Energy Return on Investment (EROI) ratio can be 1:4 or 1:7 if the modules are installed in Helsinki or Madrid respectively. There is therefore significant margin to reduce the EROI in climates with less solar resource.

For inverter, the results of Task 6 showed that the inverters designed for repair and a longer lifetime were closely matched in terms of the BAT and LLCC options. This is largely because of the anticipated reduction in the failure rate and the number of product replacements that would be needed.

Other areas of improvement identified by the LCA hot spot analysis that apply to both modules and inverters include the potential to reduce the content of metals such as copper and aluminium that contribute significantly to toxicity impact categories. As already noted, hazardous substances such as lead and cadmium contribute overall less strongly as well as bulk materials such as copper and aluminium. While requirements under the RoHS Directive don't currently apply to modules, the EU Ecolabel could include criteria controlling their presence and ensuring proper end of life treatment.

The potential benefits of advanced yield monitoring and fault diagnosis for PV systems are also highlighted by the system results in Task 6. The two best performing PV system options rely on monitoring and fault diagnosis to support repair response and maintenance. Inverters can play a key role in providing the in-line data required to achieve these improvements but to date smart monitoring capabilities, such as SCADA integration and via field or modbus communication protocols, have largely only been integrated into the specifications of large inverters targeted at commercial and large-scale systems.

EU Ecolabel criteria set option 4.1: Residential package with services

A first possible set of criteria has been configured based on the Preparatory Study findings to date, the draft evaluation report and feedback from stakeholders. The criteria address the key environmental hot spots for both modules and inverters – the manufacturing and life cycle management of module cells and inverter circuit boards - as well as addressing supporting services that could be offered by designers and installers which have the potential to address priority areas for improvement identified in Task 4 – including site specific design to optimise yield, and electrical design and ongoing maintenance to minimise losses.

It is proposed that the products scope for the package with services approach is the residential market segment, although the scope shall be written in such a way that the collective or community purchase of solar PV systems shall be included. In addition it shall be possible to use the criteria for GPP purposes.

Because the EU Ecolabel is a voluntary instrument it is difficult to estimate the possible impact of this proposed criteria set. The assumption used for the modelling is the achievement of an annual take-up of 5% of new residential systems by 2030. The improvement potential is assumed to be based on a comparison with the base case 3 kWp residential system and base case module and inverter components. See Table 174.

[434] *IEA Methodological guidelines*

Table 174. Ecolabel criteria set for modules, inverters and services

Performance aspect	**Detailed requirements**
4.1 Energy and CO_2 criteria	
4.1.1 Energy return on investment	The EU Ecolabel applicant shall calculate the energy return on investment for the module and inverter package. The EROI should be below [*to be determined*]. *The production and use stage primary energy use shall be derived using the method set out in the corresponding Ecodesign information requirement, which is proposed as being based on EN 15804 and the PEFCR.*
4.1.2 Life cycle GWP	The EU Ecolabel applicant shall calculate the life cycle GWP for the module and inverter package. The kg/CO_2.kWh shall not exceed [*to be determined*]. *The life cycle impacts shall estimated according to method set out in Ecodesign, which is based on EN 15804 and the PEFCR.* *Note:* there is an option to provide default values in tabular form as has been done by the French Government for the national PV capacity auction process.
4.2 Hazardous substances criterion This criterion will require the formal 'derogation' under Articles 6(6)/6(7) of the EU Ecolabel Regulation (EC) No. 99/2010 of a number of substances that may be present in modules and inverters.	
4.2.1 Candidate list substances	The IEC 62474 substance declaration shall be used to declare that Candidate list substances are not present at >0.1%
4.2.2 Lead and cadmium	The content of lead and cadmium in modules and inverters shall be less than 0.1% and 0.01% respectively. By weight or by Wp The cadmium level may be >0.01% if recovery of the semi-conductor can be demonstrated as part of a take back service provided.
4.2.3 Fluorinated backsheets	Module products shall be manufactured without fluorinated backsheet materials.
4.2.4 Glass additives	Antimony and arsenic in glass shall each not be present at >50 ppm
4.2.5 Flame retardants and pthalates	*The hazard restrictions of the personal computer product group on cables and main circuit boards shall apply*.
4.3. Circular economy criterion	
4.4.1 Module durability and quality	• Design type approval proposed as an Ecodesign requirement shall be implemented by an audited factory quality control system in accordance with IEC TS 6 • 2941 and IECRE OD 405 series.
4.3.2 Module degradation rate	Declaration of the rate shall be validated by the Transitional Method for Ecodesign and demonstrate an average performance degradation rate over a 30 year time period of 0.6%
4.4.3 Module design for recycling	The manufacturer shall document and report the sequence of steps and tools required to dismantle the module and recover the solar cells or semi-conductor material. *Note: the possibility exists to base this criterion on product specific standard if developed in accordance with the forthcoming horizontal standard for recyclability prEN 45555.*

4.4.4 Inverter on-site repair service	The installer shall ensure that a responsive repair service is provided for inverters, with on-site replacement of the main circuit boards forming part of the service.
4.4.5 Repairability requirements for inverters	<30 kW: The manufacturer shall ensure that the power, filter and communications circuit boards, as well as firmware updates, shall be made available for a minimum period of 7 years. >30 kW: Manufacturers shall ensure that replacement parts and firmware updates are made available in line with the recommended replacement cycle. *Note: the possibility exists to base this criterion on a product specific standard if developed in accordance with the forthcoming horizontal standard for repairability prEN 45554.*
4.5 System service criteria	
4.5.1 Optimised design	The system design shall be optimised taking into account the specific local conditions of the installation. The service provider shall demonstrate that the system design software used takes into account, as a minimum: – Orientation and possible shading, – Local climatic conditions, including temperature dependency – Exposure/access to the inverter
4.5.2 Handling and installation protocols	The contractors used to install the system shall follow a protocol designed to minimise any breakages to modules during transport to and handling on site.
4.5.3 Monitoring and maintenance	The service shall include, for a minimum of 10 years, the monitoring of the system for faults and a responsive repair and maintenance service designed to optimise performance. This shall include, as a minimum: – Fault diagnosis, – Repair and replacement cycles for major components, and – Cleaning of the modules.

Policy option 5: Green Public Procurement (GPP) criteria

Description: A criteria set would be established that would apply to the process of procuring a solar PV system, from contractor selection through to decommissioning. Additional options would be for a public authority to play a role in boosting solar PV installations either in the residential sector by acting as an intermediary or by contracting new capacity via Power Purchase Agreements.
Rationale: The public sector has a substantial stock of buildings and land on which solar PV could potentially be installed. Once a decision has been made to procure solar PV systems a public authority can in most cases exert an influence on the competencies of contractors, the design of systems, the specification of components and this influence is direct in most cases. In the case of reverse auctions or the procurement of electricity this influence can be extended to third party, installations.
Evidence: ○ Modules: both Task 5 LCA review and Task 6 results show that there is margin to reduce the life cycle primary energy use by choosing the best products currently available in the market. Moreover, in locations with lower solar resource there is the need to minimise production stage impacts in order to have a better energy return on investment. ○ Inverters: the results of Task 6 showed that the most significant opportunity to improve the life cycle performance of inverters is by extending their lifetime and ensuring they are repairable. They can also play an important role in supporting better system performance if they include smart monitoring and fault diagnosis capabilities. ○ Service/system design: a review of literature on minimising LCOE was made in the preliminary report showing the importance of the capacity of contractors in the following aspects when providing a service: surveying and simulating the installation conditions, in the electrical engineering of solar energy systems and having protocols for the handling and transport of module.
Expected benefits: ○ Guidance will be provided that any public authority could use in order to procure competent contractors, quality components and high quality systems with a good yield and performance ratio. It would also support the monitoring of the performance of systems upon installation. ○ The criteria could address both life cycle environmental impacts and the cost and value of installing a PV system. The criteria can be structured to minimise life cycle cost, minimise exposure to unexpected failures and maximise electricity revenue. ○ Local residential installations could be boosted by acting to bring down the costs (indicatively by 20-30%, based on 0.1-0.3% household annual installation rate) of each installation and by increasing confidence in the service and components.
Possible drawbacks: ○ Public authorities may prefer to procure solar electricity rather than engage in the installation of systems and the associated cost and risk. ○ Public authorities may not use the criteria because of pressure to focus only on minimising initial capital cost rather than life cycle cost. ○ As a voluntary criteria set only the easier criteria may be used so that only some of the expected benefits would be realised. The overall criteria set may only therefore be used by a limited number of front runners.

Scope of the product group

In line with the findings reported in the Task 1 report and following on the stakeholder consultation on the preliminary evaluation, the product scope and definition are proposed as follows:

Proposed GPP solar photovoltaic system scope

A photovoltaic system is an assembly of components that produce and supply electricity based on photovoltaic conversion of solar energy. It comprises the following sub-systems: module array, switches, controls, meters, power conditioning equipment, PV array support structure, and electricity storage components. It also comprises cabling connecting these components.

The scope is limited to grid connected systems at all scales. This shall include the provision of energy generated by solar PV systems as a service via arrangements such as Power Purchase Agreements. . It shall also include street furniture that incorporates solar photovoltaic cells

Excluded from the scope are systems which are only designed for the following specific applications:

- For integration with street lighting and electric vehicles
- Systems in which there are modules with DC output power of less than 50 Watts under Standard Tests Conditions (STC)
- Substations and transformers for power conditioning

Findings of the feasibility evaluation

The background evaluation for possible Green Public Procurement (GPP) criteria was published in a separate document in support of the Preparatory Study[435]. Section 7 presented the findings of an LCA hot spot analysis which, together with a focus on Life Cycle Cost (LCC), required as part of GPP criteria development, was used to identify a set of possible criteria areas. A specific focus on minimising the Levelised Cost of Electricity (LCOE) of electricity generated by systems installed by public authorities is proposed.

A qualitative evaluation made with reference to DG Environment's criteria for establishing new product groups, found there to be broadly feasibility. A summary is provided in Table 175. An important linked issue identified by stakeholders would be the need to complement performance metrics and requirements used in any mandatory policy measures brought forward, with the GPP extending or making stricter those requirements. Reference is also usually made to EU Ecolabel criteria when establishing the ambition level for Comprehensive GPP criteria.

[435] *Draft options and feasibility evaluation for the EU Ecolabel and GPP, 10/04/19, JRC evaluation report, http://susproc.jrc.ec.europa.eu/solar_photovoltaics/docs/190410_PV_Prep_study_Ecolabel_and_GPP_Preliminary_Consultation_Draft.pdf*

Table 175 Summary findings from the GPP preliminary feasibility evaluation

Evaluation criteria	Finding	Summary
Step 1: Contribution to objectives	Positive	• Support **greater deployment** and **yield optimisation** • Reduce or **manage environmental impacts along the life cycle** of solar PV systems and components • Contribute towards **achievement of grid parity** for the LCOE of solar electricity
Step 2: Determine the added value of GPP to existing policy instruments	Positive	Potential to play a strong role in promoting **better systems and components** – with a focus on quality, hazardous substances and circular design - but also through **novel procurement routes**
Step 3: Determine if GPP is the most effective instrument to achieve the objectives	Positive	Public sector has a substantial stock of buildings and land on which solar PV could potentially be installed: • the potential influence on the design and specification of components is **direct** in most cases • reverse auctions or the procurement of electricity could **extend this influence** to: - third party, citizen installations – new solar capacity under PPAs
Step 4: Determine the best form of GPP implementation	See draft proposal	A combined focus on **product** (e.g. quality), **works** (e.g. protocols) and **services** (e.g. maintenance) is proposed.

GPP criteria option 5.1: Improved PV system life cycle performance

The GPP policy option is based on the same environmental analysis presented in support of the EU Ecolabel criteria under policy option 4. In addition a focus is introduced on the project management of a PV system installation. This could extend from contractor selection through to decommissioning. An overview of the proposed criteria set is presented in Table 176.

As well as an overall focus on minimising the life cycle environmental impact of a solar PV system, the criteria would also be based on the findings of recent studies of solar PV projects that have analysed strategies to minimise LCOE and 'mitigation' risk. In Tasks 3 and 4 and in the EU Ecolabel and GPP evaluation report specific prioritised actions were identified to manage solar PV system procurement processes in order to:

- optimise the site specific potential to generate solar power,
- minimise risks to loss of income from quality issues that may arise related to equipment and the installation itself,
- minimise the LCOE along the life cycle of a project.

From the analysis made by a number of studies priority mitigation measures can be identified based on Cost Priority Number (CPN) analyses and insurance claims, and based on this evidence, the potential impact on LCOE and bankability. These measures can be grouped into preventative and corrective measures. The combined effect can be estimated to have the potential to reduce annual potential economic losses (measured as CPN) by more than 80%. The evidence from insurance claim analysis also suggests that exposure to internally and externally caused damage can also be minimised, with the cost of incidents having the potential to be in the range of 40-100 €/kWp in year 1 of operation, rising to between 140-150 €/kWp in year 10 [436]. The cost and time incurred in remedial work can also have a dramatic impact on projected payback period for projects.

The modelling assumptions for take up of these voluntary criteria are based on the public sector installation rate for solar PV systems. No distinction is made at this stage between core/comprehensive GPP criteria. It is initially estimated that 4% of annual system capacity is accounted for by public buildings to which 20% could have criteria applied to it by 2022, 40% by 2024 and 80% by 2026 onwards. These assumptions could be revised upwards if retrofit installations on public housing stock were to be included in relevant countries.

[436] *Insurance claim research report reference to be inserted*

Table 176. GPP criteria set for PV system procurement

Performance aspect	**Detailed proposed requirements**
Module and inverter factory quality and performance testing	
5.1.1 Design quality of modules and inverters	*Technical requirement for design qualification and factory quality*: – Core: Design type approval of each model deployed according to IEC 61215 and IEC 62941 – Comprehensive: Factory quality controls and auditing according to IEC TS 63157 and the associated IECRE OD *[pending a code*].
5.1.2 Module degradation rate	*Award criteria based on declared module degradation rate.* Points shall be awarded based on the validated performance degradation rate period expressed as the average annual % loss over a 30 year time. The transitional method shall be used as the basis for verification.
Design and yield estimation	
5.1.3 Energy return on investment	*Award criteria based on declared system EROI.* The EU Ecolabel applicant shall calculate and declare the energy return on investment for the system. *The production and use stage primary energy use for the modules and inverters specified shall be derived from the method set out in the corresponding Ecodesign information requirement, which is proposed as being based on EN 15804 and the PEFCR.*
5.1.4 Life cycle GWP	The EU Ecolabel applicant shall calculate the life cycle GWP for the system. The kg/CO_2.kWh shall not exceed *[threshold tbd*]. *The life cycle impacts shall estimated according to method set out in Ecodesign, which is based on EN 15804 and the PEFCR.* *Note:* there is an option to provide default values in tabular form as has been done by the French Government for the national PV capacity auction process.
5.1.4 System energy yield	*Award criteria based on an estimate of the system yield (with reference to the Energy Label EEI)* The system provider shall make a design estimate of the system yield based on the methodology for calculating the Energy Label EEI. The EEI shall be expressed in units of MWh/kWp.m^2. The contractor shall also declare a target plant Performance Ratio. Under a contract performance clause the yield and target plant performance ratio the installed system shall then be monitored according to IEC 61724.
Installation/ construction	
5.1.5 Handling and installation protocols	*Selection Criteria evidencing the use of such protocols and/or Technical Specification requiring specific actions within a protocol.* The contractors used to install the system shall follow a protocol designed to minimise any breakages to modules during transport to and handling on site.
5.1.6 Commissioning test	*Contract performance clause based on the target plant Performance Ratio* A commissioning test shall be carried out according to IEC 61724 in order to evaluate the Performance Ratio of the system. The commissioning PR shall be compared with the target plant Performance Ratio declared at bid stage.

Operation & Maintenance	
5.1.7 Inverter preventative repair cycle	*Technical Specification based on planning to respond to inverter manufacturers recommended repair cycle* In order to use a longer inverter lifetime than the default for the life cycle GWP calculation manufacturers shall provide a recommended preventative maintenance cycle. This shall include a list of parts recommended to be replaced and preventative measures to achieve an intended design technical lifetime.
5.1.8 Monitoring	*Technical Specification/Award Criteria for the granularity of monitoring system* Manufacturers shall ensure that the system design supports class [*B or C*] data monitoring according to IEC 61724-1. The system shall have physical and/or wireless connectivity capable of communicating with remote monitoring systems using a recognised data transfer protocol.
5.1.9 Maintenance	*Technical Specification/Award Criteria for the provision of aftercare services* The service shall include, for a mínimum of [*award*] years, a repair and maintenance service designed to optimise performance. This service shall include, as a minimum: – Fault diagnosis, – Responsive repair and planned replacement cycles for major components, and – Cleaning of the modules.

GPP criteria option 5.2: Facilitating increased residential system installations

As was highlighted in the draft evaluation report the GPP criteria set could also be used to boost residential deployment by promoting and providing a framework and criteria for 'reverse auctions'. A reverse auction process would see the public authority establishing criteria for the performance of installation services offered to local residents. This option consists of a two part group buying process that is managed by the public authority:

1. the registration of households interested in installing a system on their home, followed by
2. a subsequent supplier shortlisting and tender process to select an installation company on the basis of price and service offers for the registered households.

The public tender for the service may include quality specifications for the systems offered to households, including monitoring systems and an extended guarantee for each system. The auction process also has as a principle objective a reduction in the unit price of each system, with indicatively a price reduction of 35% on market rates obtained in the reference case analysed in the preliminary evaluation. This reduction is anticipated to decline in subsequent procurement rounds. The quality criteria are envisaged as mirroring some of those of the GPP proposal outlined in policy option 5.1, addressing both PV system components and the service provided.

The modelling assumptions for increased residential take-up are based on use of this process by those cities taking part in the Covenant of Mayors for climate and energy initiative. Of the EU local authorities that are signatories 23% (2,156) have established monitored initiatives on the ground [437]. For a small city of 50,000 inhabitants an initial take-up in the first round of 30 homes could be assumed, increasing to 60 and then 120 in subsequent 6 monthly procurement rounds[438]. If this were to be extrapolated to 400 of the 800 local authorities in the EU with a population greater than 50,000 this would approximate to 288 MW of new capacity per annum from 2022 onwards.

[437] *Covenant of Mayors for climate and energy initiative, Accessed 2019 https://www.covenantofmayors.eu/about/covenant-initiative/covenant-in-figures.html*

[438] *This assumption is based on the London reverse auction where out of the 12 boroughs involved the first round achieved 4000 registrations of which 1000 were converted into installations.*

GPP criteria option 5.3: Using electricity purchasing to support new capacity

Stakeholders highlighted the potential to use the electricity purchasing power of public authorities to support the installation of new solar PV capacity. Whilst recent research for DG ENV in support of revised EU GPP green electricity criteria cast doubt on the additionality from criteria that request green certificates as a form of verification, there could be potential for new installations to be tied to bilateral solar Power Purchase Agreements (PPAs). This could also be linked to the provision by the public authority of the sites and/or roofs where the PV systems can be installed.

The subject matter of tenders would be the purchase of electricity generated by new solar photovoltaic system capacity. The scope to include further criteria on how the electricity is to be generated – for example, the environmental performance of the modules or inverters used - would require further investigation, as it may be beyond the legal scope of such a call for tender.

Modelling assumptions have not been developed yet at this stage pending discussions on the legal potential of this type of criteria.

Policy option 6: Combined policy options

It could be considered to combine a number of options that have been evaluated, given that each of them can act in a different way to achieve different improvements in the market. Some of the possible synergies that could be achieved are briefly analysed in Table 177. The two combined options have been taken forward for modelling as the synergies between the mandatory and voluntary instruments are considered to be an important aspect.

Table 177. Evaluation of policy combinations

Policy combination	Advantages	Disadvantages
Mandatory Ecodesign (mandatory) + Energy Label (mandatory)	• The Ecodesign requirements can provide a performance metrics and test methods that act as uniform criteria for products entering the market • The Energy Label can help consumers to choose more efficient system design offers in the market and to expect more from system providers. • The metrics established for Ecodesign would provide input data for the Energy Label EEI	• The Energy Label would have to carefully designed so as not to impact on confidence in the market and the number of installations • Care would also need to be taken with the Ecodesign thresholds not to prevent emerging technologies from entering the market
Voluntary EU Ecolabel (voluntary) + GPP (voluntary)	• EU Ecolabel criteria usually provides the basis for comprehensive GPP criteria • Both criteria sets can address the full life cycle performance of the products including any trade-off between yield and GER • GPP might enhance the take-up of the EU Ecolabel products	• A low take-up of the EU Ecolabel may limit the number of pre-verified products meeting ambitious environmental criteria • Both instruments have a degree of uncertainty as to the take-up
Combined option 1 (COM 6.1) Ecodesign (mandatory) + Energy Label (mandatory) + GPP (voluntary)	• The metrics established for Ecodesign and the Energy Label would provide metrics and benchmarks for used in GPP • Enables procurers to follow the recommendations in the Energy Efficiency directive to use labelled products • Enables procurers to relate the yield of a PV system to the energy payback time	• May result in conflicting information if a high performing system has components that cannot meet the GPP module/inverter criteria
Combined option 2 (COM 6.2) Ecodesign (mandatory) + EU Ecolabel (voluntary) + GPP (voluntary)	• Complementarity – ecodesign would cut off the worst performing products whilst the other would reward the best performers and extend the minimum requirements. • The Ecodesign requirements can provide a performance metrics and test methods for criteria within the EU Ecolabel • The voluntary instruments would address broader life cycle aspects of performance	• Ecodesign does not provide a basis for criteria at system level.- • Both instruments have a degree of uncertainty as to the take-up

Further potential policy options using other EU policy instruments

In addition to the four policy instruments that are the focus of this Preparatory Study, the potential to use other existing policy instruments to act on aspects of solar PV performance has also been identified. This could be considered for inclusion within future revisions of two important Directives that were identified as being of relevance in Task 1 – the Renewables Directive and the Energy Performance of Buildings Directive. One important possible role for these instruments could be to encourage the entry of BNAT technologies into the market that offer improved life cycle performance.

Policy option 7.1: Renewables Directive member state capacity auction requirements

Module and inverter quality and/or performance requirements could be considered for inclusion in any public PV capacity auction process that takes place in member states. This approach has been applied in China and now in France. It is understood that one of the main drivers for the rapid entrance of module improvements such as PERx variants and TOPCon onto the global market has been the Chinese Top Runner requirements, to the extent that the EU now benefits from these products, both in terms of their performance and the manufacturing lines that EU companies supply to the Chinese to deliver the improved module performance.

Policy option 7.2 Energy Performance of Buildings technical systems requirements

Use of provisions within the EPBD that require member states to establish minimum performance requirements for major building renovations and technical building systems could be explored as a means to promote new performance and/or quality requirements. The 2010 EPBD states Article 8 that:

> *'Member States shall, for the purpose of optimising the energy use of technical building systems, set system requirements in respect of the overall energy performance, the proper installation, and the appropriate dimensioning, adjustment and control of the technical building systems which are installed in existing buildings.'*

As was noted in Task 1 solar PV is included within the scope of technical building systems for which a simplified calculation method is provided as an extension to the harmonised method EN 52000. The current scope of technical building systems could be considered for extension to address performance aspects of solar PV systems.

7.2 Scenario analysis

The objective of this section is to set up a stock model (2015-2030) and calculate the impact of different policy scenarios regarding Primary Energy which was the leading parameter from Task 6, consumer expenditure and employment depending on the market evolution of PV modules, inverters and systems. The different policy options have already been identified and possible technical performance criteria and requirements outlined in section 7.1 above.

Modelling scenarios for assessing the impacts of the policy options taken are further described below. The calculated impacts for the different scenarios are indicative and are subject to the simplifications made in previous Tasks 5 and 6 to model the market and improvement options. Proxies are used to map the improvements modelled in Tasks 5 and 6 onto policy options and scenarios.

The analyses on the previous tasks have been extended to the defined scenarios in comparison with the Base case definitions in Task 5 and the Best Available Technologies (BAT) and Least Life cycle cost (LLCC) options identified in Task 6.

7.2.1 Scenarios overview

Different scenarios have been defined to illustrate quantitatively the improvements that can be achieved at the EU level by 2050 with suitable policy actions against the Business-as-Usual (BAU) scenario.

It is also important to mention that a fixed lifetime of 30 years has been assumed for the equipment. During this lifetime, repairs can be done, for example the replacement of inverters.

The reference case and main technical improvement option scenarios based on the findings of Task 6 are defined as follows:

- **Business as Usual (BAU) scenario:** the products placed on the EU market have the same level of performance as the Base Cases defined in Task 4 and market assumptions from Task 2 which were categorized according to their application field: 1 string inverter (residential segment), 3 string inverter (commercial segment) and central inverter (utility scale segment). The system base cases proposed are representative for the market segments of residential (3 kW), commercial (20 kW) and utility scale (1.5 MW), see Task 5. These BAU scenarios are also linked to module technologies modelled in Task 2, they are: Back Surface Field multicrystalline silicon (the 2016 base case), an updated base case to reflect the 2019/20 position, PERx silicon, PERx silicon bifacial, thin film modules (CIGS/CdTe), Hetero-junction (HJT/BJT) and back contact monocrystalline silicon.
- **The Task 6 Best Available Technology and system (BAT) scenario:** It is a proxy scenario that implements all the potential improvements possible from maximum uptake of BAT technologies as identified in Task 6, thereby estimating the policy impact at both product level and system level. This scenario is set up to provide a benchmark of use as a basis for the EU Ecolabel and GPP scenarios, which are strongly based on promoting BAT. This scenario combines greater deployment of the BAT module technologies (CIGS for residential and CdTe for commercial/large scale), BAT inverter technology (longer life products) and BAT systems (design optimisation with improved operation & maintenance).
- **Ecodesign scenarios for modules and inverters:** Taking into account the time needed to elaborate and implement any regulation, the regulation is assumed to enter into force in 2022 under the scenario. Within the Regulation two policy Tiers are considered:
  - Tier 1 policy in place in 2022 and will assume effect in the scenario calculations from 2023 onwards
  - Tier 2 policy in place in 2022 and will assume effect in the scenario calculations from 2025 onwards

  The four variants of the Ecodesign scenario (2.1-2.4) have been modelled separately and in combination for the products, with each having effect on various performance aspects for the two sub-products. The module design option 'further optimisation of BoM' and the inclusion of additional benefits from the 'design for recycling' of future PERC bifacial module designs are used as proxies in order to account for improvements resulting from new designs and material selections. Option 2.5 was proposed as an information requirement only.

  - The Ecodesign performance requirements on modules on lifetime yield scenario (MOD 2.1): It is a proxy scenario for the proposed Ecodesign policy options (2.1) on modules.
  - The Ecodesign performance requirements on module performance on quality, durability and circularity (MOD 2.2): It is a proxy scenario for the proposed Ecodesign policy options (2.2) on modules.
  - The Ecodesign requirements on inverters efficiency and lifetime electricity yield scenario option 2.3 (INV 2.3): It is a proxy scenario for the proposed Ecodesign policy options (2.3) on inverters.

- The Ecodesign requirements on inverters on quality, durability and circularity scenario option 2.4 (INV 2.4): It is a proxy scenario for the proposed Ecodesign policy options (2.4) on inverters.

- **The simple residential package energy package label option 3.1 (LAB 3.1 and 3.1++):** It is a proxy scenario for a simple label based on component efficiency for the residential market to model policy option 3.1.
- **The system residential energy label option 3.2 (LAB 3.2):** It is a proxy scenario for an installers label based on encouraging higher yields from residential system designs under policy option 3.2.
- **The advanced residential EU Ecolabel criteria for packages and services option 4.1 (LAB 4.1 and LAB 4.1++)**: It is a proxy scenario for an advanced label to model policy option 4.1.
- **The GPP scenario options 5 (5.1):** It is a proxy scenario for a combination of BAT for modules, inverters and systems. A simple estimate of the possible increase in residential stock is also separately modelled for 5.2.
- **The combined effect of mandatory and voluntary options (COM 6.1 and 6.2):** It is a representation of how the policies could be combined to achieve synergetic effects in the market.

Module option 2.1 is expected to have a tiered introduction from 2023, taking full effect from 2025.

Modelling of these scenarios is done by linking the market model based on Task 2 to improvement options that were calculated in Task 6. These options are used as proxies for substitutions in the stock relative to the base included in Annex 7A. Additional assumptions have in some cases had to be applied in order to adjust the results to account for, for example, improvements as a result of factory quality systems. Label scenarios LAB 3.1, LAB 3.2 and LAB 4.1 combine the substitution of product combinations with other market effects as described below:

- LAB 3.1 + assumes a combined effect with MOD 2.1 and INV 2.3affecting the performance distribution curve of market, thereby enabling more systems to enter class A. Also it assumes a substitution of other less efficient module products by more efficient products (2020 revised base case by PERC, PERC by SHJ or back contact IBC), but without an increase in installed capacity, i.e. less modules are installed to achieve the same 3 kWp system rating. The model therefore represents the combined effects of 2.1 and 3.1.
- LAB 3.1++ is a more optimistic LAB 3.1 scenario that assumes that modules are substituted in a “like for like” fashion and there is therefore an increase in the installed capacity using the same roof area and with a resulting increase in energy yield of approximately 18% (in the residential sector). This is based on the proxy of the 2020 revised base case module technology being substituted by PERC, SHJ or back contact IBC module technology, as the driver of consumer choices would be based on yield.
- LAB 3.2 is similar to the LAB 3.1 scenario in that it assumes that modules are substituted in a “like for like” fashion and there is therefore an increase in the installed capacity using the same roof area and with a resulting increase in energy yield of approximately 18% (in the residential sector). System proxies with a higher Performance Ratio (>80) become more prevalent in the stock model. Because some of the building stock will have inherent constraints such as east-west orientation, chimneys and parapets an assumption has been made that 50% of the systems installed would be restricted to B class.
- LAB 4.1 assumes a gradual uptake of the module and inverter BAT technologies, together with system design option elements in the residential market segment. The take-up is conservative, assuming 5% of new systems annually by 2030.
- LAB 4.1++ is a more optimistic LAB 4.1 scenario that assumes both a gradual uptake of the BAT combinations in the residential market segment from 5% in 2024 rising to 30 % by 2030 and also the installation of more generation capacity on roofs as a result (as per 3.1++).

In addition the GPP scenario 5.1 is described as follows:

- LAB 5.1 is a similar scenario to LAB 4.1 to model GPP policy option 5.1, it assumes an uptake of BAT options and that 12% of commercial stock (BC2) is affected and that BAT would be applied to 20% of stock by 2022, then 40% by 2024 and 60% by 2026.

7.2.2 Scenario analysis (unit stock/sale & environmental)

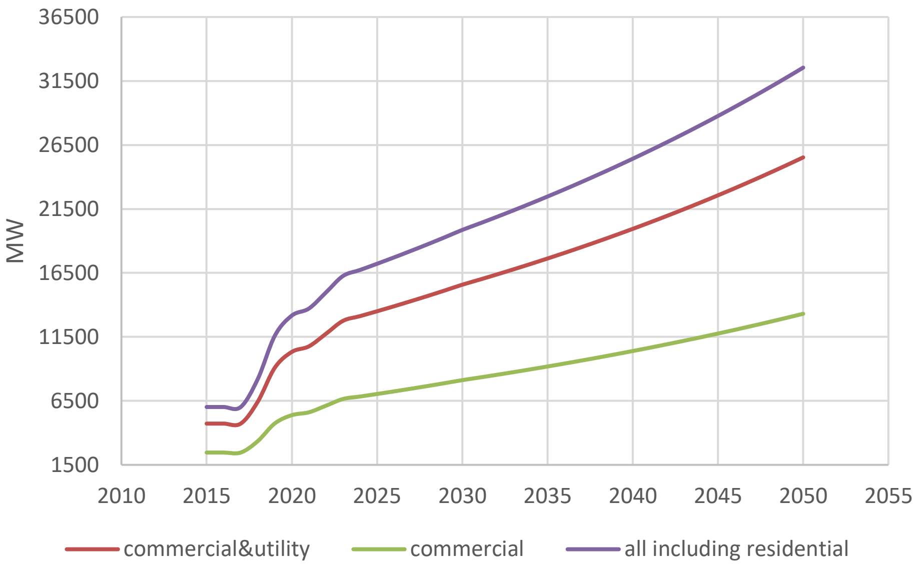
<u>Policy option 1: Business as Usual (BAU)</u>

A Business as Usual (BAU) scenario was built upon the market input data, using the assumptions described in section 7.1.3.3 (Policy option 1) and data from Annex 7A. The model is subdivided by market segment (residential, commercial and large scale) and per module technology in MWp of annual sales, see Figure 149 for the overall market projections. It is important to note that the PV market is fast moving and already the stock model includes some uptake of Task 6 design options which

may weaken the potential impact arising from the proposed policy options in the medium to long-term. The diffusion of BNAT options into the market is also uncertain and could be a further disruptive influence on the stock model.

The annual build-up of stock is based on the best available assumptions for specific periods in time rather than a continuous time series. In the juncture between each period changes in policy are assumed which result in a staggered change in PV system annual sales. The initial period to 2023 is the result of the projected end of large scale subsidies in a number of major Member States. 2030 is a key milestone for EU and Member State target setting.

Figure 149: Annual new stock MWp per market segment



For the purpose of this study a tailored scenario calculation spreadsheet was developed taking into account the impact from all life cycle stages that was derived from the Ecoreport tool from Task 6. It is based on the leading parameter selected in Task 6, which is Gross Energy Requirement (GER) from an LCA perspective. It therefore enables also extra waste streams to be added at the End-of-Life and during the lifetime (per year), e.g. for the replacement of inverters and/or the repair of components.

The approach to the modelling of inverter lifetime is intended to be compatible with the typical failure metrics for electronics (e.g. MIL-HDBK-217), which are based on failure rates [%/y] or its reciprocal value expressed as Mean Time Between Failure (MTBF). It approximately models the failure rate 'bathtub' (Weibull) distribution curve (Figure 23, Task 3) by using constant failure rates which are midlife failures occurring in between premature failures and wear out failures. Premature or warranty failures are herein assumed to be similar to manufacturing drop out and End of Life wear out. In this study, a fixed lifetime of 30 year is assumed in line with the functional unit proposed in Task 1 and also the proposed economic system lifetime.

The model also allows for the calculation of the Capital Expenditure (CAPEX) and the Operational Expenditure (OPEX) per respective year. All cost values are discounted to the reference year of 2016. The model always assumes that a full photovoltaic system is presented, meaning that when a module improvement is added the impact of this improvement option is always analysed in the context of a reference system environment. As a result, the interpretation of the scenarios should be made relative to the BAU rather than to the absolute value when considering a particular policy option. The values for all calculated scenarios are in Annex 7C.

For calculating the improvement potential both the Annual Yield (TWh) and the Gross Energy Requirement (GER) were calculated for all scenarios. When looking to the scenarios it is important to look at the impacts on both the Yield and GER, because the forecasted impact is a combination of effects between which there may be trade-offs. Improvements in performance efficiency are mostly reflected in greater yield so that the GER per functional unit is reduced correspondingly along the lifetime.

Improvements in the production stage performance are mostly reflected in a reduction in GER per functional unit, but in some cases can affect the long-term yield either positively or negatively, e.g. a module may be BAT but have lower efficiency than other design options, a module performance degradation improvement will increase lifetime yield in turn reducing the GER per functional unit. Ideally a third metric is required that links together these variables – for example, Energy Return on Investment (EROI) – and is proposed to be used in the context of the two voluntary instruments.

Figure 150 and Figure 151 presents the annual yield (TWh) and the GER (TWh) (Gross Energy Requirements) for the BAU. Herein 1 TWh GER equals 3600 TJ. The scenario forecasts about 120 TWh additional electricity generated in 2030 due to the stock increase of PV systems between 2015 and 2030. It is therefore not the total annual yield from PV in the EU which is higher due to stock of PV installed before 2015; but this is left out of the scenarios because with the performance of pre-existing stock cannot be significantly influenced by future policy unless specific repowering assumptions were to be applied from 2035/40 onwards. Worth noting is that the primary energy or GER for manufacturing in 2016 () is 1.500.000 TJ or 41,7 TWh which is 6.4 times the power generated in 2016 (6,48 TWh) from the installed PV systems, this indicates that there is an initially energy investment required before there is a break-even point.

Figure 150. Annual yield for BAU PV systems

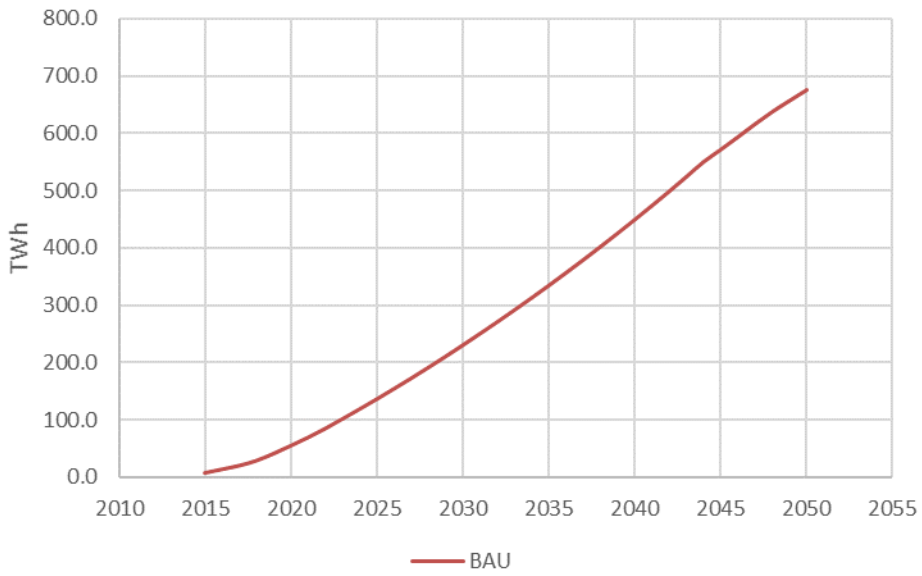
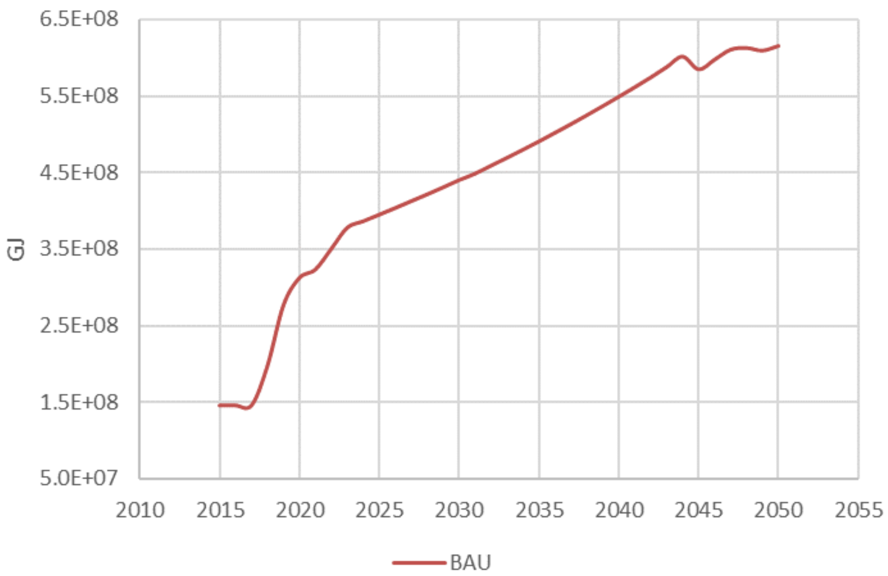


Figure 151. Gross energy requirements for the BAU for modules, inverters and systems



Policy option 2: Ecodesign requirements

The proposed scenarios for modules **MOD 2.1** and **MOD 2.2** (Figure 152 and Figure 153) apply to all market segments and the results show the improvement upon the overall system stock performance but with a change only in the module component. The results have a relatively weak but increasing long-term impact because they remove a small underperforming proportion of the market (see Annex 7B) and because a threshold for reduce degradation is not specified, only an information

requirement. No appreciable change in yield can be seen because the installed capacity is assumed to remain the same. The yield result is likely an underestimate because only modules with the base case efficiency (16%) has been substituted in the stock model, whereas models with a performance as low as 9% are on sale.

In contrast **MOD 2.1++** assumes a modest increase in yield as higher power modules replace standard modules on a like for like m^2 basis, resulting in more installed capacity. Values for this scenario are in Annex C.

The policy options MOD 2.1. and MOD 2.2 are combined in MOD COM 2.1/2. Because of an overlap between the technology options in regards to the two types of performance improvement the effects is not as great as a summation of the improvement potential from MOD 2.1 and MOD 2.2 (see Figure 152 and Figure 153).

Figure 152. Annual Yield relative to the BAU for Ecodesign module policy options

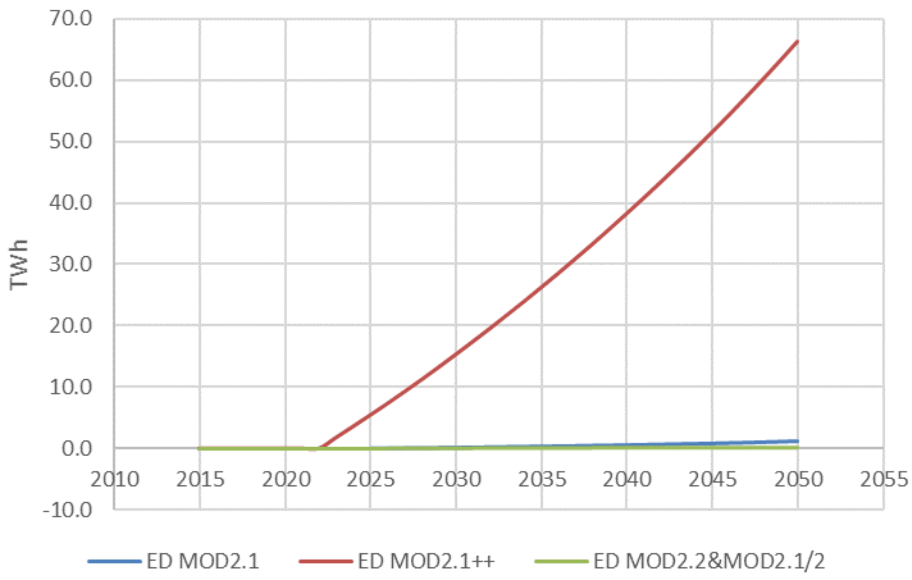
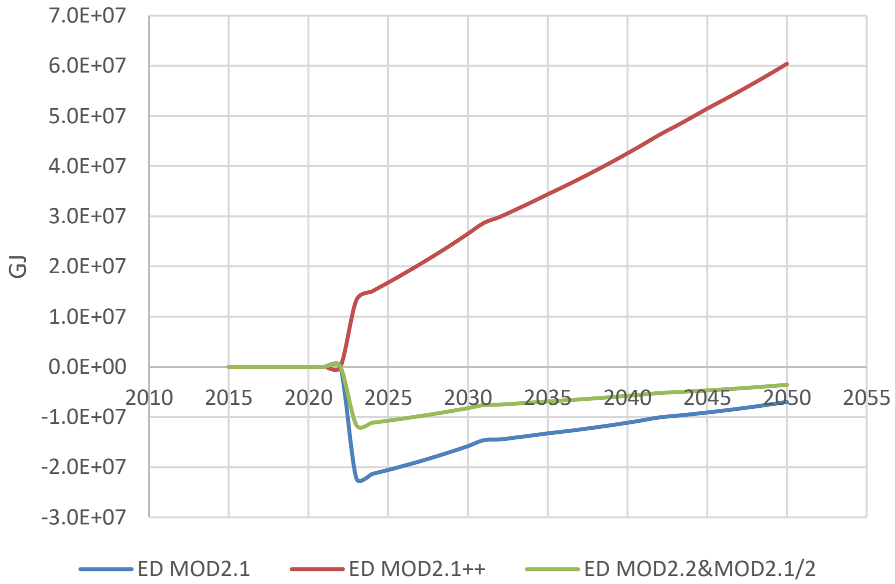


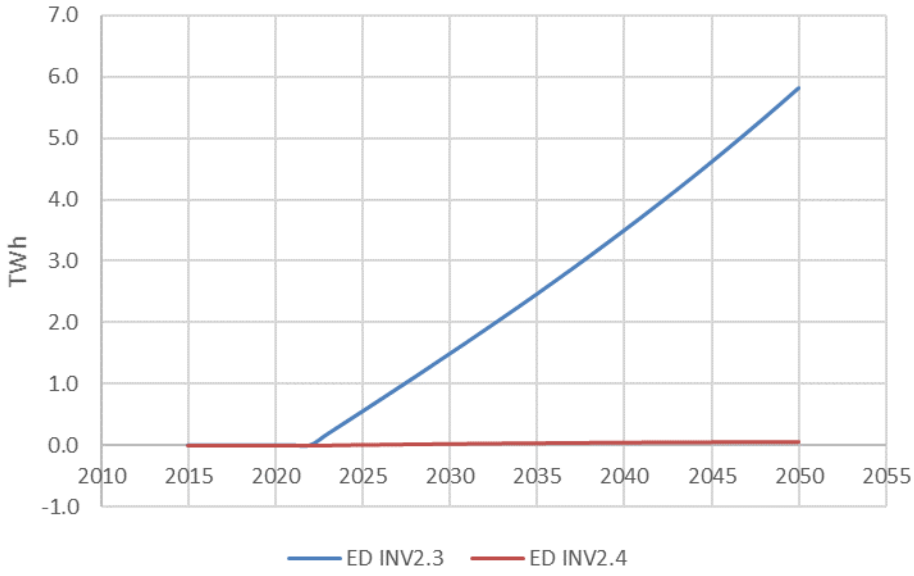
Figure 153. Gross Energy Requirement (GER) relative to the BAU for Ecodesign module policy options



The scenario with Ecodesign requirements on **inverter efficiency INV 2.3**, see Figure 154 and Figure 155; applies to all market segments and the results show the improvement upon the overall system stock performance but with a change only in the module component. No appreciable increase in the yield can be seen as the substitution of lower Euro Efficiency products only achieves a minor improvement in yield because of the small overall the margin for improvement. A minor decrease in

GER can be seen, due to a reduction in the inverter capacity needed. The yield result is likely an underestimate because only inverters with the base case efficiency (96%) have been substituted in the stock model, whereas models with a performance as low as 93% are on sale.

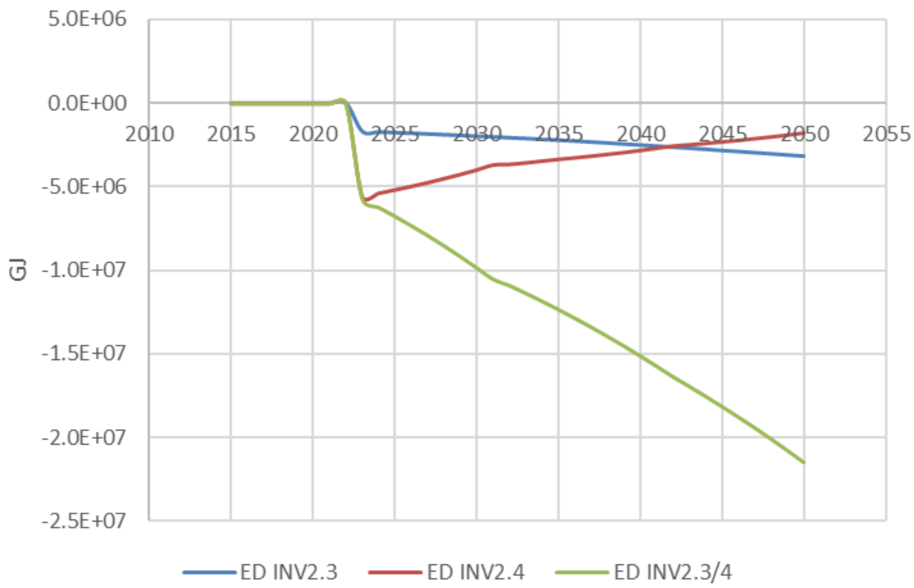
Figure 154. Annual Yield relative to the BAU for Ecodesign inverter policy options



The Ecodesign requirements on the **quality, durability and circularity of inverters INV 2.4**, see Figure 154 and Figure 155; has been applied only to the residential sector because the improvement potential was mainly identified in this segment and because the design options are already commonplace in the other segments. The results show a decrease in the GER due to less need for inverter components but the impact is relatively low because in the full system, inverters have a lower proportional contribution to GER impact relative to modules (see Task 6). Values for this scenario can be found in Annex 7C0.

The policy options INV 2.3. and INV 2.4 are combined in **INV COM 2.3/4**, with the effects summing up those obtained individually for each option, see Figure 154 and Figure 155.

Figure 155 Gross Energy Requirement (GER) relative to the BAU for Ecodesign inverter policy options

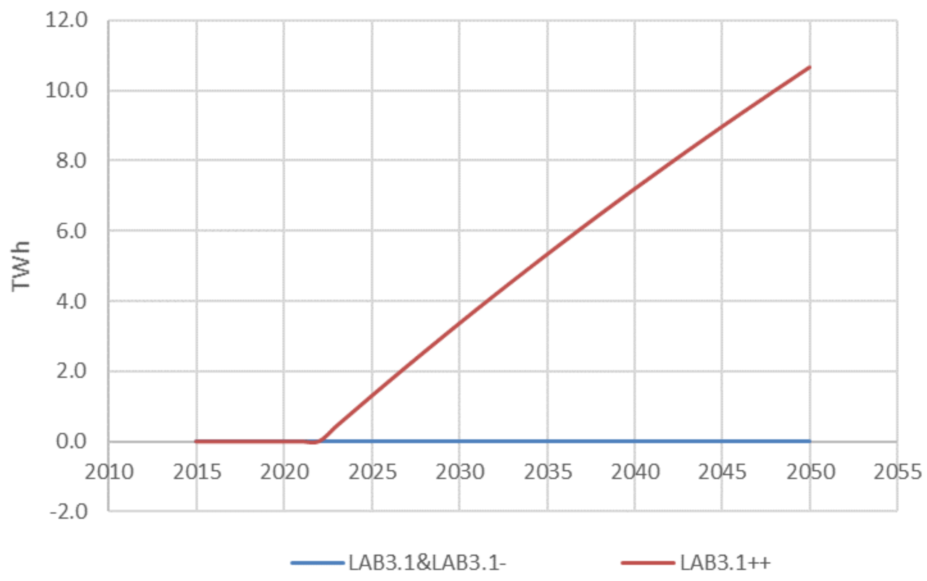


Policy option 3: Energy Label

The **package energy label LAB 3.1** applied to the residential market segment is included in Figure 156 (3.1- and 3.1). The figures show a moderate impact because it was assumed to phase out class B only in the LAB 3.1- scenario and because lower performance modules are not assumed to be substituted on the same like for like area (m^2) basis, so it is likely a conservative estimate of its impact. No appreciable change in the yield can be seen for LAB 3.1 and LAB 3.1- because only a reduction in the module stock area in m^2 to deliver the same MWp is assumed. LAB 3.1 has combines the effect of the Ecodesign cut offs in MOD 2.1 and INV 2.3 with assumptions about a modest market shift to module products in higher label classes (Reference base case>PERC, PERC>SHJ/back contact).

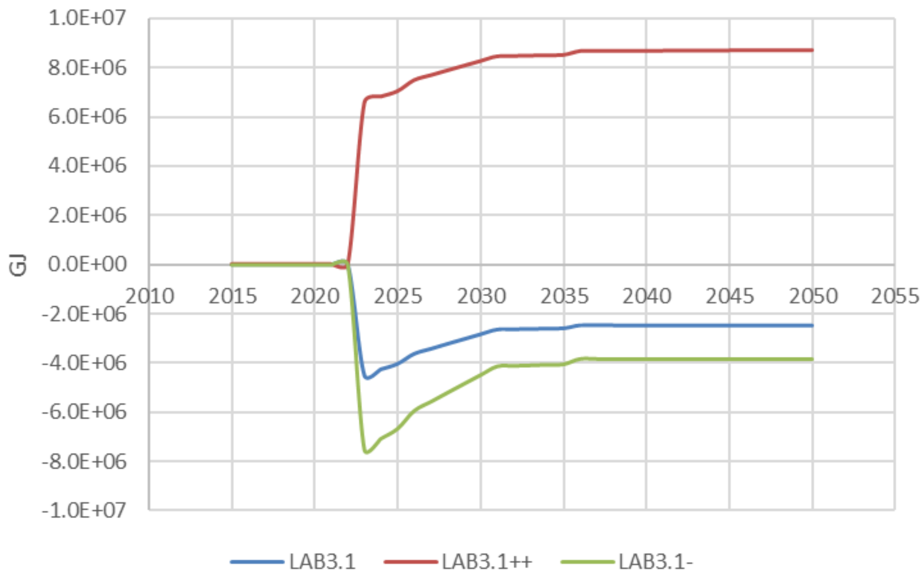
The effects of a more optimistic scenario for the energy label LAB3.1++ is applied as well to the residential market, as also shown in Figure 156 and Figure 157. This assumes an increase in yield as higher power modules replace standard modules on a like for like area (m2) basis, resulting in more installed MWp capacity (e.g. 3 kWp system with BSF modules substituted by mono PERC modules increases to 3.5 kWp with an 18% yield increase).

Figure 156 Annual Yield relative to the BAU for Energy Label policy option 3.1



It is noteworthy that the effect of the increased yield in LAB3.1++ is to increase the GER for the stock above the BAU. This is because the higher power modules that would fill the higher scales of the energy label have a greater GER per functional unit (see Task 6).

Figure 157 Gross Energy Requirement (GER) relative to the BAU for Energy Label policy 3.1



The impact of policy option **system energy label LAB 3.2** as applied to systems is similar to that of 3.1, but with a stronger improvement in yield in the case of the optimistic scenario LAB 3.2++ (see Figure 158). This is in part due to assumptions related to the use of higher yield modules with lower temperature co-efficients, such as SHJ designs, as well as a shift in the distribution curve for stock system Performance Ratios. The same trade-off can be seen in the GER, with higher yield and greater deployment increasing associated production stage impacts (see Figure 159).

Figure 158 Annual Yield relative to the BAU for Energy Label policy option 3.2

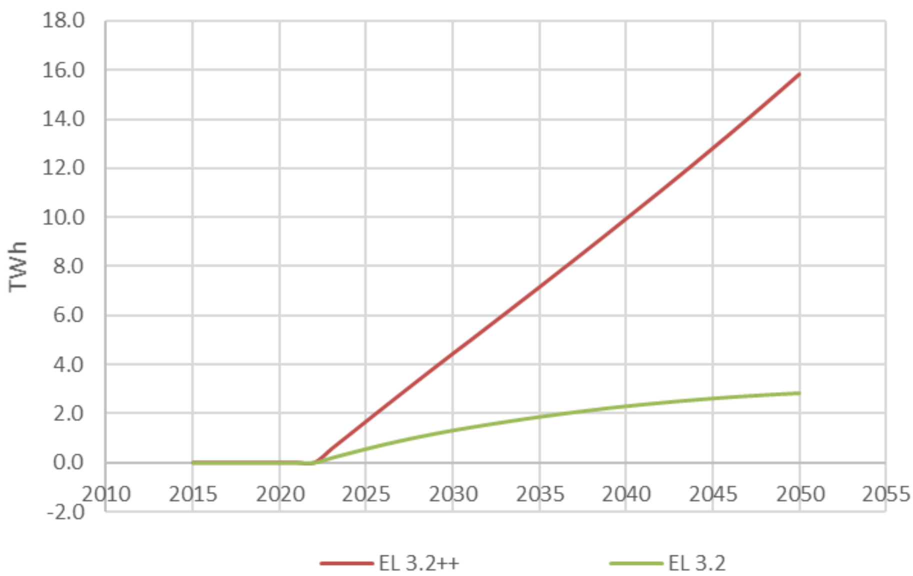
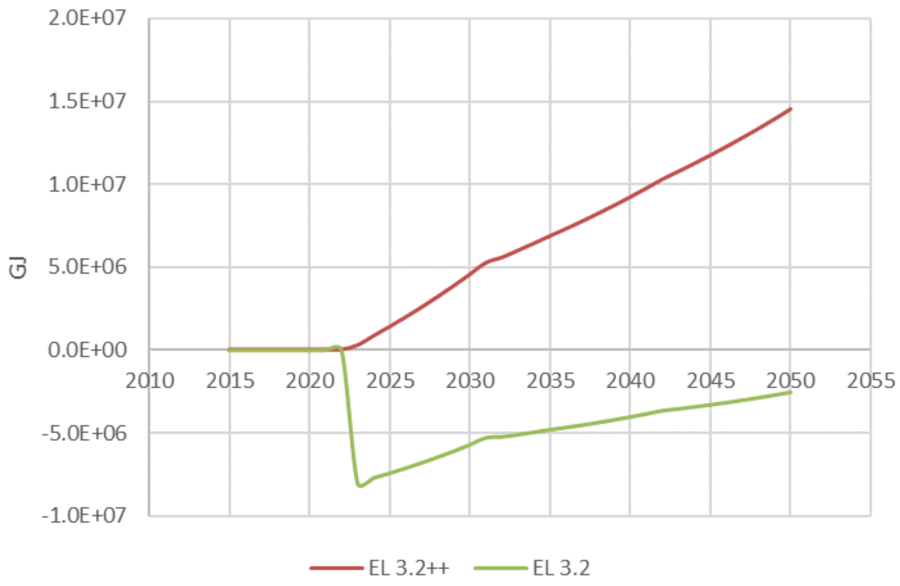


Figure 159 Gross Energy Requirement (GER) relative to the BAU for Energy Label policy 3.2



Policy option 4: EU Ecolabel

The **residential EU Ecolabel criteria for residential packages and services LAB 4.1** assumes a relative low uptake of the EU Ecolabel (up to 5% annually after 10 years). As explained in the introduction also a more optimistic scenario LAB 4.1++ has been modelled that assumes a drive in the market created by the EU Ecolabel (up to 15% annually after 10 years) and a resulting installation of more capacity. Values for this scenario can be found in Annex 7C.

Notably the increase in market confidence and consequently yield associated with option LAB 4.1++also results in an increase in GER. In order to understand whether this trade-off would still deliver an overall environmental benefit the Energy Return on Investment (EROI) requires analysis. The criteria proposal for an EROI threshold could, moreover, be used to minimise the trade-off.

Figure 160. Gross Energy Requirement (GER) relative to the BAU for EU Ecolabel policy options

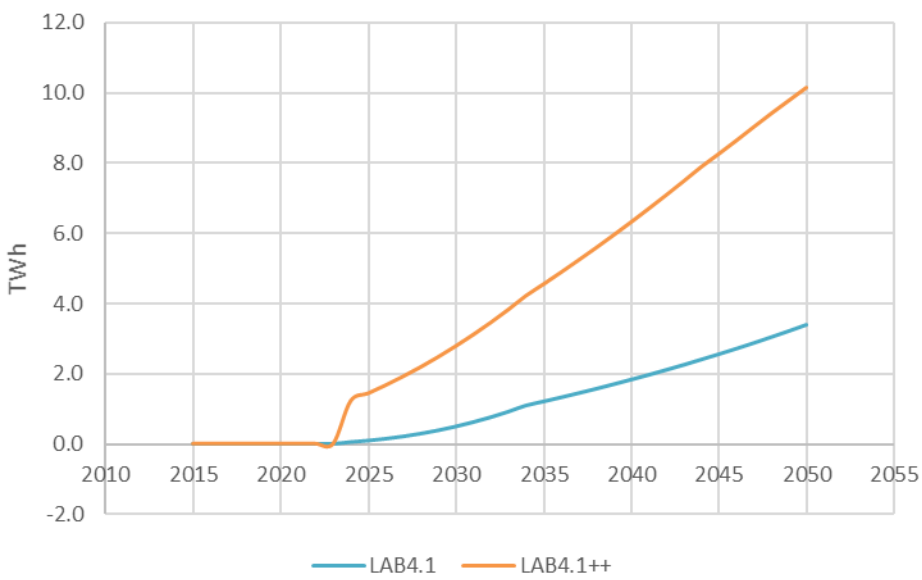
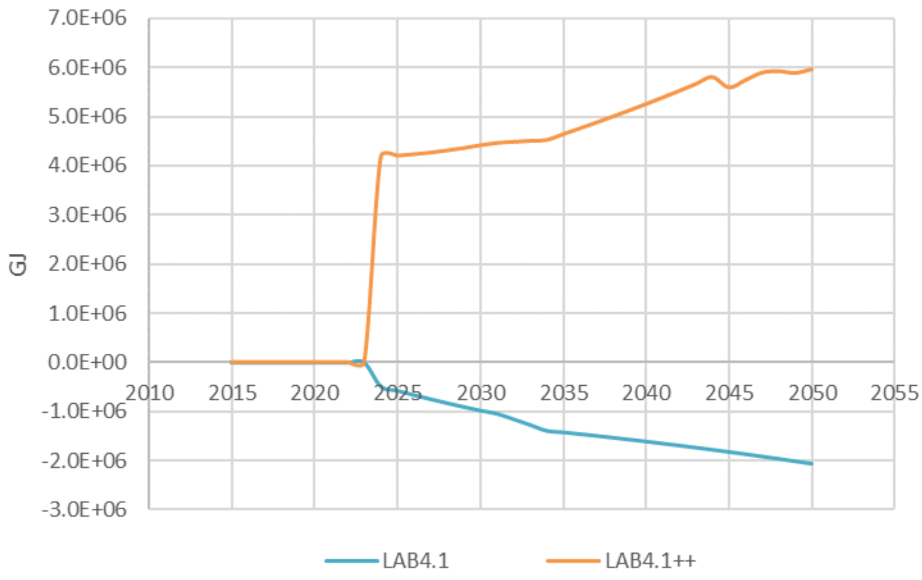


Figure 161 Gross Energy Requirement (GER) relative to the BAU for EU Ecolabel policy options



<u>Policy option 5: Green Public Procurement</u>

The projected results for the public solar PV systems GPP 5.1 policy option are in

Figure **162** and Figure 163. It is built on the commercial market segment and the uptake of BAT by the public sector within this segment (12 % of annual installation capacity).

Figure 162. Annual Yield relative to the BAU for the GPP 5.1 policy option

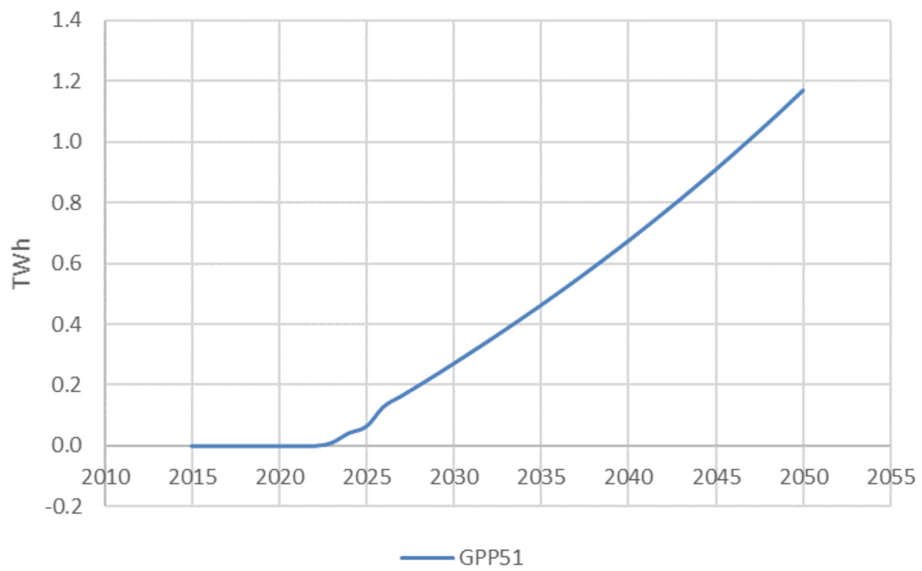
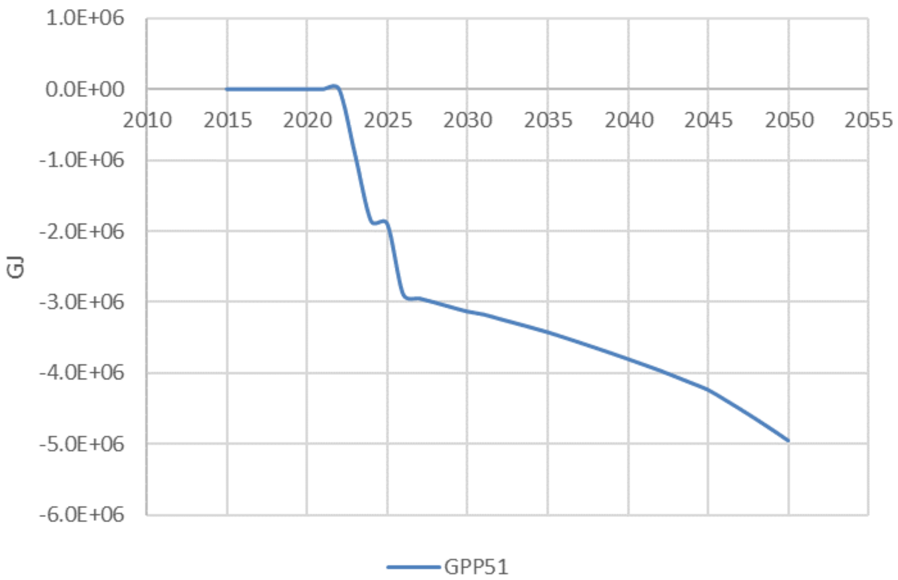
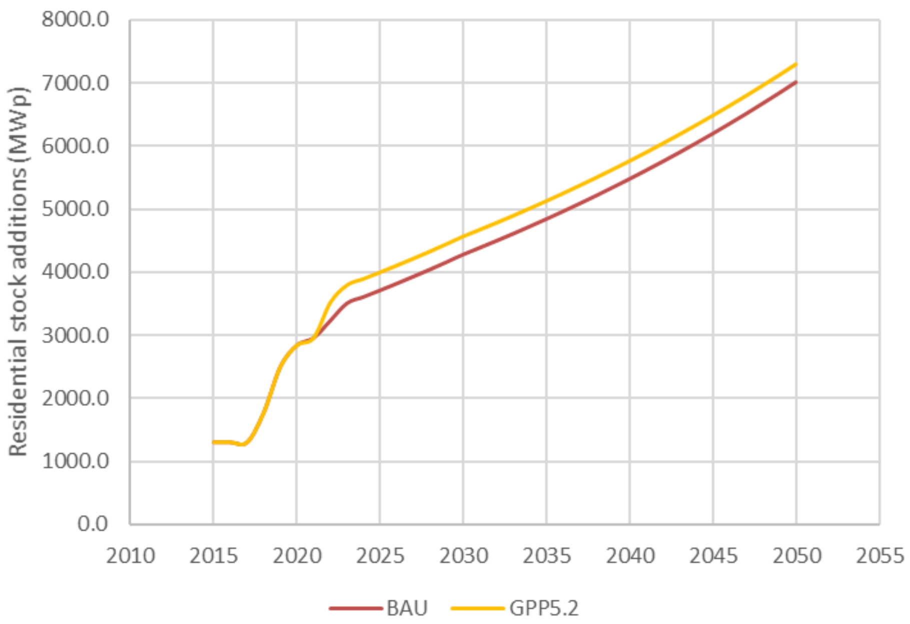


Figure 163. Annual Gross Energy Requirement (GER) relative to the BAU for the GPP5.1 policy option



For the further policy option GPP 5.2, only a simplified scenario for the possible increase in stock is shown in order to illustrate the potential impact on the market (Figure 164). Even with the modelling being based on relatively conservative assumptions (see Section 7.1.3.3, Policy option 5) the potential impact could be significant, representing an increase in the annual stock additions of approximately 30% in 2023 falling to 20% by 2050.

Figure 164. Annual stock for the GPP 5.2 policy option in comparison with the BAU stock



Combined policy options 6

One of the aims of considering both mandatory and voluntary policy instruments within the frame of the Preparatory Study has been to analyse the potential for synergies between them. Two combined policy options have therefore been modelled in order to determine the improvement potential. The two combined options are:

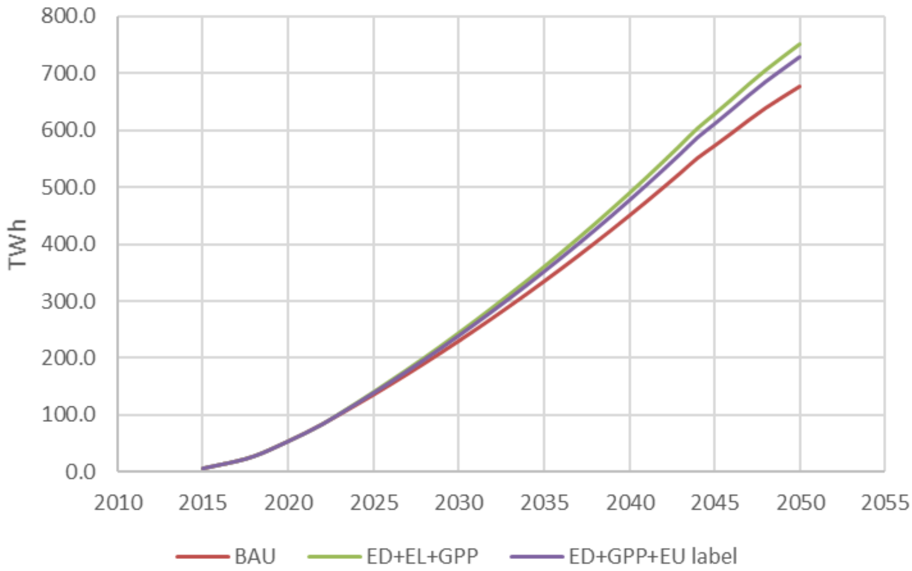
- **COM 6.1 (ED+EL+GPP)** would be led by implementation of the two mandatory instruments, namely Ecodesign and Energy Labelling, to be complemented by voluntary Green Public Procurement criteria.
- **COM 6.2 (ED+GPP+EU Ecolabel)** would be led by implementation of the two voluntary instruments, namely the EU Ecolabel and Green Public Procurement, backed by the mandatory instrument Ecodesign.

The annual yield projections for the combined options are presented in Table 178 and Figure 165. It can be seen that COM 6.1 is estimated to provide the greatest improvement in yield until 2050, initially providing an uplift of 3.4% in 2025 rising to as much as 7.7% by 2035, versus an uplift of 2.4% in 2025 and 5.4% in 2035 for COM 6.2. The difference is accounted for assumptions made in COM 6.1 about efficiency gains and improved system yields driven primarily by substitution effects in the market from the Energy Label option 3.2.

Table 178. Evolution of Improvements in annual yield relative to the BAU for the COM 6.1 and 6.2 policy options

Year	Scenario COM 6.1 (ED+EL+GPP)		Scenario COM 6.2 (ED+GPP+EU Label)	
	Stock yield (TWh)	Improvement against the BAU (TWh)	Stock yield (TWh)	Improvement against the BAU (TWh)
2015	6.5	0.0	6.5	0.0
2020	54.1	0.0	54.1	0.0
2025	140.4	4.8	139.0	3.3
2030	244.1	14.3	239.8	9.9
2035	360.1	25.8	352.3	18.1
2040	489.2	39.7	477.5	28.0
2045	628.1	56.2	611.9	40.0
2050	751.0	74.9	729.6	53.6

Figure 165. Annual Yield of the BAU and the COM 6.1 and 6.2 policy options



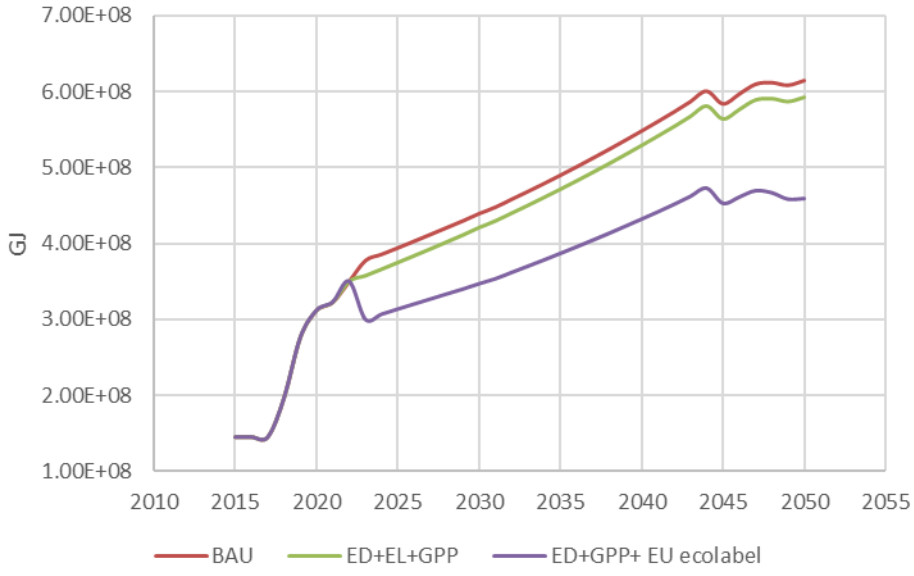
More modest assumptions about similar effects that could be driven by the EU Ecolabel criteria set still drive up yield in COM 6.2 but not to the extent of the Energy Label 3.2 option and in fact the assumptions about market confidence made for the EU Ecolabel can be considered to have a higher level of uncertainty due to it being a voluntary instrument. This could therefore increase the gap between the performance of the two options. Note also that the potential for an increase in residential deployment, as modelled in option 5.2, is not included in COM 6.1 or 6.2.

The annual GER projections are presented in Table 179 and Figure 166. The most beneficial for yield is COM 6.1 whilst the most beneficial for GER is COM 6.2. Here it can be seen that COM 6.2 achieves the greatest improvement, providing a benefit of up to 21% on the BAU by 2035. This improvement is largely driven by the mandatory Ecodesign part of the option, supported by the EU Ecolabel. The more modest improvement of 4-5% achieved by COM 6.1 is the result of a trade-off between the higher yield it achieves and, in order to achieve this yield, the deployment of module technologies that have a higher GER.

Table 179. Evolution of Improvements in the GER relative to the BAU for the COM 6.1 and 6.2 policy options

	Scenario COM 6.1 (ED+EL+GPP)		**Scenario COM 6.2 (ED+GPP+EU Label)**	
Year	**Stock GER (GJ)**	**Improvement against the BAU (GJ)**	**Stock GER (GJ)**	**Improvement against the BAU (GJ)**
2015	1.454E+08	0.000E+00	1.454E+08	0.000E+00
2020	3.121E+08	0.000E+00	3.121E+08	0.000E+00
2025	3.751E+08	-1.962E+07	3.136E+08	-8.116E+07
2030	4.211E+08	-1.879E+07	3.468E+08	-9.300E+07
2035	4.715E+08	-1.888E+07	3.867E+08	-1.037E+08
2040	5.292E+08	-1.958E+07	4.317E+08	-1.170E+08
2045	5.640E+08	-2.055E+07	4.524E+08	-1.321E+08
2050	5.925E+08	-2.261E+07	4.588E+08	-1.563E+08

Figure 166. Annual Gross Energy Requirement (GER) of the BAU and the COM 6.1 and 6.2 policy options



Consideration of BNAT technologies

These scenarios were largely built on the BAT technologies but as discussed in Task 4 and 6 there are still **BNAT** technologies under development that could further improve performance relative to the BAU and previous scenarios in the upcoming years. The most promising currently include, with their suggested production status:

Commercially available, limited lines

- TOPCon passivated contact silicon cells
- Inverters based on wide bandwidth semi-conductors

Pre-production scale

- Epitaxial or 'kerfless' silicon wafer production
- Tandem perovskite:silicon cells

Prototyping

- Back contact (IBC) silicon heterojunction cells

The near BAT design for recycling of silicon modules is also noteworthy given that stakeholders have emphasised the need to consider the end of life scenarios for a rapidly increasing module stock.

In respect to inverters the benefits of the next generation of wide bandwidth inverters – for example, the potential for higher euro efficiencies and lower temperature induced failure - is as yet unclear. Hence the impact is likely underestimated and potentially an ambitious label can support driving the market to those BNAT. Therefore it could be recommended to support related R&D and to reconsider the proposed policy options at more ambitious levels after a notional period. An additional option is to consider a broader scope of mandatory policy instruments, as suggested under options 8.1 and 8.2 in section 7.1.3.3.

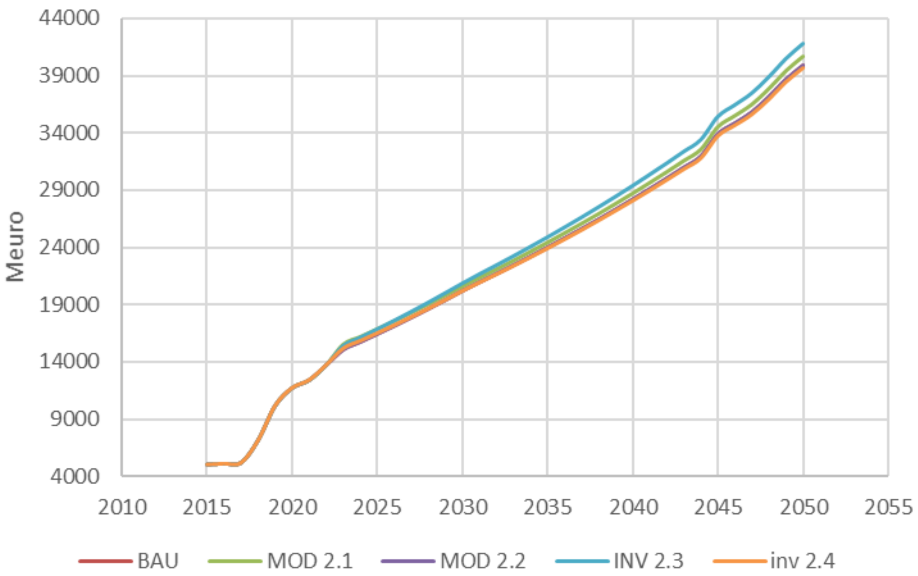
7.3 Socio-economic impact analysis

The aim of this section is to estimate the economic impact of the policy options. It therefore runs a stock model scenario 1990-2030 (2050) for EU-28 on running costs & consumer expenditure, as well as establishing multipliers for employment by upstream and downstream activity and market segment.

7.3.1 Estimated impact on income and expenditure

Based on the previous stock model and Task 6 economic modelling, the total EU annual long-term expected impact on expenditure was calculated (see Figure 167). For the Ecodesign policy scenarios MOD and INV a limited economic impact arises from the computation, meaning that the proposed measures have a positive impact and are anticipated to entail minimal additional cost. All values are discounted relative to 2016.

Figure 167. Calculated total annual expenditure for different scenarios (Discounted to reference year 2016)



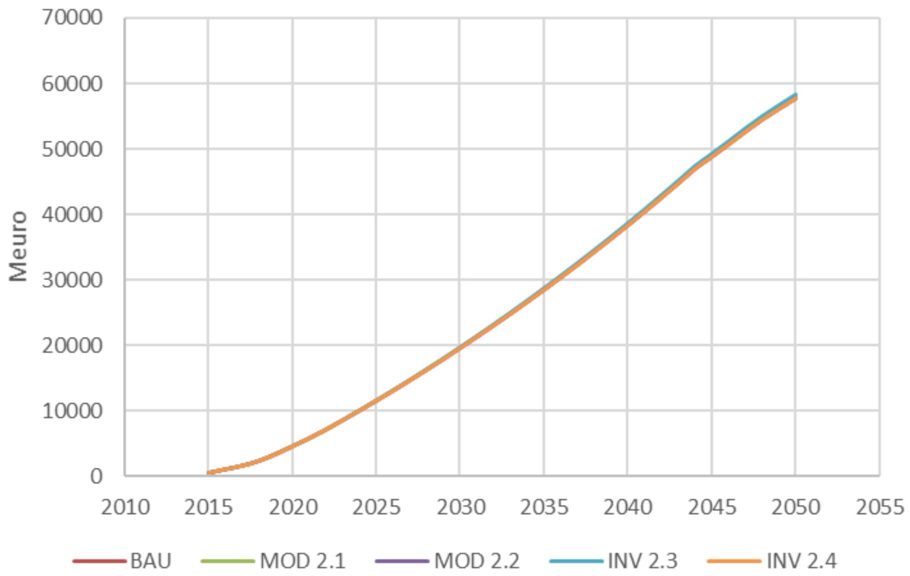
As opposed to typical energy consuming products there is for photovoltaics no trade-off between running energy cost and capital expenditure. Therefore for photovoltaics it is proposed to compare the annual expenditures relative to the expected economic value of generated electricity, based on the average expected 85.5 Euro/MWh for 2035 from the PRIMES model (see Table 180).

Table 180. PRIMES projected electricity prices to 2050 (source: PRIMES[439])

	2015	2020	2025	2030	2035	2040	2045	2050
Decomposition of electricity generation costs and prices (6)								
Average cost of electricity generation (Euro'13 per MW	95,1	105,2	103,0	101,0	96,0	92,5	91,3	87,7
Annual capital cost	45,4	50,5	44,6	40,8	**33,5**	30,5	30,3	30,3
Fixed O&M cost	19,5	20,6	19,3	19,6	**19,7**	18,5	18,3	18,1
Variable non fuel cost (7)	1,6	1,7	1,8	1,9	**1,9**	2,0	2,4	3,2
Fuel cost	23,9	26,1	28,8	28,8	**30,4**	31,3	29,5	26,6
Tax on fuels and ETS auction payments	4,7	6,3	8,4	10,0	10,4	10,1	10,7	9,5
Additional supply costs (Euro'13 per MWhe)	28,1	26,6	32,9	37,9	46,8	50,0	49,6	52,0
Transmission, distribution and sales costs	27,4	25,9	31,9	36,8	45,6	48,7	48,2	50,3
Other costs	0,7	0,7	0,9	1,1	1,2	1,3	1,4	1,7
Estimation of RES supporting costs passed on to cor	20,0	24,2	23,2	19,0	11,8	4,7	1,7	1,3
Average price of electricity (pre-tax) (Euro'13 per MWhe)	123,1	131,9	135,9	138,9	142,8	142,5	140,9	139,6
Excise tax and VAT on electricity (Euro'13 per MWhe)	17,7	18,0	18,2	18,6	19,1	19,2	19,2	19,2
Average price of electricity (after tax) (Euro'13 per MWhe)	140,8	149,9	154,1	157,6	161,9	161,6	160,0	158,8
	0	0	0	0	0	0	0	0
(8) extra costs due to renewable recovery which are passed on to consumers								
average used for this study (euro/MWh)					**85,5**			

As can be seen comparing total societal expenditure from Figure 167 with the economic benefits in **Figure 168**, the revenues outperform the calculated costs but with some delay. This is due to the high upfront capital cost and the associated long-term return on investment.

Figure 168. Value of generated electricity per year



The previous expenditure calculation allows for the estimation of the impact on employment which is assumed to be proportional to expenditures by market segment. The impact on EU employment on a macroeconomic scale is difficult to assess as most of the upstream cell and module manufacturing takes place outside Europe (see Task 2).

7.3.2 Assumptions for the economic impact analysis

In this section the base assumptions used within the economic impact analysis on the economy and employment are compiled. These include the potential response of the market, supply chain impacts and learning rates.

[439] *EU Reference Scenario 2016. Energy, transport and GHG emissions. Trends to 2050. https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf*

7.3.2.1 Price and response of the market

The elasticity of demand for PV systems, and their associated modules and inverters, is complex to determine because the market has to date been heavily reliant on subsidy programmes that act in a very punctuated way. Moreover, capital investment in residential solar PV systems is different from other consumer products studied under Ecodesign because of the significantly higher upfront investment required into a 'non-essential', long life asset on which consumer decisions may be easily postponed relative to spending decisions on 'essential' items.

Programmes in Spain, Italy and the UK have triggered very fast responses from the market because of a high latent demand for solar PV installations and because the economic returns that can be achieved from a PV system were intentionally adjusted by setting subsidy levels at appropriate rates. The projections developed in Task 2 and which form the basis for the Business as Usual stock model suggest that post 2020 the EU solar PV market will move to a more stable growth pattern based on price parity with conventional forms of electricity generation that it will therefore be less dependent on subsidy regimes.

Analysis of price elasticity in local PV markets has been made in the USA. Modelling for the residential sector suggests a price elasticity in the range of -0.4 and -1.2 [440] [441]. If this assumption is used then the demand price for PV systems is likely to be relatively inelastic to change. This would also accord with solar PV systems being a non-essential, long life asset. Market interventions that go beyond price support may therefore need to be considered in order to stimulate greater take-up.

7.3.2.2 Upstream and downstream economic impacts

As was described in Task 2 the value chain for the PV sector within the EU can be split between upstream and downstream activities.

- Upstream activities to manufacture system components: manufacturing of multi-silicon, wafers, cells, modules, inverters, mounting and tracking systems and electrical components (Balance of System).
- Downstream activities that provide services related to PV systems: engineering/studies/administration, installation, operations & maintenance and decommissioning.

In the reference year 2016 the total number of Full Time Equivalent (FTE) jobs created by the EU PV sector were 81,319, projected to rise to 174,682 by 2021[442]. The latter estimate is based on the medium growth market scenario defined by the PV Market Alliance.

In order to model the potential impact of any change in the quantum or nature of demand for modules or inverters the upstream and downstream supply chain for PV technologies and services can be further sub-divided into the constituent activities that add value to the delivery of a PV system to a client. Table 181applies a percentage split of activities to the EU employment figures for the reference year of 2016 and an estimate for 2021 based on the medium PV Market Alliance scenario, which can be equated to policy scenario 1 'business as usual' (BAU).

It can be seen that upstream employment accounts for a lesser proportion of the total employment with modules in particular projected to decline further whilst Balance of System is projected to increase. These trends reflect the culmination of a trend towards the loss of EU module and inverter manufacturing as large scale production has necessitated the establishment of lower cost factories outside of the EU.

An important feature of the EU PV industry's current employment structure is the significance of the downstream activities. This is particularly important to consider when analysing the impact of policy scenarios because actions that influence the deployment of PV systems will have a disproportionate impact on EU employment. A survey of the skill profile of downstream actors in the German PV market suggested that the majority of employees completed vocational training (60%), a high proportion had a university degree (35%) and that only a small proportion having no vocational training (6%) [443].

The three main downstream activities support the project life cycle for PV system installation and by necessity the employment is located in local EU markets. Related to these activities, existing upstream EU competencies in other BoS

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[440] Rogers E, Sexton S. 2014. *Effectiveness of subsidies for residential rooftop solar adoption: Lessons from California*. North Carolina State University Working Paper

[441] Hughes JE, Podolefsky M. 2015. *Getting green with solar subsidies: Evidence from the California solar initiative*. Journal of the Association of Environmental and Resource Economists 2: 235–275.

[442] Ernst & Young and Solar Power Europe, Solar PV - jobs and valued added in Europe, November 2017

[443] German Federal Ministry for the Environment (2012) Renewably employed – short and long-term impacts of the expansion of renewable energy on the German labour market.

components such as cabling, mounting structures and control systems are projected to generate an increase in employment in function of the further increase in PV system installations and associated downstream employment.

Table 181. EU employment supported by the PV industry in the reference year and 2021 (BAU)

Supply chain	**Activity**	**Employment (% FTE, FTE/MWp)**					
		2016			**2021 (BAU projected)**		
Upstream	Silicon	1%	813	0.1	1%	1747	0.2
	Wafer	3%	2440	0.4	2%	3494	0.4
	Cells	3%	2440	0.4	2%	3494	0.4
	Modules	5%	4066	0.7	3%	5241	0.6
	Inverters	2%	1626	0.3	2%	3494	0.4
	BoS components	11%	8945	1.5	15%	26202	2.9
	Total	*25%*	*20330*	*3.4*	*25%*	*43671*	*4.9*
Downstream	Engineering studies	23%	18703	3.1	31%	54151	6.1
	Installation	16%	13011	2.2	22%	38430	4.3
	Operation & Maintenance	36%	29275	4.9	22%	38430	4.3
	Total	*75%*	*60989*	*10.1*	*75%*	*131012*	*14.7*

Adapted from Ernst & Young (2017)

The potential impact of the policy options on the upstream and downstream activities are analysed qualitatively in Table 182 The intention is to identify which supply chain activities each policy option acts upon more strongly. For example, policy option 2 would be anticipated to have a direct impact on upstream module and inverter manufacturing with the majority of manufacturers having their production capacity located extra-EU, whereas in contrast the procurement of system services within the frame of public tenders would directly impact on downstream service providers in local markets within the EU. Only an increase in the demand for installation services is assumed to generate an impact on employment otherwise there is only anticipated a change in the nature of the services called upon by clients e.g. if the energy label places requirements on system performance this may require more attention on system designs by existing installers.

Table 182. Qualitative analysis of upstream and downstream economic impacts for the main policy options

Policy options	Upstream impacts	Downstream impacts
1. Business as usual	Continued decline in EU module and inverter manufacturing.	Projected growth in engineering studies, installation services and O&M services.
2. Ecodesign requirements on module and inverters	Direct (external) impact on imported module and inverter products.	Indirect price internal impact on the pricing of low end performance module and inverter products.
3. Energy label requirements for residential packages **3.1/2 Package approach**	Positive consumer choices may have a direct impact on better performing products, including EU module and inverter designs and manufacturing equipment.	Greater confidence in packages could foster residential demand across all three service activities.
3.3 System approach		Greater confidence in system designs could foster residential demand across all three service activities.
4. EU Ecolabel criteria: residential package with services	Positive choices may have a direct impact on better performing products, including EU module and inverter designs and manufacturing equipment.	Improved information on module, inverter and system performance could foster increased consumer confidence.
5. Green Public Procurement criteria: PV systems ***5.1 Public buildings***	Quality specifications may have a direct impact on imported module and inverter products (core criteria). Life cycle specifications may have potential to support EU module and inverter designs and manufacturing equipment (comprehensive criteria).	Greater call for life cycle management to optimise LCOE and performance could foster demand for extended O&M services.
5.2 Reverse auctions	Quality specifications may have a direct impact on better performing products, including EU module and inverter designs and manufacturing equipment.	Growth in residential demand from novel procurement routes could foster all three service activities.

Key to the colour coded evaluation of potential impact

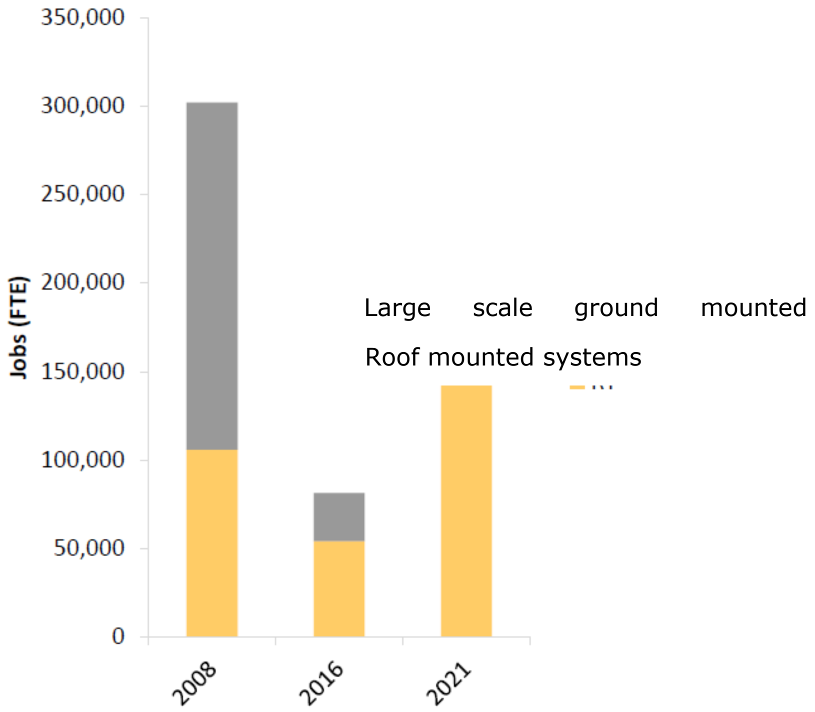
Business as Usual	Minimal or unknown	Moderate	Significant	Very significant

Another important feature of the EU PV industry's current employment structure are the system market segments that have been analysed by this study – namely residential, commercial and large scale (utility). These are also important to consider when analysing the impact of policy scenarios because actions that influence the deployment of smaller scale roof mounted PV systems will result in a disproportionately greater impact on EU employment.

It can be seen in Figure 169 that the large scale ground mounted systems, which accounted for 31% of the installed capacity in 2016, accounted for 27,400 FTE (33%) whilst roof mounted residential and commercial systems accounted for 56,340 FTE (67%). A clear shift towards roof mounted installations is then projected under the medium to long-term market scenarios described under the Business as Usual (BAU) policy option. The large scale ground mounted and roof mounted segments are projected to rise to 30,335 FTE (17%) and 145,179 FTE (83%) respectively by 2021.

In the BAU policy scenario future EU employment is projected to be dominated by activities related to roof mounted systems, which will include BoS components that are distinct to those of large scale ground mounted systems. As was identified in Tasks 2 and 3 further opportunities also exist to develop the (downstream) demand for systems in the residential sector and related to this the demand for system design/quotation studies, installation services and the operation & maintenance service offer.

Figure 169. Upstream and downstream employment supported by EU PV system installations



Source: Ernst & Young (2017)

7.3.2.3 Residential system cost structure

In order to support modelling for the residential market segment, which in previous tasks has been identified as the segment with the greatest potential for growth and the implementation of BAT measures, an indicative cost structure has been defined (see Table 183) This cost structure is based on installations in a mature PV market (Germany) and the module and inverter costs have been updated to reflect the reference year 2016. From this cost structure the person hours involved in implementing an installation and the unit costs per kWp of capacity can be estimated and scaled. Maintenance and operation are not currently accounted for in this cost structure.

Table 183. Indicative cost structure for a residential solar PV system installation

Cost item		Person hours	Cost (Euro)	Unit cost (Euro/kWp)	% of total cost
Components	Modules	n/a	1500	500	37%
	Inverter	n/a	234.6	78.2	6%
	Mounting structure	n/a	420	140	10%
	Cabling	n/a	60	20	1%
	Total	*n/a*	*2214.6*	*738.2*	*55%*
Installation	Customer acquisition	5	105	35	3%
	Permitting	0.67	13.8	4.6	0%
	Grid connection	1.5	31.8	10.6	1%
	Installation	45	945	315	24%
	Commissioning	2.5	52.8	17.6	1%
	Marketing	-	43.2	14.4	1%
	Overheads & profit	-	595.8	198.6	15%
	Total	*54.7*	*1787.4*	*595.8*	*45%*

Adapted from Strupeit.L and Neij.L (2017)

An additional factor to take into account in the cost structure is the Weighted Cost of Capital (WACC). At retail loan interest rates of between 5% and 7% this can account for between 30% and 35% of the life cycle cost of a PV system.

The channel to market also has an influence on the cost structure, with large national installers, utilities and DIY chains able to reduce supply chain costs and overheads. Group purchasing structures of the kind described in Policy Option 5 can also achieve similar reductions in the overall cost.

7.3.2.4 Module manufacturing cost structure

Despite a >97% decrease in costs since 1980 and an average learning rate of 21% [444] [445], modules still account for a significant proportion of the cost of PV systems – typically within the range of 30-50% depending on the market segment. The potential response of module manufacturers to policy instruments that act specifically on module performance characteristics is therefore important to analyse.

On one hand analysts suggest that the scope for further cost reduction within existing crystalline silicon technology platforms may be constrained [446]. This is because the technology is characterised by high capital costs, long lead times in reacting to changing demand and, based on current pricing, relatively small operating margins. These factors have recently led to oversupply and may in the future pose problems for sustaining growth in output , reflected in the Minimum Sustainable Price (MSP) for modules. Expert analysis suggests that the MSP may lie between 0.14 and 0.36 Euro/Wp although spot market

[444] *Fraunhofer ISE (2015) Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. Study on behalf of Agora Energiewende.*

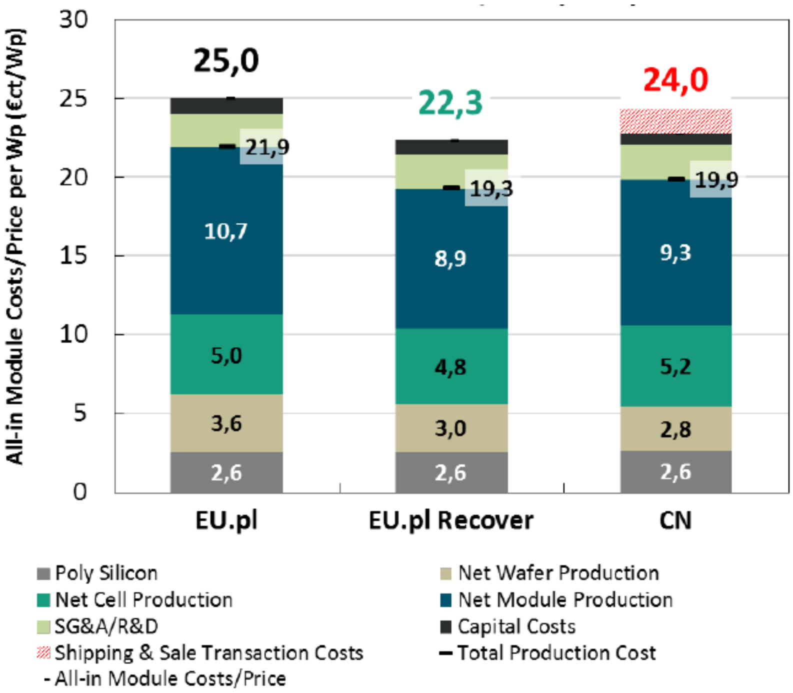
[445] *Kavlak et al, Evaluating the causes of cost reduction in photovoltaic modules, Energy Policy 123 (2018) 700–710*

[446] *Powell et al, The capital intensity of photovoltaics manufacturing: barrier to scale and opportunity for innovation, Energy & Environmental science, Royal Society of Chemistry, 2015, 8, 3395*

prices are for some mainstream products are already within this price window [447]. Figure 170 illustrates an indicative cost structure for a module manufacturing plant and associated expenditure related to upstream processes.

On the other hand existing production platforms have, according to the experts consulted, proved flexible in responding to demand for new crystalline cell technologies such as PERx that can be integrated into the existing module production lines and form factors. Thin film products such as CdTe have also been able to demonstrate the scaling up and optimisation of manufacturing lines. The capability of existing production platforms to respond appears therefore to be an important consideration if mandatory Ecodesign or Energy Labelling measures are used to require the substitution of existing products.

Figure 170. Indicative cost structure for a crystalline module manufacturing plants in Europe and China (CN)



Source: Fraunhofer ISE (2019)

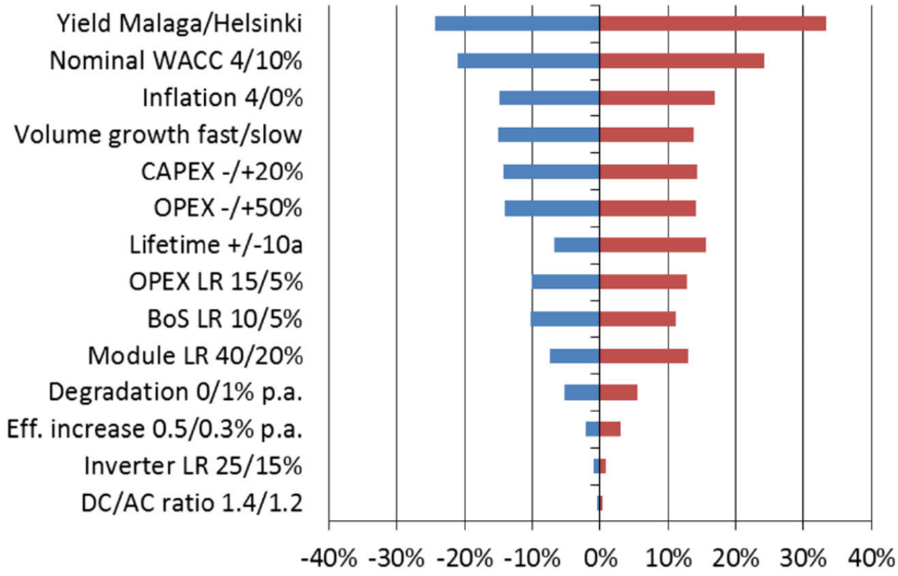
[447] *See footnote 444*

7.4 Sensitivity analysis

The aim of this section is to establish the basis for a sensitivity analysis of the policy scenario modelling, covering the relevant factors (such as the price of energy or other resources, production costs, discount rates). In particular, a sensitivity analysis is proposed for the BAT and LLCC design options from Task 6 that have been mapped onto Ecodesign policy options in section 7.1.3.

Reference studies that analysed the sensitivity of solar PV system LCOE (PVTP 2015, Vartiainen et al 2019) have highlighted the relative importance of the climate zone, the Weighted Cost of Capital, Operational expenditure and Capital expenditure as having greater significance than technical parameters such as lifetime and degradation (see Figure 171).

Figure 171. Sensitivity analysis of LCOE (%)



Source: Vartiainen et al (2019)

Considering Tasks 1 to 6 and the proposed policy options the following parameters are judged relevant in the context of this study for a sensitivity analysis:

A. In Task 1 the economic lifetime of a PV system for the functional unit was set at 30 years, it is proposed to analyse +/- 5 years.
B. In Task 3 the reference yield (Yr) was defined as corresponding to a reference central EU location (Strasbourg) which formed the basis for the Task 6 modelling. Yield is climate sensitive and therefore it is proposed to analyse 3-4 additional locations that are representative of broad climate zones in the EU.
C. Task 4 suggested that there are some uncertainties associated with modelling the prices (euro/Wp) for HJT/BJT, CIGS/CdTE and epitaxial-wafer based modules, therefore it is proposed to vary module prices with +/- 20 %. Price varies in different market segments as a function of volume, either through direct supply or via distributors.
D. Task 2 and the MEErP methodology proposed a discount rate of 4 % to be applied but this can have a strong impact on the calculated Life Cycle Cost (LCC) or LCOE. The rate could be geared to market segment, for example the large scale ground mounted segment could, indicatively, be tested at 8-12% (private capital rates), the residential segment at 5-6% (personal loan rates) and the public sector segment at 2-3%.

A further sensitivity could focus on the efficiency of modules given that an absolute figure was used to model each technology, whereas in reality a series of models with different efficiencies are offered (e.g. CIGS 13.8 – 16%).

It is also important to note that much of the Life Cycle Inventory (LCI) data used as the basis for the LCA analysis in Tasks 5 and 6 has a large degree of uncertainty but it is not deemed useful and possible to apply a sensitivity analysis on this.

8 Task 8: Policy recommendations

This task provides policy recommendations based on the results of policy analysis in Task 7, in particular in terms of the feasibility of proposing Ecodesign, Energy labelling, EU Ecolabel and GPP requirements, and bearing in mind the specificities of the different policy processes. In this context, the added value brought by each scheme and the potential synergies is considered as well as the relevance and feasibility of potentially having the product(s) covered by one or several schemes.

The task report is structured according to the four policy instruments under study. For each policy instrument the recommended approach and package of requirements is put forward. The preferred options for combinations of policy instruments are then put forward, with identification of the package of requirements and the potential synergies.

8.1 Recommendation 1: Ecodesign requirements for modules and inverters

In this first recommendation, requirements are proposed to be set that would apply to individual modules and inverter products placed on the EU market and intended for use in photovoltaic systems for grid-connected electricity generation. Specifically excluded from the scope would be:

For modules

- Module level power electronics, containing micro-inverters and power optimisers
- Modules with a DC output power of less than 50 Watts under Standard Test Conditions (STC)
- Building Integrated Photovoltaic (BIPV) products that incorporate solar photovoltaic cells
- Modules intended for mobile applications or integration into consumer electronic products.

For inverters

- Central inverters that are packaged with transformers (sometimes referred to as central solutions) as defined in Commission Regulation (EU) No 548/2014 on Ecodesign requirements for small, medium and large power transformers.

The aim of this market intervention would be to:

- foster module and inverter designs that have improved long-term energy yield, circularity and smart readiness;
- take products off the market that are of a low quality and that have higher life cycle costs
- introduce a requirement for transparency on the life cycle Gross Energy Requirement (GER) and Global Warming Potential (GWP) of modules.

The following technical justifications for the recommendation can be given:

- Module and inverter manufacturers require greater encouragement to ensure that designs are easier to repair and recycle. A voluntary intervention is not deemed sufficient, because as solar PV industry moves towards mass deployment, the scale of the challenge will increase rapidly and substantially.
- The material complexity and long-term exposure in the field of module products means that it is difficult to specify individual durability tests. Instead, a carefully specified series of test sequences is required that address priority areas identified from observations of failure modes in the field.
- Solar inverters have a key role to play in the smart readiness of homes but this is not currently a standardised feature. Intervention is therefore needed to ensure a minimum functionality across all inverters.
- There is the need to ensure comparability in the market between claims relating to module yield, long-term performance degradation and life cycle GER and GWP. By driving the use of new and existing calculation methods for these parameters, and by requiring reporting on performance against these parameters for all products on the market, the quality and availability of data as input to other calculations will increase, such as an overall system performance

Moreover, an approach focussed specifically on both modules and inverters and not PV systems is considered to be justified because they are business to business (B2B) components of all PV systems. The market intervention does not rely on consumer visibility as such and would act to cut off products at the point of being placed on the market to distributors, retailers, installers and consumers. This approach could, in turn, support a labelling instrument at package or system level.

8.1.1 Preferred module option 2.1: Requirements on lifetime electricity yield

The preferred option is for an Ecodesign requirement based on a declaration (and potentially in a later revision a threshold) for the yield calculated according to IEC 61853-part 3 and with reference to the climatic zones in part 4. The reason for selecting this option is that it is more representative of performance under real life conditions. In addition to the power rating it takes

into account PV module performance characteristics such as coefficients for spectral response under low light conditions and the potential loss of performance at high temperatures.

Given that this is a relatively new performance measurement, having been first introduced as a standard in 2018, it is not yet considered possible to establish thresholds that could form the basis for mandatory minimum requirements. Instead, as the initial proposal is for an information requirement in order to stimulate its adoption as a standard metric to be reported on module product datasheets.

If a yield threshold were to be pursued as the basis for a minimum requirement, further data gathering would be required in order to determine the market spread of yield, as this information is not yet readily available. Consideration would also need to be given as to how new technologies that initially enter the market with lower yields should be treated. This would be with the aim of not dissuading innovation.

Table 184. Preferred module policy option 2.1: Yield information requirement

Performance aspect	**Detailed proposed requirements**
Preferred option: Module energy yield	The module energy output (yield) expressed in kWh/kWp and calculated according to IEC 61853-3 for each of the three reference EU climate zones shall be declared by the manufacturer.

8.1.2 Preferred module option 2.2: Performance requirements on quality, durability and circularity

This further Ecodesign option would introduce a more stringent set of quality and durability tests for module products. The design qualification of modules according to test sequence set out in IEC 61215 is proposed as a Minimum Requirement. Although the test sequence is costly and has a long duration, it is understood to already be considered as a market entry requirement by major manufacturers. It is also considered difficult to separate the test sequences and/or to introduce new aspects (such as encapsulant browning or inspections for cell cracking).

Customers in the commercial and large-scale solar PV system market segments currently request this design type approval as standard. Moreover, all feed-in tariff schemes to date reviewed as part of this study have requested this standard for residential contracts, so it can be seen to have been established in the residential market segment as an entry requirement.

Requiring such a design type approval would, however require further legal analysis because, although there are some enabling provisions within the annexes of the Ecodesign Directive 2009/125/EC, they have to date not been used. Moreover, from the point of view of minimising regulatory burden some of the testing within the overall sequence is already mandatory for CE marking, as mandated by the Low Voltage Directive 2014/35/EU.

In order to ensure factory (mass production) conformity with the design type approval it is also considered important to request factory quality controls and auditing according to IEC TS 62941. However, this is not as suitable to be considered as an Ecodesign requirement given that it would not relate to the testing of specific product characteristics as such.

Long-term performance degradation of modules can have a significant impact on lifetime electricity generation. Claims made by manufacturers for their products' degradation rate or, linked this, the power guarantee, currently don't have a standardised basis and are not usually backed up by an explanation of the method by which they have been derived. A transitional method has therefore been developed by the JRC, specifying the need for claims to be based on field observations over a minimum period of time. 'Unvalidated' claims that are not supported by field observations would still be permitted as long as their experimental basis was explained, if not prescribed values should be used. For the purpose of market harmonisation, the transitional method could become mandatory after a given time.

This market intervention would also seek to ensure that, via information requirements, modules were possible to disassemble and dismantle in order to facilitate repairing and recycling. The requirement signals where future design priorities should focus.

Table 185. Preferred module policy option 2.2: Quality, durability and circularity requirements

Performance aspect	**Detailed proposed requirements**
Performance requirements	
2.2.1 Durability product test sequence	• Each model shall be certified to have passed the product test sequence required for qualification under IEC 61215. • This requirement could be further extended to require factory quality controls and auditing according to IEC TS 62941 and IECRE OD 405 series.
Information requirements	
2.2.2 Lifetime performance degradation	The manufacturer shall declare the average linear degradation rate expected over a notional service lifetime of 30 years. This shall be the same rate that is used as the basis for the power warranty (if offered). The declaration shall be clearly identified as being either: – *Validated:* The manufacturer's claim shall be an average derived from a series of field observations made according to the Transitional Method, in regard to the number, geographical coverage and the time series. – *Unvalidated:* on the manufacturer shall report on the basis for their claimed rate with reference to accelerate life testing methods and modelling.
2.2.3 Repairability	The manufacturer shall report on: – the possibility to access and replace the bypass diodes in the junction box [448], – the possibility to replace the whole junction box of the module *Note: the possibility exists to prescribe reparability, or to include a semi-quantitative criterion if a product specific standard is developed in accordance with the forthcoming horizontal standard for repairability prEN 45554.*
2.2.4 Dismantleability	The manufacturers shall report on the potential to separate and recover the semi-conductor from the frame, glass, encapsulants and backsheet. Design measures to prevent breakage and enable a clean separation of the glass, contacts and internal layers during the operations shall be detailed. *Note: the possibility exists to prescribe that full material dismantleability is ensured, or to include a semi-quantitative criterion if a product specific standard is developed in accordance with the forthcoming horizontal standard for recyclability prEN 45555.*
2.2.5 Material disclosure	The manufacturer shall declare the content in grams of the following materials in the product: – Antimony – Cadmium – Gallium – Indium – Lead – Silicon metal – Silver – Tellurium For the encapsulant and backsheet the manufacturer shall also declare the type of polymers used (including if it is fluorinated or contains fluorinated additives) and the content in grams.

[448] This was identified as the main option available for the repair of a module in order to minimise yield loss during the lifetime of the product.

8.1.3 Preferred inverter option 2.3: Performance requirements on efficiency

This preferred option is based on the EN 50530 method for calculating the 'Euro Efficiency' of an inverter. This is an important derating factor for the performance of a solar PV system, so the removal of the worst performing, sub 94% efficient inverters would contribute as a minimum requirements for the inverter derating factor. It is also considered important to request improved and more consistent additional information in the form of tabulated efficiency values and the inverter's temperature dependency.

The increasing role in the future of hybrid inverters incorporating battery storage introduces the possibility that such efficiency gains could be reversed in order to raise self-consumption, so it is also considered important to have complementary requirements on the efficiency of hybrid systems. This would entail reference to the private German Effizienzleitfaden standard [449], which may shortly be developed into a national DIN (Deutsches Institut für Normung) standard.

An additional requirement is proposed to facilitate the *'smart readiness'* of PV systems in support of the Commission's proposed overall initiative to develop a Smart Readiness Indicator (SRI) for buildings. For residential inverter applications, a minimum functionality is proposed to be requested, based on both hardware and software. This functionality would facilitate the two best performing PV system design options in Task 6, which rely on monitoring and fault diagnosis to support repair response and maintenance. It would also support the proposed EU Ecolabel criteria relating to an on-site repair service for inverters.

Table 186. Preferred inverter policy option 2.3: Efficiency requirements

Performance aspect	**Detailed proposed requirements**
2.3.1 Euro Efficiency minimum requirement for PV inverters without storage	Require a minimum Euro efficiency at Tier 1 of 94% and Tier 2 at 96% measured according to EN 50530. *Allowances shall be provided for micro-inverters and hybrid inverters to offset for their other benefits.*
2.3.2 Euro Efficiency supporting information requirement	In addition the following supporting information shall be provided: - The efficiency values shall be presented in a tabulated form. - An annual temperature derating factor for the climate zones defined in IEC 61853-4 and calculated relative to 25°C
2.3.2 Efficiency requirements for PV inverters with possibility to connect storage or with integrated storage	Require a minimum system efficiency of 90% at 25% of nominal power, at minimum MPP voltage with the battery at around 50% state of charge. Measurement to be made according 'Effizienzleitfaden 2.0'.
2.3.3 Smart readiness	Manufacturers shall ensure that the inverter supports class C data monitoring according to IEC 61724-1. The inverter shall have physical and/or wireless connectivity and be capable of communicating with other devices using the Modbus data transfer protocol in accordance with IEC 61158..

8.1.4 Preferred inverter option 2.4: Performance requirements on quality, durability and circularity

This preferred option is based on the introduction of a standardised basis for the minimum durability of inverters placed on the market, together with a focus on information about the repairability of the inverter. These requirements are an important first step in extending the potential service life of inverters, particularly for those intended to be placed in outdoor environments, where the failure rate during the first ten years can be high. Failures provoked by high temperature operating conditions are a focus of attention.

The design qualification of inverters according to test sequence set out in IEC 62093 is proposed as a Minimum Requirement. Requiring such a design type approval would, however, require further legal analysis because, although there are some enabling provisions within the annexes the Ecodesign Directive 2009/125/EC, they have to date not been used. Moreover, from the point of view of minimising regulatory burden some of the testing within the overall sequence is already mandatory for CE marking, as mandated by the Low Voltage Directive 2014/35/EU.

[449] *BVES, Effizienzleitfaden für PV-Speichersysteme v. 2.0.1, July 2019, https://www.bves.de/effizienzleitfaden_2/*

In order to ensure factory (mass production) conformity with the design type approval, it is also considered important to request factory quality controls and auditing according to IEC TS 63157. However, this is not as suitable to be considered as an Ecodesign requirement given that it would not relate to the testing of specific product characteristics as such.

The potential to maintain the functionality of the inverter on-site is also considered important in order to minimise the life cycle impacts associated with short replacement cycles. To this end, repairability requirements are proposed that seek to inform professionals and consumers about the maintenance and repair potential of the product. The outcome is anticipated to be an improved focus on mid-life wear-out and preventative maintenance in the residential and commercial market segments.

Table 187. Preferred inverter policy option 2.4: Quality, durability and circularity requirements

Performance aspect	**Detailed proposed requirements**
2.4.1 Durability product test sequence	• Each model shall be certified to have passed the product test sequence required for qualification under IEC 62093, clearly stating whether the product is for indoor or outdoor applications. • This requirement could be further extended to require factory quality controls and auditing according to IEC TS 63157 and the associated IECRE OD [pending a code].
Additional information requirements	
2.4.2 Repairability requirements for inverters <30 kW	The manufacturer shall identify which of the circuit boards can be replaced on site.
2.4.3 Repairability requirements for inverters >30 kW	Manufacturers shall provide a preventative maintenance and replacement cycle. This shall include a list of parts that may be replaced and the timing of preventative measures to achieve a declared intended design technical lifetime (as required in IEC TS 63157). *Note: the possibility exists to include semi-quantitative criterion if a product specific standard is developed in accordance with the forthcoming horizontal standard for repairability prEN 45554.*
2.4.4 Material disclosure	The manufacturer shall declare the content in grams of the following materials in the product as a whole and in the replaceable circuit boards: - Lead - Cadmium - Silicon carbide - Silver - Indium - Gallium - Tantalum

8.1.5 Preferred Ecodesign option 2.5: Life cycle GER and GWP information requirement

This additional overarching Ecodesign option would establish a standardised basis for the collection, analysis and presentation of module and inverter life cycle data and Life Cycle Assessment (LCA) results in the EU. The initial focus would be on two impact categories – primary energy (GER) and Global Warming Potential (GWP). The latter is also sometimes referred to as a carbon footprint or embodied CO_2 emissions.

This requirement would represent a first step in establishing a consistent basis for comparing the life cycle impacts of the products, in turn providing data in support of life cycle criteria for the EU Ecolabel and/or Green Public Procurement, if taken forward. It is anticipated that, if introduced, a delayed introduction would be needed so that manufacturers would have time to prepare EPDs.

Establishing such an Ecodesign information requirement is anticipated to support and establish synergies with a number of other EU policy instruments:

- The EU Taxonomy on sustainable activities: A regulation on the establishment of a framework to facilitate sustainable investment. is currently undergoing Impact Assessment [450] and accompanying technical screening criteria for economic activities, including renewable electricity generation, are currently under development and are currently proposed as including a requirement to disclose to investors the life cycle CO_2 emissions of solar PV systems. It is anticipated that in the future this disclosure would be expected as a condition for investment and/or companies with solar PV assets would have to disclose this data to equity investors. This will particularly apply to large-scale systems.
- Construction Product Regulation: The reference to sustainability within the Basic Works Requirements has already mandated the development of the two standards EN 15804 (PCR for construction products) and EN 15978 (LCA for buildings). However, the availability of EPDs for construction products is still limited, particularly for building technical services. Given that solar PV is the favoured technology for NZEB buildings, there is the need to develop more EPDs for system components.
- European Green Deal: The new European Commission has approved proposals for a 'European Green Deal'. This includes proposals for a border requirement or tax relating to embodied CO_2 emissions. This would require a mandatory standardised basis for declarations of performance.

However, in order for this proposal to be made 'operational' within an Ecodesign implementing regulation, a dedicated check on the legal feasibility of such a requirement in the framework of the Ecodesign Directive would need to be carried out.

Table 188. Preferred Ecodesign policy option 2.5: Life cycle data information requirement

Performance aspect	**Detailed proposed requirements**
2.5.1 Life cycle GER and GWP product declaration	• At the latest by [*delayed year of introduction*] and for a representative product from each module series placed on the market, an Environmental Product Declaration for, as a minimum, life cycle primary energy (GER) and Global Warming Potential (GWP) shall be developed and provided. *For further discussion: options are for the EPD to be in conformity with EN 15804 or the PEFCR and to have been registered with a Type III Product Category Rule operator.*

[450] Commission legislative proposals on sustainable finance, 24th May 2018, https://ec.europa.eu/info/publications/180524-proposal-sustainable-finance_en#investment

8.2 Recommendation 2: Energy Label for residential systems

In this second recommendation it is proposed to establish an Energy Label for solar PV systems that is targeted at systems installed on residential buildings – referring to any building, public or private, that is intended for use as a permanent dwelling.. This shall include Building Integrated Photovoltaic (BIPV) systems made up of one discrete array consisting of a homogenous PV product. For simplicity, it is proposed that the labelling requirements would be placed on the *as-built* rather than the *monitored* performance of a system. It is also proposed that systems that incorporate Building Integrated (BIPV) photovoltaic arrays could be labelled.

The aim of the label would be to optimise and increase the energy yield of residential installations by enabling consumers to make an informed choice based on the performance of system designs offered by retailers and installers. Installers and designers would in turn be free to develop designs and packages of system components and maintenance services that can improve the energy yield, and therefore the label rating of systems.

From a technical perspective, evidence from selected Member States suggests that the distribution curve of normalised energy yields and performance ratios for the system stock has the potential to be shifted positively upwards through a combination of:

- better design to take into account of site-specific conditions,
- learning and experience from installation practices on site,
- reduced losses due to equipment, cabling and maintenance practices.

In this respect, both the repowering of old systems and the optimisation of new system have the potential to contribute - although the main focus of these recommendations is on installations on new systems.

This recommendation would be complemented and supported by Recommendation 1 in so far as module energy yield (MOD 2.1) and inverter Euro efficiency (INV 2.3) are required as input data for yield calculation transitional method. Normalisation of the calculated yield to the rated power and area of the module array are essential in order to maximise the potential benefits of this policy recommendation. This is because retail customers should be encouraged to upgrade performance on a like for like area (m^2) basis.

In establishing such a label it will be important to carefully adapt format of the labelling scale, so as not to portray systems with site constraints in a negative light e.g. a residential roof with an east-west orientation. In the context of EU renewable energy targets and the need for mass deployment of the technology, all new solar PV capacity should be considered advantageous and it will be important to inform rather than dissuade consumers.

Table 189. Preferred energy label policy option 3.2: System yield-based EEI

Performance aspect	**Detailed proposed requirements**
3.2 System yield-based Energy Efficiency Index (EEI)	The system provider shall follow instructions for the calculation of the overall yield derived from the module yield and Performance Ratio for the system design. In addition the yield shall be calculated on the following basis according to the transitional method: – For a notional 30 year service life. – For the closest representative EU climate zone. – By applying the listed derate factors, together with prescribed (default) values, which will be provided in the Implementing Regulation. The EEI shall be expressed in units of $MWh/kWp.m^2$.
NOTE: the present analysis deals with techo-economic aspects. In parallel, a check is ongoing on the legal feasibility of an Energy labelling scheme for PV products/system, in the form of a delegated act in the framework of Regulation 2017/1369	

8.3 Recommendation 3: EU Ecolabel for residential systems

In this third recommendation it is proposed that if a new EU Ecolabel product group is established it should be targeted at systems intended to be installed on residential buildings and with low voltage connections that facilitate self-consumption of the electricity generated by the occupants. Residential buildings refers to any building, public or private, that is intended for use as a permanent dwelling.

A qualitative evaluation, which was made with reference to DG Environment's criteria for establishing new product groups, found it to be feasible but indicated some areas of uncertainty. One of the most important areas related to metrics and benchmarks. Whilst initial criteria areas with metrics are proposed as an outcome of this study, the setting of the thresholds will require further dialogue and evidence gathering in conjunction with industry stakeholders.

Taking into account the need for the verification and award of products or services by EU Ecolabel Competent Bodies prior to them being placed on the market, the multi-criteria set is recommended to comprise the following two aspects:

1. Package approach: There would be criteria for modules and inverters. The criteria could make use of input data from Policy Recommendations 1 (Ecodesign) and 2 (Energy Label) in order to set criteria that have an extended and stricter focus with pass/fail criteria on:
   - life cycle performance,
   - hazardous substances
   - circular design.
2. Service approach: There would be a criteria covering aspects of the service provided by system installers, to include the system design, site protocols and aftercare (monitoring and maintenance).

The scope shall allow for inclusion of collective or community owned solar PV systems where shares can be purchased by individual consumers. This may include systems installed on buildings or free standing ground mounted systems.

An important consideration in seeking to establish a new product group is the potential for products to comply with Articles 6(6) and 6(7) of the Ecolabel Regulation (EC) 66/2010. The product group is considered feasible subject to the acceptance of a series of derogations for hazardous substances that are required to be present in order to ensure the performance or durability of certain product variants. An overview of the principal derogations that have been identified as being required is presented below. If the policy recommendation is taken forward, it is to be further discussed with industry stakeholders the extent to which the three Candidate List substances identified are necessary and the potential impact on potential uptake if their derogation was not to be granted.

Anticipated derogations under Articles 6(6) and 6(7) of the Ecolabel Regulation (EC) 66/2010

Given the need to comply with Articles 6(6) and (7) of the Ecolabel Regulation, it is already anticipated that the following substances are likely to require formal 'derogation' in order to allow module or inverter products to be awarded the EU Ecolabel:

- REACH Candidate List substances (0.10% w/w screening threshold)
- Cadmium sulphide (semi-conductor)
- lead (solder/metallisation)
- diarsenic trioxide (module glass)
- CLP hazard classification (0.10% w/w screening threshold)
- Substitute plasticisers with a more favourable hazard profile used in cables,
- Substitute flame retardants with a more favourable hazard profile used in inverter PCBs,
- Diantimony trioxide (crystalline module glass)
- Titanium dioxide, zinc dioxide (antisoiling)

A further important consideration of the label, if taken forward, will be alignment with other international labels and standards. A priority will be compatibility with the NSF/ANSI 457 Sustainable Leadership standard for modules and inverters, now to be adopted as an EPEAT standard. Although the criteria in the standard are largely process-based, as opposed to the EU Ecolabel which must have pass/fail criteria, the potential for the management processes, standards and practices specified within the criteria to form a basis for the verification for performance under specific EU Ecolabel criteria should be ensured. Examples include:

- Required criterion 7.1.1 - Conducting life cycle assessment [including primary energy and GWP]
- Required criterion 9.1.1 - Product take-back service and processing requirements (corporate)
- Optional criterion 5.2.2 - Presence of substances on the European Union REACH Regulation Candidate List of Substances of Very High Concern
- Optional criterion 5.1.5 – [Substance] Alternatives assessment
- Optional criterion 9.2.1 — Identification of materials for EOL management

Table 190. Preferred EU Ecolabel criteria set for modules, inverters and services

Performance aspect	**Detailed requirements**
4.1 Energy and CO_2 criteria	
4.1.1 Energy return on investment	The EU Ecolabel applicant shall calculate the energy return on investment for the module and inverter package. The EROI should be below [*threshold tbd*]. *The production and use stage primary energy use shall be derived from the method set out in the corresponding Ecodesign information requirement, which is proposed as being based on EN 15804 and the PEFCR.*
4.1.2 Life cycle GWP	The EU Ecolabel applicant shall calculate the life cycle GWP for the module and inverter package. The kg/CO_2.kWh shall not exceed [*threshold tbd]* *The life cycle impacts shall estimated according to method set out in Ecodesign, which is based on EN 15804 and the PEFCR.*
4.2 Hazardous substances criterion This criterion will require the formal 'derogation' under Articles 6(6)/6(7) of the EU Ecolabel Regulation (EC) No. 99/2010 of a number of substances that may be present in modules and inverters.	
4.2.1 Candidate list substances	The IEC 62474 substance declaration shall be used to declare that Candidate list substances are not present at >0.1%
4.2.2 Lead and cadmium	The content of lead and cadmium in modules and inverters shall be less than 0.1% and 0.01% respectively. By weight or by Wp The cadmium level may be >0.01% if recovery of the semi-conductor can be demonstrated as part of a take back service provided.
4.2.3 Fluorinated backsheets	Module products shall not be manufactured with fluorinated backsheet materials.
4.2.4 Glass additives	Antimony and arsenic in glass shall not be present at >50 ppm
4.2.5 Flame retardants and pthalates	The hazard restrictions of the personal computer product group on cables and main circuit boards shall apply.
4.3. Circular economy criterion	
4.4.1 Module durability and quality	Design type approval proposed as an Ecodesign requirement shall be implemented by an audited factory quality control system in accordance with IEC TS 62941 and IECRE OD 405 series.
4.3.2 Module degradation rate	Declaration of the rate shall be validated by the Transitional Method for Ecodesign and demonstrate an average performance degradation rate over a 30 year time period of 0.6%
4.4.3 Module design for recycling	The manufacturer shall document and report the sequence of steps and tools required to dismantle the module and recover the solar cells or semi-conductor material.

4.4.4 Inverter on-site repair service	The installer shall ensure that a responsive repair service is provided for inverters, with on-site replacement of the main circuit boards forming part of the service.
4.4.5 Repairability requirements for inverters	<30 kW: The manufacturer shall ensure that the power, filter and communications circuit boards as well as firmware updates shall be made available for a minimum period of 7 years. >30 kW: Manufacturers shall ensure that replacement parts and firmware updates are made available in line with the recommended replacement cycle.
4.5 System service criteria	
4.5.1 Optimised design	The system design shall be optimised taking into account the specific local conditions of the installation. The service provider shall demonstrate that the system design software used takes into account, as a minimum: – Orientation and possible shading, – Local climatic conditions, including temperature dependency – Exposure/access to the inverter
4.5.2 Handling and installation protocols	The contractors used to install the system shall follow a protocol designed to minimise any breakages to modules during transport to and handling on site.
4.5.3 Monitoring and maintenance	The service shall include, for a minimum of 10 years, the monitoring of the system for faults and a responsive repair and maintenance service designed to optimise performance. This shall include, as a minimum: – Fault diagnosis, – Repair and replacement cycles for major components, and – Cleaning of the modules.

8.4 Recommendation 4: EU Green Public Procurement criteria for PV systems

In this fourth recommendation it is proposed that if a new GPP product group is established that it should be targeted at the procurement of PV systems for grid connected power generation by public authorities, but with an additional, broader focus on the public authority acting as a catalyst to increase local residential PV system installations and to create demand for green (solar) electricity.

These product group GPP criteria could be established independently of a new EU Ecolabel for the corresponding products. Whilst they could make use of some of the recommendations for Ecodesign and Energy labelling, they go beyond them in order to adopt a life cycle perspective and to address more comprehensively circular economy aspects.

A qualitative evaluation, which was made with reference to DG Environment's criteria for establishing new product groups, found it to be feasible. The main focus of the criteria set for direct use by public authorities would be the project management of a PV system installation to minimise life cycle cost and environmental impacts. This could extend from contractor selection through to decommissioning and would seek to manage solar PV system procurement processes in order to:

- optimise the site specific potential to generate solar power,
- seek a balance between optimising energy yield and life cycle energy/GWP of the installations
- minimise risks to loss of income from quality issues that may arise related to equipment and the installation itself,
- minimise the Levelised Cost of Electricity (LCOE) along the life cycle of a project.

Because the development of local markets for solar PV appears to be in part driven by visibility and peer pressure, GPP criteria have a potentially important leadership role. The public sector has a substantial stock of buildings and land on which solar PV could potentially be installed – either by direct procurement or via access rights. They also have a substantial demand for electricity which could be used via bilateral arrangements such as Power Purchase Agreements to drive investment in new solar generating capacity.

Once a decision has been made to procure solar PV systems a public authority can in most cases exert a direct influence on the competencies of contractors, the design of systems and the specification of components. In the case of reverse auctions or the procurement of electricity this influence can be extended to third party, installations.

Table 191. GPP criteria set for PV system procurement

Performance aspect	**Detailed proposed requirements**
Module and inverter factory quality and performance testing	
5.1.1 Design quality of modules and inverters	*Technical requirement for design qualification and factory quality*: – Core: Design type approval of each model deployed according to IEC 61215 and IEC 62941 – Comprehensive: Factory quality controls and auditing according to IEC TS 63157 and the associated IECRE OD [pending a code].
5.1.2 Module degradation rate	*Award criteria based on declared module degradation rate.* Points shall be awarded based on the validated performance degradation rate period expressed as the average annual % loss over a 30 year time. The transitional method shall be used as the basis for verification.
Design and yield estimation	
5.1.3 Energy return on investment	*Award criteria based on declared system EROI.* The tenderer shall calculate and declare the energy return on investment for the system. *The production and use stage primary energy use for the modules and inverters specified shall be derived from the corresponding Ecodesign information requirement, which is proposed as being based on EN 15804 and the PEFCR.*

5.1.4 Life cycle GWP	The tenderer shall calculate the life cycle GWP for the system. The kg/CO_2.kWh shall not exceed [threshold tbd]. *The life cycle impacts shall estimated according to method set out in Ecodesign, which is based on EN 15804 and the PEFCR.* *Note:* there is an option to provide default values in tabular form as has been done by the French Government for the national PV capacity auction process.
5.1.4 System energy yield	*Award criteria based on an estimate of the system yield (with reference to the Energy Label EEI)* The tenderer shall make a design estimate of the system yield based on the methodology for calculating the Energy Label EEI. The EEI shall be expressed in units of MWh/kWp.m^2. The contractor shall also declare a target plant Performance Ratio. Under a contract performance clause the yield and target plant performance ratio the installed system shall then be monitored according to IEC 61724.
Installation/ construction	
5.1.5 Handling and installation protocols	*Selection Criteria evidencing the use of such protocols and/or Technical Specification requiring specific actions within a protocol.* The tenderers for installation of the system shall follow a protocol designed to minimise any breakages to modules during transport to and handling on site.
5.1.6 Commissioning test	*Contract performance clause based on the target plant Performance Ratio* A commissioning test shall be carried out according to IEC 61724 in order to evaluate the Performance Ratio of the system. The commissioning PR shall be compared with the target plant Performance Ratio declared at bid stage.
Operation & Maintenance	
5.1.7 Inverter preventative repair cycle	*Technical Specification based on planning to respond to inverter manufacturers recommended repair cycle* In order to use a longer inverter lifetime than the default for the life cycle GWP calculation tenderers shall provide a recommended preventative maintenance cycle. This shall include a list of parts recommended to be replaced and preventative measures to achieve an intended design technical lifetime.
5.1.8 Monitoring	*Technical Specification/Award Criteria for the granularity of monitoring system* The tenderers shall ensure that the system design supports class C data monitoring according to IEC 61724-1. The system shall have physical and/or wireless connectivity capable of communicating with remote monitoring systems using a recognised data transfer protocol.
5.1.9 Maintenance	*Technical Specification/Award Criteria for the provision of aftercare services* The service shall include, for a minimum of [award] years, a repair and maintenance service designed to optimise performance. This service shall include, as a minimum: – Fault diagnosis, – Responsive repair and planned replacement cycles for major components, and – Cleaning of the modules.

8.5 Combined policy option recommendations

One of the aims of considering both mandatory and voluntary policy instruments within the frame of the Preparatory Study has been to analyse the potential for synergies between them. Two combined policy options were therefore identified and modelled in Task 7 in order to determine the improvement potential. The two combined options reflect the mandatory and voluntary nature of the instruments and the differing ways in which they may act on the market:

- **COM 6.1 (ED+EL+GPP)** would be led by implementation of the two mandatory instruments, namely Ecodesign and Energy Labelling, to be complemented by voluntary Green Public Procurement criteria.
- **COM 6.2 (ED+GPP+EU Ecolabel)** would be led by implementation of the two voluntary instruments, namely the EU Ecolabel and Green Public Procurement, backed by the mandatory instrument Ecodesign.

The two options are further compared and contrasted in the following sections 8.5.1 and 8.5.2 before an overall recommendation is made in section 8.5.3.

8.5.1 Combined policy option 6.1: Mandatory instruments complemented by Green Public Procurement (GPP)

The basis for this option would be the implementation of the two mandatory instruments, namely **Ecodesign and Energy Labelling**, to be complemented by voluntary **Green Public Procurement** criteria. Table 8-9 provides an overview of the metrics and requirements that would be brought together under this policy option and which were modelled in Task 7 as COM 6.1. The proposals in Table 8-9 reflect the state of the art (in particular in terms of metrics) at the moment of drafting the present Task (December 2019). The availability of future metrics could entail changes in the nature of the proposed requirements (e.g. from Ecodesign information requirements to mandatory threshold requirements).

Introduction of the two mandatory instruments would ensure a consistent focus in the market on long-term performance and circularity, acting at both component and system level. An important aim of introducing the GPP criteria would then be to use public sector influence, in particular at regional and local level, to exploit a range of synergies with the mandatory instruments by providing guidance and criteria in three key areas:

1. The *direct procurement of new solar PV systems*, with reference to component life cycle requirements established under Ecodesign.
2. The establishment of *procurement frameworks for residential 'reverse auctions'* that would facilitate an increase in residential installations, with reference to component requirements established under Ecodesign and the system EEI under the Energy Label.
3. The auction of *usage rights for public assets* (land and roofs) as the basis for green (solar) electricity generation, with bilateral Power Purchase Agreements as a related option.

The GPP criteria would also seek to influence the practices of system installation contractors and the supply chain.

Table 192 Metrics and requirements for combined policy option COM 6.1: Mandatory instruments + Green Public Procurement (GPP)

Metric/requirement	**Ecodesign**	**Energy Label**	**GPP**
Life cycle performance and yield			
Euro efficiency (Inverter)	MR	As input data	As input data
Energy yield (module)	IR	As input data	*CSER as input data*
Energy yield (system)		EEI	*EEI used for AC*
Design optimisation (system)		User defined data	*EEI used for AC*
Operation and maintenance (system)		User defined data	TS
Long-term degradation (module)	IR	As input data	AC
Life cycle GER and GWP	IR		AC
Energy Return on Investment			*EEI and life cycle data used for AC*
Smart readiness	MR		TS
Material efficiency and circularity			
– Durability (IEC tests)	MR		TS
– Factory quality (IECRE)			TS
– Warranty			TS/AC
– Repairability	IR (MR?)		TS/AC
– Recyclability	IR (MR?)		AC
– Hazardous substances	IR		
– Material content	IR		

Key to acronyms used:

MR Minimum Requirement

IR Information Requirement

EEI Energy Efficiency Index

TS Technical Specification

AC Award Criterion

8.5.2 Combined policy option 6.2: Voluntary instruments supported by Ecodesign

The basis for this option would be the implementation of the two voluntary instruments, namely the **EU Ecolabel** and **Green Public Procurement**, backed by the mandatory instrument **Ecodesign**. Table 193 provides an overview of the metrics and requirements that would be brought together under this policy option and which were modelled in Task 7 as COM 6.2. The proposals of Table 8-10 reflect the state of the art (in particular in terms of metrics) at the moment of drafting the present Task (December 2019). The availability of future metrics changes in the nature of the proposed requirements (e.g. from Ecodesign information requirements to mandatory threshold requirements).

The two voluntary instruments would provide a means of stimulating green innovation in a coherent framework of criteria that address life cycle hot spots:

- The EU Ecolabel would focus attention on *module and inverter designs* that have a high Energy Return on Investment, a low life cycle GWP, contain less hazardous substances and which facilitate future repair and recycling. These criteria would in turn provide the basis for Comprehensive GPP criteria.
- Both the instruments would have a focus on the *system service 'offer'* of installers, addressing design, monitoring and maintenance aspects, and aiming to maximise the *Energy Return on Investment and life cycle performance of systems*.

The establishment of mandatory Ecodesign requirements would lay down the units of measurement and methods that would be required for a number of the voluntary criteria – specifically: energy yield, derating factors, performance degradation, life cycle GER and GWP.

Table 193. Metrics and requirements for combined policy option COM 6.2: Voluntary instruments + Ecodesign

Metric/requirement	Ecodesign	EU Ecolabel	EU GPP
Life cycle performance and yield			
Euro efficiency (Inverter)	MR		*As input data*
Energy yield (module)	IR	*As input data*	*CSER as input data*
Energy yield (system)			TS/AC
Design optimisation (system)		*Modelling requirements*	*EEI used for AC*
Operation and maintenance (system)		EC	TS
Long-term degradation (module)	IR	EC	AC
Life cycle GER and GWP	IR	EC	AC
Energy Return on Investment		EC	AC
Smart readiness	MR	EC	TS
Material efficiency and circularity			
– Durability (IEC tests)	MR	EC	TS
– Factory quality (IECRE)		EC	TS
– Warranty			TS/AC
– Repairability	IR (MR?)	EC	TS/AC
– Recyclability	IR (MR?)	EC	AC
– Hazardous substances	IR	EC	
– Material content	IR		

Key to acronyms used:

MR Minimum Requirement

IR Information Requirement

EEI Energy Efficiency Index

EC Ecological criterion

TS Technical Specification

AC Award Criterion

8.5.3 Recommendation on the combined policy options

The results of the scenario modelling in Task 7 showed that COM 6.1 was estimated to provide the greatest improvement in yield until 2050, initially providing an uplift of 3.4% in 2025 rising to as much as 7.7% by 2035, versus an uplift of 2.4% in 2025 and 5.4% in 2035 for COM 6.2. The difference is accounted for assumptions made in COM 6.1 about efficiency gains and improved system yields driven primarily by substitution effects in the market from the mandatory Energy Label option 3.2.

More modest assumptions about similar effects that could be driven by the EU Ecolabel criteria set still drive up yield in COM 6.2 but not to the extent of the Energy Label 3.2 option and in fact the assumptions about market confidence made for the EU Ecolabel can be considered to have a higher level of uncertainty due to it being a voluntary instrument. This could therefore increase the gap between the performance of the two options. Note also that the potential for GPP to have a broader market influence – primarily through facilitating an increase in residential deployment, as modelled in option 5.2, was not included in the modelling for either COM 6.1 or 6.2.

In terms of the annual GER, the results of the scenario modelling in Task 7 showed that the most beneficial combined scenario for GER was COM 6.2. This scenario was modelled as providing a benefit of up to 21% on the BAU in the period 2025 – 2035 with the improvement largely driven by the mandatory Ecodesign instrument, supported by the EU Ecolabel. The more modest improvement of 4-5% achieved by COM 6.1 is the result of a trade-off between the higher yield it achieves and, in order to achieve this yield, the deployment of module technologies that have a higher GER.

Given the policy significance of renewable energy deployment and consequently renewable energy yield to the EU's climate change mitigation objectives, it is considered that COM 6.1 is the preferred option. This option is driven by mandatory instruments that can exert a strong influence on life cycle energy yield and in the case of Ecodesign this can be used to lay down market entry requirements that can exert an influence on the stock life cycle GER. The GPP voluntary instrument could, moreover, be used to exert a range of broader market influences via local and regional government, with a particular focus on increasing residential solar PV system deployment. In the case of the EU Ecolabel the potential influence on the residential market segment is considered to have a higher level of uncertainty.

Although there is a trade-off in a lower improvement in GER from option COM 6.1, this study has also identified that solar PV technology achieves a relatively high Energy Return on Investment across all the policy options. This is because the energy invested in the production stage to extract raw materials and manufacture modules and inverters is, even in the worst case scenarios modelled, a factor of approximately 4-7 times less than the use stage benefit from energy generation. Moreover, further improvements in GER could be achieved in option COM 6.1 by making further progressive updates in the Ecodesign requirements described under option 2.2 and 2.4.

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List of abbreviations and definitions

AC	Alternated current
aSi	Amorphous silicon
BAPV	Building attached photovoltaics
BAT	Best available technology
BAU	Business as usual
BIPV	Building integrated photovoltaics
BSF	Back Surface Field
BOS	Balance of system
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CdTe	Cadmium Telluride
CIGS	Cadmium Indium Gallium Selenium
CPA	Classifications of Products by Activity
CPC	Contract performance clauses
CTM	Cell to module
cSi	Crystalline Silicon
Derate factors	Factors that quantify individual sources of loss with respect to the nameplate's DC power rating
DRcapture	Factor representing combined array capture losses
DRshading	Factor representing shading losses
DRsnow	Factor representing snow cover losses
SL	Factor representing soiling losses
DRarraywr	Factor representing DC array cable losses
DRMISM	Factor representing array mismatch losses
DRrefl	Factor representing optical reflection losses
DRcap-mod	Factor representing other module level capture losses
DRtherm	Factor representing module thermal capture loss
DRdegrad	Factor representing module degradation capture loss
DRrefl	Factor representing optical reflection losses
Drspect	Factor representing spectral effects
DRBOS	Factor representing balance of system (BOS) efficiency
DRacwire	Factor representing AC wiring losses
Drtrafo	Factor representing AC transformer losses (if available)
DRcurt	Factor representing losses due to network availability (curtailment)
DRinv-fail	Factor representing losses due to inverter failures (drop out)
DRinv	Factor representing inverter losses (= DRinv-ns x ninv)
DRinv-ns	Factor representing derating non standard inverter total
DRinv-load	Factor representing derating non standard inverter loading
DRinv-MPPT	Factor representing derating non standard MPPT transients
nt-inv	Factor representing total inverter efficiency standard conditions

nconv	Factor representing static inverter converter efficiency
DFS	Design for Serviceability
DN	Distribution network
DHW	Domestic hot water
Diffuse radiation	Solar radiation reaching the Earth's surface after having been scattered from the direct solar beam by molecules or particulates in the atmosphere
Direct sunlight	Also called "beam radiation" or "direct beam radiation". Used to describe solar radiation traveling on a straight line from the sun down to the surface of the earth
DRM	Demand response management
DSSC	Dye sensitized solar cells
EoL	End of Life
EPBD	Energy Performance of Buildings Directive
EPC	Companies that are prepared to provide services linked to the Engineering, Procurement and Construction disciplines of a project
ErPs	Energy-related Products
ESCO	Energy service company
FiT	Feed-in tariff
GaN	Gallium nitride
GIS	Geographic information systems
GPP	Green public procurement
GEC	Green energy certificates
GHG	Greenhouse gas
GPP	Green public procurement
GVA	Gross value added
GWP	Global-warming potential
HSW	Hot sanitary water
HVAC	Heating, ventilation, and air conditioning
IEA	International energy agency
IEC	International electrotechnical commission
IGBT	Insulated-gate bipolar transistor
IMD	Insulation Monitoring Device
IPP	Independent power producer
ITRPV	International Technology Roadmap for photovoltaics
LCA	Life cycle analysis
LCC	Life cycle cost
LCOE	Levelized Cost of Electricity: net present value of the unit-cost of electricity over the lifetime of a generating asset allowing the comparison of different technologies (e.g., wind, solar, natural gas) of unequal life spans, project size, different capital cost, risk, return, and capacities
LED	Light emitting diode
MEErP	Methodology for the Ecodesign of Energy-related Products
MFI	Monetary financial institutions

MLPE	Module-level power electronic
MPP	Maximum power point
MPPT	Maximum power point tracking
NACE	Nomenclature statistique des activités économiques dans la Communauté européenne
NZEB	Nearly zero energy buildings
OEM	Original Equipment manufacture
PERC	Passivated Emitter and Rear Cell
PHS	Pumped hydro storage
PID	Potential-induced degradation
PO	Polyolefines
PPA	Power purchase agreement
PR	Performance ratio
PVB	Polyvinyl butyral
RCD	Residual current detector
RES	Renewable Energy Systems
SiC	Silicon carbide
SRI	Smart readiness indicator
STC	Standard test conditions
TFPV	Thin film PV
TN	Transmission network
TPSE	Thermoplastic silicone
VAT	Value added tax
WACC	Weighted Average Cost of Capital
WBG	Wide bandgap semiconductors
WEEE	Waste Electrical and Electronic Equipment

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Annexes

Annex 1A: Standards for the assessment of the environmental performance of photovoltaic modules, power conditioning components and photovoltaic systems

Annex 5A: Materials added to the MEErP EcoReport tool

Due to the structure of the life cycle inventory, it is not possible to distinguish between process water and cooling water. The water input mentioned under process water is an input for both cooling and process water.

nr	Name material	Recycle %*	Primairy Energy (MJ)	Electr energy (MJ)	feedstock	water proces	Water cool	waste haz	waste non	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
unit	New Materials production phase (category '**Extra**')	%	MJ	MJ	MJ	L	L	g	g	kg CO2 eq.	g SO2 eq.	mg	ng i-Teq	mg Ni eq.	mg Ni eq.	g	mg Hg/20	mg PO4
100	**Office paper (from recycled paper)**		15.14	3.81		20.46				0.93	2.57					2.45		0.35
101	**Office paper (from primary cellulose)**		39.71	1.80		52.23		0.00	0.02	1.20	9.09					8.45		0.74
102	**photovoltaic cell, multi-Si, at plant - China, per kg**		3598.92			24220.01		322.63	34184.73	288.74	2423.32	31.27	82.12	740.27	54.82	302.31	107.30	115545.19
103	**Tin, at regional storage/RER U**		305.59			1411.40		0.35	496.45	16.11	427.38	19.53	1.57	21.31	5.06	212.93	1.80	7625.44
104	**Lead, at regional storage/RER U**		15.32			34.11		0.04	249.00	1.02	22.84	0.57	12.72	15.18	0.21	1.03	8.61	1421.71
105	**Ethylvinylacetate, foil, at plant/RER U**		90.85			155.45		0.03	137.20	2.54	7.75	2.35	0.21	4.38	0.33	0.95	0.27	2814.26
106	**Polyvinylfluoride film, at plant/US U**		324.21			526.72		0.32	1139.31	22.40	132.31	3.76	5.85	30.98	1.90	5.17	3.42	12121.27
107	**Silicone product, at plant/RER U**		61.17			274.16		0.02	179.23	2.67	9.98	1.19	0.27	4.40	0.31	1.40	12.72	1023.80
108	**solar glass and tempering**		17.76			15.59		0.01	81.21	1.32	11.30	0.41	0.12	1.74	0.08	0.81	0.46	512.82
109																		

Annex 5B: External costs for society

All results are presented per kWh.

Modules

Multi-Si modules

		Prod & Distr. emissions mass	Ppext in EUR	Use phase emissions mass	Oeext in EUR	EoL emissions mass	EOLext in EUR	TOTAL emission	TOTAL EURO	Rate external marginal costs to society
GHG	kg CO2 eq.	6.11E-02	8.56E-04	4.68E-04	6.56E-06	1.23E-02	1.73E-04	7.39E-02	1.04E-03	0.014
AP	g SO2 eq.	4.36E-01	3.70E-03	3.87E-03	3.29E-05	1.02E-01	8.67E-04	5.42E-01	4.60E-03	0.0085
VOC	g	9.80E-03	7.45E-06	7.61E-05	5.78E-08	1.39E-03	1.06E-06	1.13E-02	8.57E-06	0.00076
POP	ng i-Teq	1.46E-02	3.95E-07	1.36E-04	3.66E-09	3.74E-03	1.01E-07	1.85E-02	4.99E-07	0.000027
HM1	mg Ni eq.	1.10E-01	1.92E-05	1.04E-03	1.81E-07	2.68E-02	4.69E-06	1.37E-01	2.40E-05	0.000175
HM2	mg Ni eq.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00004
HM3	mg Ni eq.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0003
PAH	mg Ni eq.	5.98E-02	7.65E-05	5.66E-04	7.24E-07	2.07E-02	2.64E-05	8.10E-02	1.04E-04	0.001279
PM	g	1.05E-01	1.63E-03	5.09E-04	7.88E-06	1.52E-02	2.35E-04	1.21E-01	1.87E-03	0.01546
Total			**6.29E-03**		**4.83E-05**		**1.31E-03**		7.64E-03	

Inverter

2500 W inverter

		Prod & Distr. emissions mass	Ppext in EUR	Use phase emissions mass	Oeext in EUR	EoL emissions mass	EOLext in EUR	TOTAL emission	TOTAL EURO	Rate external marginal costs to society
GHG	kg CO2 eq.	6.79E-03	9.50E-05	5.73E-05	8.02E-07	1.35E-03	1.89E-05	8.19E-03	1.15E-04	0.014
AP	g SO2 eq.	4.42E-02	3.76E-04	3.99E-04	3.39E-06	9.88E-03	8.40E-05	5.45E-02	4.63E-04	0.0085
VOC	g	6.83E-04	5.19E-07	5.80E-06	4.41E-09	1.24E-04	9.41E-08	8.13E-04	6.18E-07	0.00076
POP	ng i-Teq	8.36E-03	2.26E-07	8.22E-05	2.22E-09	3.07E-03	8.30E-08	1.15E-02	3.11E-07	0.000027
HM1	mg Ni eq.	8.92E-03	1.56E-06	8.33E-05	1.46E-08	2.33E-03	4.08E-07	1.13E-02	1.98E-06	0.000175
HM2	mg Ni eq.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00004
HM3	mg Ni eq.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0003
PAH	mg Ni eq.	4.05E-03	5.18E-06	3.79E-05	4.85E-08	1.41E-03	1.81E-06	5.50E-03	7.03E-06	0.001279
PM	g	3.88E-03	5.99E-05	2.45E-05	3.79E-07	7.28E-04	1.13E-05	4.63E-03	7.16E-05	0.01546
Total			**5.38E-04**		**4.65E-06**		**1.17E-04**		6.59E-04	

20 kW inverter

		Prod & Distr. emissions mass	Ppext in EUR	Use phase emissions mass	Oeext in EUR	EoL emissions mass	EOLext in EUR	TOTAL emission	TOTAL EURO	Rate external marginal costs to society
GHG	kg CO2 eq.	3.31E-03	4.63E-05	2.90E-05	4.06E-07	6.82E-04	9.55E-06	4.02E-03	5.63E-05	0.014
AP	g SO2 eq.	2.20E-02	1.87E-04	2.02E-04	1.72E-06	5.00E-03	4.25E-05	2.72E-02	2.31E-04	0.0085
VOC	g	3.37E-04	2.56E-07	2.94E-06	2.23E-09	6.27E-05	4.76E-08	4.02E-04	3.06E-07	0.00076
POP	ng i-Teq	4.22E-03	1.14E-07	4.15E-05	1.12E-09	1.55E-03	4.20E-08	5.81E-03	1.57E-07	0.000027
HM1	mg Ni eq.	4.46E-03	7.81E-07	4.22E-05	7.38E-09	1.18E-03	2.06E-07	5.68E-03	9.95E-07	0.000175
HM2	mg Ni eq.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00004
HM3	mg Ni eq.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0003
PAH	mg Ni eq.	2.01E-03	2.57E-06	1.92E-05	2.45E-08	7.14E-04	9.13E-07	2.74E-03	3.51E-06	0.001279
PM	g	2.76E-03	4.27E-05	1.24E-05	1.92E-07	3.68E-04	5.69E-06	3.14E-03	4.85E-05	0.01546
Total			**2.79E-04**		**2.35E-06**		**5.90E-05**		3.41E-04	

1500 kW inverter

		Prod & Distr. emissions mass	Ppext in EUR	Use phase emissions mass	Oeext in EUR	EoL emissions mass	EOLext in EUR	TOTAL emission	TOTAL EURO	Rate external marginal costs to society
GHG	kg CO2 eq.	6.75E-04	9.44E-06	3.75E-06	5.24E-08	1.30E-04	1.83E-06	8.09E-04	1.13E-05	0.014
AP	g SO2 eq.	3.60E-03	3.06E-05	2.46E-05	2.09E-07	8.75E-04	7.43E-06	4.49E-03	3.82E-05	0.0085
VOC	g	5.14E-05	3.91E-08	1.22E-07	9.27E-11	4.51E-06	3.43E-09	5.61E-05	4.26E-08	0.00076
POP	ng i-Teq	2.79E-03	7.53E-08	2.67E-05	7.21E-10	1.03E-03	2.77E-08	3.84E-03	1.04E-07	0.000027
HM1	mg Ni eq.	1.74E-03	3.05E-07	1.35E-05	2.37E-09	5.17E-04	9.06E-08	2.27E-03	3.98E-07	0.000175
HM2	mg Ni eq.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00004
HM3	mg Ni eq.	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0003
PAH	mg Ni eq.	3.52E-04	4.50E-07	2.62E-06	3.34E-09	9.94E-05	1.27E-07	4.54E-04	5.81E-07	0.001279
PM	g	3.96E-03	6.13E-05	3.19E-06	4.93E-08	1.17E-04	1.81E-06	4.08E-03	6.31E-05	0.01546
Total			**1.02E-04**		**3.17E-07**		**1.13E-05**		1.14E-04	

Annex 5C: Overview of LCA literature

File Name	key words	Year of publication	Authors	Journal/source	Country/ Region	Title	Manufacture	Use	End of life
Vellini_2017	eol - BAT CdTe	2017	Michela Vellini, Marco Gambini, Valentina Prattella	Energy	Rome	Environmental impacts of PV technology throughout the life cycle:Importance of the end-of-life management for Si-panels and CdTepanels	✓	✓	✓
Bracquenea_2018	parameteric LCA	2018	Ellen Bracquenea, Jef R. Peeters, Wim Dewulf, Joost R. Du	25th CIRP Life Cycle Eng	Copenhag	Taking evolution into account in a parametric LCA model for PV panels	✓	-	✓
Bogacka_2017	eol	2017	M. Bogacka, K. Pikon, M. Landrat	Waste Management	Poland	Environmental impact of PV cell waste scenario	✓	-	✓
Sagani_2017	BIPV	2017	Angeliki Sagani, John Mihelis, Vassilis Dedoussis	Energy and Buildings	Greece	Techno-economic analysis and life-cycle environmental impacts of small-scale building-integrated PV systems in Greece	✓	✓	✓
Ling-Chin_2016		2016	J. Ling-Chin, O. Heidrich, A.P. Roskilly	Renewable and Sustair	UK	Life cycle assessment (LCA) – from analysing methodology development to introducing an LCA framework for marine photovoltaic (	✓	✓	✓
Kadro_2017		2017	Jeannette M. Kadro and Anders Hagfeldt	Joule	Switzerlar	The End-of-Life of Perovskite PV	✓		✓
Latunussa_2016	eol	2016	Cynthia E.L. Latunussa, Fulvio Ardente, Gian Andrea Bleng	Solar Energy Materials	Italy	Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels	-	-	✓
Lunardi_Moore_2018	BAT_SHJ heteroju	2018	Marina M. Lunardi, Stephen Moore, J.P. Alvarez-Gaitan, C	Energy	Australia	A comparative life cycle assessment of chalcogenide/Si tandem solar modules	✓	✓	✓
Wu_2017		2017	Peishi Wu, Xiaoming Ma, Junping Ji, Yunrong Ma	The 8th International C	China	Review on life cycle assessment of greenhouse gas emission profit of solar photovoltaic systems	✓	✓	-
Wong_2016		2016	J.H. Wong, M. Royapoor, C.W. Chan	Renewable and Sustair	UK	Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic sys	✓	✓	✓
Lamnatou_2016		2016	Chr. Lamnatou, H. Baig, D. Chemisana, T.K. Mallick	Journal of Cleaner Proc	UK	Environmental assessment of a building-integrated linear dielectric-based concentrating photovoltaic according to multiple life-cy	✓	✓	✓

File Name	key words	Year of publication	Authors	Journal/source	Country/ Region	Title	Manufacture	Use	End of life
Good_2015		2015	Clara Good	Renewable and Sustair	Norway	Environmental impact assessments of hybrid photovoltaic–thermal (PV/T) systems – A review	-	-	-
Chen_2016		2016	Wei Chen, Jinglan Hong, Xueliang Yuan, Jiurong Liu	Journal of Cleaner Proc	China	Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China	✓	-	-
Savvilotidou_2017	ecolabel eol	2017	Vasiliki Savvilotidou, Alexandra Antoniou, Evangelos Gida	Waste Management	Greece	Toxicity assessment and feasible recycling process for amorphous silicon and CIS waste photovoltaic panels	-	-	✓
Pagnanelli_2017	eol	2017	Francesca Pagnanelli, Emanuela Moscardini, Giuseppe Gra	Waste Management	Italy, Japa	Physical and chemical treatment of end of life panels: An integrated automatic approach viable for different photovoltaic technologies			
Brun_2016	ecolabel	2016	Nadja Rebecca Brun, Bernhard Wehrli, Karl Fent	Science of the Total En	Switzerlar	Ecotoxicological assessment of solar cell leachates: Copper indium gallium selenide (CIGS) cells show higher activity than organic p	-	✓	✓
Lamnatou_Chemisana_2015		2015	Chr. Lamnatou, D. Chemisana	Building and Environm	Spain	Evaluation of photovoltaic-green and other roofing systems by means of ReCiPe and multiple life cycle based environmental indica	✓	✓	✓
Lamnatou_Baig_2015	BIPV	2015	Chr. Lamnatou, H. Baig, D. Chemisana, T.K. Mallick	Energy and Buildings	Spain, UK	Life cycle energy analysis and embodied carbon of a lineardielectric-based concentrating photovoltaic appropriate for building-inte	✓	✓	✓
Fu_2015		2015	Yinyin Fu, Xin Liu, Zengwei Yuan	Journal of Cleaner Proc	China	Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China	✓	-	-
Yang_2015		2015	Dong Yang, Jingru Liu, Jianxin Yang, Ning Ding	Journal of Cleaner Proc	China	Life-cycle assessment of China's multi-crystalline silicon photovoltaic modules considering international trade	✓	-	-
Wyss_2015_PEFCR screening report		2015	Wyss F., Frischknecht R., de Wild-Scholten M., Stolz P.	-	Switzerlar	PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rule	✓	✓	✓
Frishknecht_2015_IEA taks 12		2015	Frischknecht R., Itten R., Sinha P., de Wild-Scholten M., Zh	-		Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, International Energy Agency (IEA) PVPS Task 12, Report T12-04:2015.			
UNEP_2016		2015	UNEP	http://web.unep.org/ourplanet/		Summary for Policymakers, Green Energy Choices: The Benefits, Risks and Trade-Offs of Low-Carbon Technologies for Electricity Production			
Lecissi_2016		2016	Lecissi E., Raugei M., Fthenakis V.	Energies 9, 622; doi:10.3390/en90		The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update	✓	-	-
Chatzisideris_2016		2016	Chatzisideris M., Espinosa N., Laurent A., Krebs F.	Solar Energy Materials	Denmark	Ecodesign perspective of thin-film photovoltaictechnologies: A review of life cycle assessment studies	-	-	-
Lunardi_AlvarezGaitan_2018	BAT_PERC	2018	Lunardi M., Alvarez-Gaitan J.P., Chang N., Corkish R.	Solar Energy Materials	China as n	Life cycle assessment on PERC solar modules	✓	✓	✓
Lunardi_2017	BAT_HIT	2017	Lunardi M., Ho-Baillie A., Alvarez-Gaitan J.P., Moore S., Corkish R.	Progress in photovoltaics		A life cycle assessment of perovskite/silicon tandem solar cells			
Sica_2018	circ econ, market p	2018	Sica D., Malandrinoa O., Supinob S., Testaa M., Lucchettic	Renewable and Sustainable Energ		Management of end-of-life photovoltaic panels as a step towards a circular economy			
Stolz_2016	recycling	2016	Stolz P., Frischknecht R.	website Treeze		Life cycle assessment of photovoltaic module recycling			

File Name	System boundaries	Technology	Functional unit	Lifetime	Capacity	Type of system	Environmental Impact Categories	Method	Database	Software	Data quality	Quality rating	Hotspots
Vellini_2017	cradle to grave" analysis: it	Si, CdTe	1 m^2 of photovoltaic module area	-	-	-	GWP, AP, EP, POCP, ODP, ETF, ADPE, ADPF, huma	CML	Ecoinvent (ve	Gabi software (version 5.0)			For Si panels Cell and panel production Cell production > 95 % for ADPE MG-Silicon purification (Siemens) for GWP, ODP, ADPF, EP EoL for ETF and TETP For CdTe panels CdTe panel production and EoL Te extraction for ADP
Bracquenea_2018	the Balance of System (BoS) components, such as inverters, charge controllers, batteries and mounting structures, have been omitted from the system boundary	Si	1 Wp of multi-crystalline Silicon pane	-	1 Wp	-	GWP, ODP, AP, EP, PM, ETF IRHH, LUO (agricultura	The "allocation default" system model is used. ReCiPe H/A to calculate normalized potential of environmental impact.	Ecoinvent 3.3	SimaPro 8.3			Silicon wafers Panel assembly increasingly important
Bogacka_2017	Production, transport and r	Si	1 module and it contains 36 single wa	28	-	-	GWP, ODP, Terrestrial acidification, EP (freshwat	ReCiPe	Ecoinvent 3.0	SimaPro			Production of PV panels
Sagani_2017	It involves (1) the producti	Polycrystaline s	PV system with 5 different rated pow	25	2,59 / 4,94	Rooftop	GWP, Primary Energy Requirement	CML 2 baseline 2000 and	Ecoinvent	SimaPro 7.1			-
Ling-Chin_2016	Cradle-to-grave	Marine photovo	The PV system has a power of 288kW	30	288 kWp	Marine PV system	By CML: Marine Aquatic Ecotoxicity Potential, ETF, GWP, Human Toxicity Potential, AP, Terrestric Ecotoxicity Potential, POCP By Eco-Indicator 99: Ecosystem Quality – Ecotoxicity, Resources – Minerals, Ecosystem Quality – Acidification/Nutrification, Ecosystem Quality – Land Use By ILCD: ETF, GWP, Total Freshwater Consumption, POCP, Terrestrial Eutrophication, Acidification	CML; Eco-Indicator 99; ILCD					EoL, module and cell manufacturing
Kadro_2017	Cradle-to-grave, no inform	Perovskite sola	1 kWh	-	-	-	GWP, HTCE, HTnCE, Respiratory inorganics, Ionizi	ILCD	Ecoinvent	-			EoL
Latunussa_2016	This FU includes internal ca	crystlline silicor	The functional unit(FU) of the LCA wa	-	-	-	ADPE, Cumulative Energy Demand, ETF, Marine e	ILCD; According to the ISO	FRELP process	SimaPro 8.0			Transport of PV waste to treatment plant. Sieving, acid leaching, electrolysis, and neutralization. Incineration of PV sandwich and fly ash disposal, for freshwater ecotoxicity, HTCE, HTnCE, GWP Energy recovery has a positive impact on some categories
Lunardi_Moore_2018	Cradle-to-grave	Si and chalcoger	functional unit of 1 kWh	20	-	-	GWP, HTCE, HTnCE, freshwater eutrophication potential, ETF, abiotic depletion potential	ILCD	IEA - Photovo	Gabi LCA software			Production of solar grade Si For some categories and technologies: Modules, Buffer layers and Installation/Landfill
Wu_2017	Production of panels, starti	multi-Si PV	1 kWh	LCA is bas	-	-	GWP	sourced from 4 different	sourced from	sourced from 4 different studies			-
Wong_2016	Cradle-to-grave	Crystalline PV	1 kWh	This pape	-	Ground mounted o	GWP	literature review	literature rev	literature review			-
Lamnatou_2016	The phases of material mar	Building-integra	1 kWp, which includes 43 modules (3.	-	1 kWp	-	Resources, Ecosystem, Human health, HTCP, HTn	ReCiPe, Eco-indicator 99,	Ecoinvent 3	SimaPro 8			Mostly glass cover and PV cells. Material and module manufacturing. Use phase.

File Name	System boundaries	Technology	Functional unit	Lifetime	Capacity	Type of system	Environmental Impact Categories	Method	Database	Software	Data quality	Quality rating	Hotspots
Good_2015	Depending of the scope of each individual study that has been reviewed.	a hybrid photov	The choice of functional unit varies significantly between the studies. Some use 1 m² module area [8], 1m² roof area [11], 1 kWp installation [12], or the whole PV/system [13]. In other cases, no functional unit is specified. This study recalculates the results from other studies, and uses 1 m² of installation as a functional unit.	Expected	-	Roof top, Building i	Embodied emissions, Embodied energy	Some of the publications	The data on p	Some of the research groups have used Sim			-
Chen_2016	Included: processes of infrastructure, raw materials and energy consumption, waste disposal, transport, and direct emissions of mono-Si PV cell production stage. The use and final disposal of the mono-Si PV cell are excluded in this study.	monocrystalline	1 kWp mono-Si PV cell	25	1 kWp	-	GWP, ODP, Terrestrial acidification, Human toxici	ReCiPe	Annual statist	not mentioned			Electricity and Ag paste
Savvilotidou_2017	Recycling process	i) tandem a-Si:H	1 kg of dry weight panel	-	-	-	Mg, Al, Si, Ca, Ti, Cr, Mn, Fe, Ni, Cu, Zn, Ga, As, Se	TTLC and TCLP	Own measure	-			-
Pagnanelli_2017		(Si-based panels and CdTe panels)											
Brun_2016	Effects of different types o	Organic PV and	-	-	-	-	Embryo toxicity (Hatching; Heart edema), Oxidati	TRSP-ICP-MS	Own measure	Visual MINTEQ 3.1			The results show that damaged CIGS cells pose a significantly higher risk to the environment than the OPV cells. Conditions simulating roof-top acidic rain run-off and disposal in marinewater environment indicate leaching of multiple metals with a prevalence of Ag, Cd, Cu, Fe, Mo, Sn, and Zn.
Lamnatou_Chemisana_2015	The system boundaries incl	PV-gravel, PV-g	The whole roofing system (300 m2) is	30	13,8 kWp	Roofing system	Human health, Ecosystems, Resources, GWP (20a	ReCiPe	Ecoinvent 3.2	SimaPro 8			PV laminates (multi-Si) and steel components (joist, decking, balance of system)
Lamnatou_Baig_2015	The following phases are ta	Concentrating P	1 kWp	20 & 30	1 kWp	-	Embodied energy, Embodied carbon	ISO14040:2006 and ISO 14044:2006		ICE and ALCOI	SimaPro 8	for evaluation of w	PV and Compound Parabolic Concentrator
Fu_2015	From quartz mining until pr	multi-crystalline	1 kWh	25	200 Wp	-	Primary energy demand, AP, EP, GWP, Human to:	CML	Data collecte	GaBi4			Transformation of metallic silicon into solar silicon
Yang_2015	cradle to gate	multi-crystalline	1 kWp	-	1 kWp	-	GWP, ADP, AP, EP, HTP, Freshwater aquatic ecotc	CML	International	SimaPro 7.3			International trade of raw materials, multi-crystalline silicon PV production and PV module packaging
Wyss_2015_PEFCR screening re	product stage, construction	CdTe, CIS, micro	1kWh of DC electricity generated by a	30	3 kWp, 57	integrated in roof, r	all 15 PEF impact categories considered	PEF method	Ecoinvent 2.2	SimaPro 7.3.3		PEF DQR - at least g	Production of the panels Installation and mounting The product stage contributes between 50% (micro-Si PV panels) and 99% (CIS PV panels) to the total weighted life cycle results
Frishknecht_2015_IEA taks 12							Primary energ demand, Energy payback time, Greenhouse Gas emissions						
UNEP_2016		Multi-c-Si, CdTe, CIGS					Carbon footprint, human health (ionizing radiation, photochemical oxidant formation, particulate matter, human toxicity, ozone depletion), ecosystems (freshwater ecotoxicity, freshwater						
Lecissi_2016	manufacture, BOS included	Mono-c-Si, mult	1kWp			Fixed-Tilt Ground-M	CED, GWP, AP, ODP, EPBT	CML	ecoinvent 3.1	SimaPro 8	Ecoinvent	Questionable if it c	depends on impact category and technology
Chatzisideris_2016	Depending of the scope of	Thin-film PV: Cc	-	-	-	PV technologies su	Primary energy demand, GWP, ODP, POCP, AP, E	Eco-indicator 95/99, CML	-	-			Electricity consumption during the metal deposition processes BOS Disposal stage
Lunardi_AlvarezGaitan_2018	BOS, recycling processes ar	Al_BSF and PER(	1 kWh of generated direct current ele	25			GWP, human tox cancer, human tox non cancer, f	IPCC, usetox	Gabi	Gabi			
Lunardi_2017													
Sica_2018													
Stolz_2016													

Annex 5D: Results production in absolute values

All results are presented per kWh.

1. Modules

Results for the production (material input) of 1 kWh by a multi Si module using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	1,27E-01	4,58E-01	3,08E+00	4,11E-02	4,35E+00	3,68E-02	3,09E-01	3,98E-03	1,05E-02	9,43E-02	6,98E-03	3,85E-02	1,37E-02	1,47E+01
interconnection - Tin	3,08E-03	9,40E-04	4,34E-03	1,07E-06	1,53E-03	4,96E-05	1,32E-03	6,01E-05	4,82E-06	6,56E-05	1,56E-05	6,55E-04	5,54E-06	2,35E-02
interconnection - Lead	1,73E-04	2,65E-06	5,91E-06	6,42E-09	4,31E-05	1,77E-07	3,96E-06	9,94E-08	2,20E-06	2,63E-06	3,67E-08	1,78E-07	1,49E-06	2,46E-04
interconnection - Copper	2,45E-02	2,86E-03	0,00E+00	5,93E-06	2,98E-04	1,52E-04	7,16E-03	2,36E-07	9,17E-05	1,35E-03	1,32E-04	6,96E-05	2,31E-03	3,79E-03
encapsulation - ethylvinylacetate	2,09E-01	1,90E-02	3,25E-02	5,32E-06	2,87E-02	5,30E-04	1,62E-03	4,92E-04	4,49E-05	9,16E-04	6,85E-05	1,99E-04	5,57E-05	5,89E-01
backsheet - PVF	2,67E-02	8,67E-03	1,41E-02	8,54E-06	3,05E-02	5,99E-04	3,54E-03	1,01E-04	1,56E-04	8,28E-04	5,08E-05	1,38E-04	9,16E-05	3,24E-01
backsheet - PET	8,26E-02	6,51E-03	6,03E-04	1,32E-04	7,61E-03	2,57E-04	2,84E-03	1,07E-04	0,00E+00	1,87E-04	1,20E-04	4,13E-04	1,65E-07	3,14E-02
pottant & sealing	2,91E-02	1,78E-03	7,99E-03	5,31E-07	5,22E-03	7,77E-05	2,91E-04	3,46E-05	7,83E-06	1,28E-04	9,12E-06	4,07E-05	3,70E-04	2,98E-02
alu frame	5,08E-01	9,78E-02	0,00E+00	0,00E+00	1,83E-01	5,26E-03	3,42E-02	3,36E-05	2,54E-03	1,85E-03	4,90E-02	8,59E-03	1,78E-02	2,51E-03
solar glass	2,11E+00	3,74E-02	3,28E-02	1,84E-05	1,71E-01	2,77E-03	2,38E-02	8,66E-04	2,51E-04	3,67E-03	1,61E-04	1,71E-03	9,60E-04	1,08E+00
junction box - diode	6,72E-04	2,00E-03	6,22E-04	8,78E-05	1,90E-03	1,12E-04	1,09E-03	5,03E-06	1,01E-05	2,83E-04	3,04E-06	3,42E-05	9,91E-06	1,48E-03
junction box - HDPE	5,68E-03	4,35E-04	1,93E-05	3,09E-05	2,18E-04	1,03E-05	3,46E-05	9,08E-07	0,00E+00	0,00E+00	1,95E-06	4,88E-06	0,00E+00	1,69E-04
junction box - glass fibre	7,05E-02	4,64E-03	3,83E-03	4,97E-04	2,19E-02	2,37E-04	2,06E-03	3,27E-07	0,00E+00	0,00E+00	4,57E-06	5,74E-04	3,34E-03	2,22E-01
Total	**3,19E+00**	**6,40E-01**	**3,18E+00**	**4,19E-02**	**4,81E+00**	**4,68E-02**	**3,87E-01**	**5,68E-03**	**1,36E-02**	**1,04E-01**	**5,66E-02**	**5,09E-02**	**3,86E-02**	**1,70E+01**

2. Inverters

Results for production (material input) of 1 kWh by a 2500 W inverter using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
aluminium	1,70E-01	9,38E-03	0,00E+00	0,00E+00	2,55E-02	6,03E-04	2,66E-03	1,25E-05	5,69E-03	1,42E-04	3,01E-03	6,89E-04	1,10E-03	2,06E-04
copper	6,60E-02	3,35E-03	0,00E+00	3,78E-07	9,47E-04	1,79E-04	4,11E-03	3,19E-07	6,92E-04	2,20E-03	3,52E-04	9,62E-05	2,46E-03	4,05E-03
steel	3,10E-02	1,04E-03	0,00E+00	0,00E+00	5,33E-02	8,75E-05	2,31E-04	4,22E-06	8,05E-04	1,10E-04	2,14E-06	8,38E-05	1,10E-04	2,02E-03
pp	3,01E-02	2,19E-03	1,45E-04	1,33E-04	8,47E-04	5,94E-05	1,69E-04	5,42E-07	0,00E+00	0,00E+00	1,15E-05	2,26E-05	0,00E+00	4,95E-03
PC	4,11E-02	4,80E-03	5,76E-04	4,11E-04	7,26E-03	2,22E-04	1,05E-03	0,00E+00	0,00E+00	0,00E+00	1,49E-05	2,76E-04	6,75E-06	2,07E-02
cable	4,48E-03	5,22E-04	0,00E+00	1,08E-06	5,45E-05	2,78E-05	1,31E-03	4,31E-08	1,68E-05	2,47E-04	2,41E-05	1,27E-05	4,22E-04	6,92E-04
integrated circuits	7,61E-03	6,11E-02	0,00E+00	1,80E-03	6,69E-02	3,85E-03	2,12E-02	5,25E-04	3,72E-04	3,40E-03	1,12E-04	5,54E-04	2,85E-02	1,63E-01
ferrite	1,70E-03	1,69E-04	5,16E-04	1,13E-07	3,70E-03	1,11E-05	1,55E-04	6,67E-06	5,39E-05	5,63E-05	1,80E-06	7,53E-05	3,33E-06	2,60E-03
PVC	1,05E-02	5,97E-04	1,16E-04	5,27E-05	7,07E-04	2,28E-05	1,58E-04	0,00E+00	0,00E+00	0,00E+00	3,02E-07	3,06E-05	2,97E-05	3,31E-03
PA	5,35E-03	6,39E-04	8,55E-05	1,02E-04	9,42E-04	4,58E-05	2,09E-04	4,81E-08	0,00E+00	0,00E+00	2,16E-06	2,89E-05	2,62E-04	1,00E-02
PWB	1,12E-02	4,13E-03	5,45E-03	2,13E-02	4,58E-02	1,76E-04	4,45E-03	1,15E-05	5,72E-05	7,87E-04	7,74E-05	4,16E-04	1,41E-03	2,75E-02
tin	3,27E-04	1,00E-04	4,62E-04	1,13E-07	1,63E-04	5,27E-06	1,40E-04	6,39E-06	5,12E-07	6,97E-06	1,66E-06	6,97E-05	5,90E-07	2,50E-03
transistor/diode/resistor	2,34E-03	6,95E-03	2,17E-03	3,06E-04	6,63E-03	3,91E-04	3,80E-03	1,75E-05	3,51E-05	9,88E-04	1,06E-05	1,19E-04	3,45E-05	5,14E-03
capacitor	1,47E-02	8,49E-04	4,20E-05	8,51E-06	1,72E-03	4,98E-05	4,13E-04	1,06E-06	4,47E-04	3,50E-04	1,79E-04	4,57E-05	1,09E-04	1,96E-04
Total	**3,97E-01**	**9,58E-02**	**9,56E-03**	**2,41E-02**	**2,14E-01**	**5,73E-03**	**4,01E-02**	**5,86E-04**	**8,17E-03**	**8,29E-03**	**3,79E-03**	**2,52E-03**	**3,44E-02**	**2,47E-01**

Results for production (material input) 20 kW inverter using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
aluminium	8,59E-02	4,74E-03	0,00E+00	0,00E+00	1,29E-02	3,05E-04	1,34E-03	6,29E-06	2,88E-03	7,19E-05	1,52E-03	3,48E-04	5,56E-04	1,04E-04
copper	3,34E-02	1,70E-03	0,00E+00	1,91E-07	4,79E-04	9,07E-05	2,08E-03	1,61E-07	3,50E-04	1,12E-03	1,78E-04	4,87E-05	1,25E-03	2,05E-03
steel	1,57E-02	5,28E-04	0,00E+00	0,00E+00	2,69E-02	4,43E-05	1,17E-04	2,13E-06	4,07E-04	5,55E-05	1,08E-06	4,24E-05	5,56E-05	1,02E-03
pp	1,52E-02	1,11E-03	7,31E-05	6,75E-05	4,29E-04	3,01E-05	8,55E-05	2,74E-07	0,00E+00	0,00E+00	5,84E-06	1,14E-05	0,00E+00	2,51E-03
PC	2,08E-02	2,43E-03	2,91E-04	2,08E-04	3,67E-03	1,12E-04	5,29E-04	0,00E+00	0,00E+00	0,00E+00	7,55E-06	1,39E-04	3,41E-06	1,05E-02
cable	2,27E-03	2,65E-04	0,00E+00	5,49E-07	2,76E-05	1,41E-05	6,63E-04	2,19E-08	8,50E-06	1,25E-04	1,22E-05	6,45E-06	2,14E-04	3,51E-04
integrated circuits	3,86E-03	3,09E-02	0,00E+00	9,13E-04	3,39E-02	1,95E-03	1,07E-02	2,66E-04	1,88E-04	1,72E-03	5,67E-05	2,81E-04	1,44E-02	8,28E-02
ferrite	8,58E-04	8,56E-05	2,61E-04	5,73E-08	1,87E-03	5,60E-06	7,84E-05	3,37E-06	2,73E-05	2,85E-05	9,09E-07	3,80E-05	1,68E-06	1,32E-03
PVC	5,34E-03	3,02E-04	5,88E-05	2,67E-05	3,58E-04	1,16E-05	8,01E-05	0,00E+00	0,00E+00	0,00E+00	1,53E-07	1,55E-05	1,50E-05	1,68E-03
PA	2,69E-03	3,22E-04	4,31E-05	5,12E-05	4,75E-04	2,31E-05	1,05E-04	2,42E-08	0,00E+00	0,00E+00	1,09E-06	1,45E-05	1,32E-04	5,04E-03
PWB	5,69E-03	2,09E-03	2,76E-03	1,08E-02	2,32E-02	8,93E-05	2,25E-03	5,84E-06	2,90E-05	3,99E-04	3,92E-05	2,11E-04	7,14E-04	1,39E-02
tin	1,65E-04	5,05E-05	2,33E-04	5,73E-08	8,21E-05	2,66E-06	7,07E-05	3,23E-06	2,59E-07	3,52E-06	8,37E-07	3,52E-05	2,98E-07	1,26E-03
transistor/diode/resistor	1,19E-03	3,52E-03	1,10E-03	1,55E-04	3,36E-03	1,98E-04	1,92E-03	8,87E-06	1,78E-05	5,00E-04	5,36E-06	6,03E-05	1,75E-05	2,60E-03
capacitor	7,46E-03	4,30E-04	2,13E-05	4,31E-06	8,74E-04	2,52E-05	2,09E-04	5,36E-07	2,26E-04	1,77E-04	9,06E-05	2,32E-05	5,54E-05	9,95E-05
Total	**2,01E-01**	**4,85E-02**	**4,84E-03**	**1,22E-02**	**1,09E-01**	**2,90E-03**	**2,03E-02**	**2,97E-04**	**4,13E-03**	**4,20E-03**	**1,92E-03**	**1,27E-03**	**1,74E-02**	**1,25E-01**

Results for production (material input) 1500 kW central inverter using EcoReport tool

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
aluminium	7,15E-03	3,94E-04	0,00E+00	0,00E+00	1,07E-03	2,54E-05	1,12E-04	5,24E-07	2,40E-04	5,99E-06	1,26E-04	2,90E-05	4,63E-05	8,68E-06
copper	2,61E-02	1,23E-03	0,00E+00	3,53E-06	5,90E-04	6,40E-05	1,42E-03	1,66E-07	3,86E-04	1,05E-03	1,25E-04	3,62E-05	7,58E-04	1,25E-03
steel	7,85E-02	2,65E-03	0,00E+00	0,00E+00	1,35E-01	2,22E-04	5,86E-04	1,07E-05	2,04E-03	2,78E-04	5,44E-06	2,13E-04	2,79E-04	5,12E-03
HDPE	1,20E-03	9,20E-05	4,09E-06	6,53E-06	4,61E-05	2,17E-06	7,32E-06	1,92E-07	0,00E+00	0,00E+00	4,13E-07	1,03E-06	0,00E+00	3,58E-05
PC	5,75E-05	6,72E-06	8,05E-07	5,75E-07	1,02E-05	3,10E-07	1,46E-06	0,00E+00	0,00E+00	0,00E+00	2,09E-08	3,85E-07	9,43E-09	2,90E-05
alkyd paint	1,20E-03	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
integrated circuits	4,59E-06	3,68E-05	0,00E+00	1,09E-06	4,03E-05	2,32E-06	1,28E-05	3,17E-07	2,24E-07	2,05E-06	6,74E-08	3,34E-07	1,72E-05	9,85E-05
ferrite	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
PVC	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
PA	6,28E-03	7,51E-04	1,00E-04	1,19E-04	1,11E-03	5,38E-05	2,45E-04	5,65E-08	0,00E+00	0,00E+00	2,53E-06	3,39E-05	3,08E-04	1,18E-02
PWB	1,20E-04	4,40E-05	5,82E-05	2,27E-04	4,89E-04	1,88E-06	4,75E-05	1,23E-07	6,11E-07	8,40E-06	8,26E-07	4,44E-06	1,50E-05	2,93E-04
tin	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
transistor/diode/resistor	1,47E-05	4,36E-05	1,36E-05	1,92E-06	4,16E-05	2,45E-06	2,38E-05	1,10E-07	2,20E-07	6,19E-06	6,64E-08	7,46E-07	2,16E-07	3,22E-05
capacitor	1,02E-04	4,71E-06	0,00E+00	2,54E-08	9,38E-06	2,66E-07	2,68E-06	3,97E-09	2,98E-06	3,23E-06	1,01E-06	2,57E-07	7,97E-07	9,01E-07
Total	**1,21E-01**	**5,25E-03**	**1,77E-04**	**3,60E-04**	**1,39E-01**	**3,75E-04**	**2,46E-03**	**1,22E-05**	**2,67E-03**	**1,35E-03**	**2,62E-04**	**3,19E-04**	**1,42E-03**	**1,86E-02**

Annex 6A: Bill of Materials in EcoReport format for modules

Multi-Si: reference

Version 3.06 VHK for European Commission 2011,
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Document subject to a legal notice (see below)

ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS
Environmental Impact

Assessment of

Nr	multi Si panel 1 kWh Products	Date	Author vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell, multi-Si	1,26E-01	8-Extra	102-Photovoltaic cell, multi-Si wafer per kg	
4					
5	**interconnection**				
6	Tin	3,29E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,85E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	2,63E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	2,23E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Polyvinylfluoride film	2,86E-02	8-Extra	106-Polyvinylfluoride {GLO}| market for | Cut-off,	
15	Polyethylene terephthalate	8,82E-02	1-BlkPlastics	10 -PET	
16					
17	**pottant & sealing**				
18	Silicone product	3,11E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	5,43E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	2,25E+00	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	7,16E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	6,07E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	7,52E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	1,28E+00	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	Hydrogen fluoride	1,59E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-off	
34	Potassium hydroxide	1,31E-02	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	4,06E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	3,75E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

BAT PERC 2020

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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS
Environmental Impact

Assessment of

Nr	PERC panel 1 kWh Products	Date	Author vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	9,21E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,72E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,53E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	2,17E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,84E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Polyvinylfluoride film	2,36E-02	8-Extra	106-Polyvinylfluoride {GLO}|	No
15	Polyethylene terephthalate	7,29E-02	1-BlkPlastics	10 -PET	No
16					
17	**pottant & sealing**				
18	Silicone product	2,57E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	4,49E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	1,69E+00	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,92E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	5,02E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	6,22E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	1,06E+00	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,32E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	1,08E-02	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	3,35E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	3,10E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

BAT PERC 2019

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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS
Environmental Impact

Assessment of

Nr	PERC panel 1 kWh Products	Date	Author vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	8,52E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,40E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,35E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	1,92E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,63E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Polyvinylfluoride film	2,08E-02	8-Extra	106-Polyvinylfluoride {GLO}| market for | Cut-off,	
15	Polyethylene terephthalate	6,44E-02	1-BlkPlastics	10 -PET	
16					
17	**pottant & sealing**				
18	Silicone product	2,27E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	3,96E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	1,64E+00	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,23E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	4,43E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	5,49E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	9,36E-01	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,16E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-off	
34	potassium hydroxide	9,57E-03	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	2,96E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	2,74E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

BAT PERCbi 2019 (bifacial)

Nr	PERC + bifacial panel 1 kWh Products		Date	Author vito	
Pos nr	**MATERIALS Extraction & Production** Description of component	**Weight** in g	**Category** Click &select	**Material or Process** select Category first !	**Recyclable?**
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	8,52E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,40E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,35E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	1,92E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,63E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Solar glass, low-iron & Tempering, flat glass	9,31E-01	8-Extra	108-solar glass and tempering - GLO	
15					
16					
17	**pottant & sealing**				
18	Silicone product	2,27E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	3,96E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	9,31E-01	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,23E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	4,43E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	5,49E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	9,36E-01	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,16E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	9,57E-03	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	2,96E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	2,74E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

CdTe

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EcoReport 2014: INPUTS
Environmental Impact

Assessment of

ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

Nr	CdTe panel 1 kWh Products	Date	Author vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	Solar glass and tempering	1,82E+00	8-Extra	102-solar glass and tempering - GLO	
3	Flat glass (uncoated)	1,69E+00	8-Extra	103-Flat glass, uncoated {GLO}| market for | Cut-	
4	Copper	2,38E-03	4-Non-ferro	30 -Cu wire	
5	Cadmium sulphide	7,29E-04	8-Extra	104-Cadmium sulfide, semiconductor-grade {GLO	
6	Cadmium telluride	4,92E-03	8-Extra	105-Cadmium telluride, semiconductor-grade {GL	
7	Ethylene vinyl acetate (EVA)	1,01E-01	8-Extra	106-Ethylvinylacetate, foil {GLO}| market for | Cu	
8	Glass fibre reinforced plastic	2,24E-02	2-TecPlastics	19 -E-glass fibre	
9	Silicone	6,36E-04	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
10	Silica sand	9,69E-03	8-Extra	108-Silica sand {GLO}| market for | Cut-off, U	
11	Tap water	4,12E+01	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
12	Nitrogen	1,52E-02	8-Extra	110-Nitrogen, liquid {RER}| market for | Cut-off, U	
13	Helium	7,54E-03	8-Extra	111-Helium {GLO}| market for | Cut-off, U	
14	Nitric acid	1,18E-02	8-Extra	112-Nitric acid, without water, in 50% solution st	
15	Sulphuric acid	8,14E-03	8-Extra	113-Sulfuric acid {GLO}| market for | Cut-off, U	
16	Hydrogen peroxide	3,46E-03	8-Extra	114-Hydrogen peroxide, without water, in 50% so	
17	Sodium hydroxide	1,02E-02	8-Extra	115-Sodium hydroxide, without water, in 50% sol	
18	Sodium chloride	9,38E-03	8-Extra	116-Sodium chloride, powder {GLO}| market for |	
19	Isopropanol	4,31E-04	8-Extra	117-Isopropanol {GLO}| market for | Cut-off, U	
20	Chemicals organic	2,02E-03	8-Extra		
21	Chemicals inorganic	7,78E-03	8-Extra		
22					
23					
24					
25					
26					
27					
28					
29					
30					
31					
32					
33					
34					
35					
36					
37					
38					
39					
40					

CIGS

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014			Document subject to a legal notice (see below)	
ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS		EcoReport 2014: INPUTS Environmental Impact		Assessment of
Nr	CIGS panel 1 kWh Products	Date	Author vito	

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	**Laminate**				
3	Solar glass and tempering	2,00E+00	8-Extra	102-solar glass and tempering - GLO	
4	Flat glass (uncoated)	1,37E+00	8-Extra	103-Flat glass, uncoated {GLO}| market for | Cut-	
5	Aluminium	1,15E-02	4-Non-ferro	27 -Al sheet/extrusion	
6	Copper wire	2,54E-03	4-Non-ferro	30 -Cu wire	
7	Tin	3,20E-03	8-Extra	104-Tin {GLO}| market for | Cut-off, U	
8	Zinc oxide	2,36E-03	8-Extra	105-Zinc oxide {GLO}| market for | Cut-off, U	
9	Molybdenum	1,58E-03	8-Extra	106-Molybdenum {GLO}| market for | Cut-off, U	
10	Indium	7,33E-04	8-Extra	107-Indium {GLO}| market for | Cut-off, U	
11	Gallium	2,34E-04	8-Extra	108-Gallium, semiconductor-grade {GLO}| marke	
12	Selenium	1,46E-03	8-Extra	109-Selenium {GLO}| market for | Cut-off, U	
13	Cadmium sulphide	7,00E-05	8-Extra	110-Cadmium sulfide, semiconductor-grade {GLO	
14	Diode	3,75E-04	6-Electronics	49 -SMD/ LED's avg.	
15	Flux	3,20E-03	8-Extra	111-Flux, for wave soldering {GLO}| market for |	
16	Ethylene vinyl acetate (EVA)	1,95E-01	8-Extra	112-Ethylvinylacetate, foil {GLO}| market for | Cu	
17	Polyvinyl butyral (PVB)	4,91E-02	8-Extra	113-Polyvinyl Butyral Granulate (PVB) | polymeri	
18	Polyethylene terephthalate (PET)	8,74E-02	1-BlkPlastics	10 -PET	
19	High-density polyethylene (HDPE)	1,26E-02	1-BlkPlastics	2 -HDPE	
20	Polyphenylene sulphide (PPS)	2,23E-02	1-BlkPlastics	5 -PS	
21	Silicone	1,05E-01	8-Extra	114-Silicone product {GLO}| market for | Cut-off,	
22	Nitrogen	4,08E+00	8-Extra	115-Nitrogen, liquid {RER}| market for | Cut-off, U	
23	Argon	4,94E-03	8-Extra	116-Argon, liquid {GLO}| market for | Cut-off, U	
24	Ammonia	2,42E-02	8-Extra	117-Ammonia, liquid {RER}| market for | Cut-off,	
25	Urea	2,99E-04	8-Extra	118-Urea, as N {GLO}| market for | Cut-off, U	
26	Hydrogen peroxide	6,01E-03	8-Extra	119-Hydrogen peroxide, without water, in 50% so	
27	Sodium hydroxide	8,69E-03	8-Extra	120-Sodium hydroxide, without water, in 50% sol	
28	Hydrochloric acid	2,58E-02	8-Extra	120-Hydrochloric acid, without water, in 30% sol	
29	Sulphuric acid	8,61E-03	8-Extra	120-Sulfuric acid {GLO}| market for | Cut-off, U	
30	Hydrogen sulphide	4,97E-02	8-Extra	120-Hydrogen sulfide {GLO}| market for | Cut-off,	
31	Butyl acrylate	2,63E-02	8-Extra	120-Butyl acetate {GLO}| market for | Cut-off, U	
32	Diborane	5,23E-05	8-Extra	120-Diborane {GLO}| market for | Cut-off, U	
33					
34	**Panel**				
35	Aluminium alloy	5,72E-01	4-Non-ferro	27 -Al sheet/extrusion	
36	Glass fibre reinforced plastic	1,04E-02	2-TecPlastics	19 -E-glass fibre	
37					
38					
39					
40					

SHJ

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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS
Environmental Impact

Assessment of

Nr	SHJ panel 1 kWh Products	Date	Author vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	7,93E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,73E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,54E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	2,18E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,85E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Polyvinylfluoride film	2,37E-02	8-Extra	106-Polyvinylfluoride {GLO}| market for | Cut-off,	
15	Polyethylene terephthalate	7,34E-02	1-BlkPlastics	10 -PET	
16					
17	**pottant & sealing**				
18	Silicone product	2,59E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	4,52E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	1,87E+00	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,95E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	5,05E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	6,25E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	1,07E+00	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,32E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	1,09E-02	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	3,37E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	3,12E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

BAT PERC 2025

Nr	PERC 2025 panel 1 kWh Products		Date	Author vito	
Pos nr	**MATERIALS Extraction & Production** Description of component	**Weight** in g	**Category** Click &select	**Material or Process** select Category first !	**Recyclable?**
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	6,09E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,31E-02	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Copper solder	7,15E-04	4-Non-ferro	30 -Cu wire	
8	Copper	1,89E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,61E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	HDPE	6,41E-02	1-BlkPlastics	2 -HDPE	
15	PA	1,04E-02	2-TecPlastics	12 -PA 6	
16	TiO2	6,94E-03	8-Extra	114-Titanium dioxide {RER}| market for | Cut-off,	
17	**pottant & sealing**				
18	Silicone product	2,24E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	3,91E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	1,15E+00	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,16E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	4,37E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	5,42E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	9,24E-01	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,15E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	9,44E-03	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	2,92E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	2,70E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

BNAT PERCbi 2025 + recycled wafer

Nr	PERCbifacial + rec wafer panel 1 kWh Products		Date	Author vito	
Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	8,52E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,40E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,35E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	1,92E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,63E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Solar glass, low-iron & Tempering, flat glass	9,31E-01	8-Extra	108-solar glass and tempering - GLO	
15					
16					
17	**pottant & sealing**				
18	Silicone product	2,27E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	3,96E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	9,31E-01	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,23E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	4,43E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	5,49E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	9,36E-01	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,16E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	9,57E-03	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	2,96E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	2,74E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

Annex 6B: Bill of Materials in EcoReport format for inverters.

BC1 – reference + efficient + monitoring + MLI

As the Bill of materials are expressed per kWh they differ slightly per design option as the generated kWh are different per design option and a consequence also the number of inverters necessary per kWh. The BOM below is for the reference inverter.

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014

Document subject to a legal notice (see below)

ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS — EcoReport 2014: INPUTS — Assessment of Environmental Impact

Nr	1500 W inverter - 3 units Products	Date	Author Vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click&select	Material or Process select Category first !	Recyclable?
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	1,76E-01	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	7,82E-03	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	7,04E-02	4-Non-ferro	31 - Cu tube/sheet	
5	steel, low-alloyed, at plant	3,34E-02	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	3,25E-02	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	7,45E-03	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	4,83E-03	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	3,21E-02	8-Extra	111-Inductor, ring core choke type, at plant/GL	
10	integrated circuit, IC, logic type, at plant	2,44E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	1,29E-03	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	1,10E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	4,83E-03	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	1,21E-02	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	3,54E-04	8-Extra	109-Tin {GLO}| market for | Cut-off, U	
17	connector, clamp connection, at plant	8,99E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
18	inductor, ring core choke type, at plant	4,83E-03	8-Extra	111-Inductor, ring core choke type, at plant/GL	
19	inductor, miniature RF chip type, MRFI, at plant	4,06E-05	8-Extra	104-Inductor, miniature radio frequency chip {(	
20	integrated circuit, IC, logic type, at plant	5,71E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	6,89E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	7,08E-04	6-Electronics	48 - IC's avg., 1% Si	
23	transistor, SMD type, surface mounting, at plant	1,54E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
24	diode, glass-, SMD type, surface mounting, at plant	7,41E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
25	light emitting diode, LED, at plant	5,31E-07	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	6,12E-03	8-Extra	105-Capacitor, film type, for through-hole mou	
27	capacitor, electrolyte type, > 2cm height, at plant	9,47E-03	8-Extra	106-Capacitor, electrolyte type, > 2cm height {	
28	capacitor, electrolyte type, < 2cm height, at plant	2,47E-04	8-Extra	107-Capacitor, electrolyte type, < 2cm height {	
29	capacitor, SMD type, surface-mounting, at plant	4,90E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
30	resistor, wirewound, through-hole mounting, at plant	4,13E-05	8-Extra	108-Resistor, wirewound, through-hole mount	
31	resistor, SMD type, surface mounting, at plant	1,68E-04	8-Extra	110-Resistor, SMD type, surface mounting, at p	
32	ferrite, at plant	9,40E-07	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	1,48E-03	8-Extra	111-Inductor, ring core choke type {GLO}| mark	
34	plugs, inlet and outlet, for network cable, at plant	1,03E-02	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	9,44E-04	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	8,85E-06	4-Non-ferro	30 - Cu wire	
37					
38					
39					
40					

BC 1 – longer life

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014				Document subject to a legal notice (see below)	
	ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS		EcoReport 2014: INPUTS Environmental Impact	Assessment of	
Nr	1500 W inverter - 1,156 units Products		Date	Author Vito	
Pos nr	**MATERIALS Extraction & Production Description of component**	**Weight in g**	**Category Click &select**	**Material or Process select Category first !**	**Recyclable?**
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	6,78E-02	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	3,01E-03	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	2,71E-02	4-Non-ferro	31 - Cu tube/sheet	
5	steel, low-alloyed, at plant	1,29E-02	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	1,25E-02	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	2,87E-03	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	1,86E-03	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	1,24E-02	8-Extra	111- Inductor, ring core choke type, at plant/GL	
10	integrated circuit, IC, logic type, at plant	9,39E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	4,96E-04	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	4,25E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	1,86E-03	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	4,68E-03	6-Electronics	51 - PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	1,36E-04	8-Extra	109-Tin {GLO}| market for | Cut-off, U	
17	connector, clamp connection, at plant	3,47E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
18	inductor, ring core choke type, at plant	1,86E-03	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
19	inductor, miniature RF chip type, MRFI, at plant	1,56E-05	8-Extra	104-Inductor, miniature radio frequency chip {(	
20	integrated circuit, IC, logic type, at plant	2,20E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	2,66E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	2,73E-04	6-Electronics	48 - IC's avg., 1% Si	
23	transistor, SMD type, surface mounting, at plant	5,92E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
24	diode, glass-, SMD type, surface mounting, at plant	2,86E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
25	light emitting diode, LED, at plant	2,05E-07	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	2,36E-03	8-Extra	105-Capacitor, film type, for through-hole mou	
27	capacitor, electrolyte type, > 2cm height, at plant	3,65E-03	8-Extra	106-Capacitor, electrolyte type, > 2cm height {	
28	capacitor, electrolyte type, < 2cm height, at plant	9,53E-05	8-Extra	107-Capacitor, electrolyte type, < 2cm height {	
29	capacitor, SMD type, surface-mounting, at plant	1,89E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
30	resistor, wirewound, through-hole mounting, at plant	1,59E-05	8-Extra	108-Resistor, wirewound, through-hole mount	
31	resistor, SMD type, surface mounting, at plant	6,49E-05	8-Extra	110-Resistor, SMD type, surface mounting, at p	
32	ferrite, at plant	3,62E-07	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	5,70E-04	8-Extra	111- Inductor, ring core choke type, at plant/GL	
34	plugs, inlet and outlet, for network cable, at plant	3,96E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	3,64E-04	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	3,41E-06	4-Non-ferro	30 - Cu wire	
37					
38					
39					
40					

BC 1 – increased repair

The table below combines failures into groups (see color coding).

Table 4 on inverter failure from task 4		
Inverter failure area	% of tickets	% of kWh lost
no-fault-found failures = software update	28,00%	15,00%
Card/board	13,00%	22,00%
AC Contactor	12,00%	13,00%
Fan(s)	6,00%	5,00%
Matrix/IGBT	6,00%	6,00%
Power supply	5,00%	5,00%
AC Fuses	4,00%	12,00%
DC Contactor	4,00%	1,00%
Surge Protection	3,00%	1,00%
GFI Components	3,00%	2,00%
Capacitors	3,00%	7,00%
Internal Fuses	3,00%	4,00%
Internal Relay/Swithces	3,00%	2,00%
DC Input Fuses	2,00%	1,00%
Other	5,00%	2,00%

The table below shows the number of tickets per group. A total of 61% of the tickets has been allocated to the different groups. Software failures have no implications on the BOM. Fans are not used anymore in new inverters. Also, the tickets under 'other' could not be allocated to a component of the bill of materials.

Translate task 4 data into input for task 6 report:	% tickets	rescale to 100%
Fuse/contactor	34%	56%
Card/board	13%	21%
Matrix/IGBT	6%	10%
Capacitors	3%	5%
Power supply	5%	8%
Total	61%	100%

In a next step a link has been made between the failure of the different components and the available bill of materials (see table below).

BOM Task 5 report - based on Treeze publication on LCA of inverters		infuence on BOM
individual components	**match with table task 4**	
aluminium, production mix, cast alloy, at plant		1
aluminium alloy, AlMg3, at plant		1
copper, at regional storage		1
steel, low-alloyed, at plant		1
polypropylene, granulate, at plant		1
polycarbonate, at plant		1
cable, connector for computer, without plugs, at plant		1
inductor, ring core choke type, at plant	Fuse/contactor	BOM*(1+(2*0,56))
integrated circuit, IC, logic type, at plant		1
ferrite, at plant		1
plugs, inlet and outlet, for network cable, at plant	Fuse/contactor	BOM*(1+(2*0,56))
glass fibre reinforced plastic, polyamide, injection moulding, at plant		1
printed board assembly		
printed wiring board, surface mount, lead-free surface, at plant	card/board	BOM*(1+(2*0,21))
tin, at regional storage		1
connector, clamp connection, at plant	card/board	BOM*(1+(2*0,21))
inductor, ring core choke type, at plant	card/board	BOM*(1+(2*0,21))
inductor, miniature RF chip type, MRFI, at plant	card/board	BOM*(1+(2*0,21))
integrated circuit, IC, logic type, at plant	card/board	BOM*(1+(2*0,21))
integrated circuit, IC, memory type, at plant	card/board	BOM*(1+(2*0,21))
transistor, unspecified, at plant	Matrix/IGBT	BOM*(1+(2*0,1))
transistor, SMD type, surface mounting, at plant	Matrix/IGBT	BOM*(1+(2*0,1))
diode, glass-, SMD type, surface mounting, at plant	card/board	BOM*(1+(2*0,21))
light emitting diode, LED, at plant	card/board	BOM*(1+(2*0,21))
capacitor, film, through-hole mounting, at plant	card/board	BOM*(1+(2*0,21))
capacitor, electrolyte type, > 2cm height, at plant	capacitors	BOM*(1+(2*0,05))
capacitor, electrolyte type, < 2cm height, at plant	capacitors	BOM*(1+(2*0,05))
capacitor, SMD type, surface-mounting, at plant	card/board	BOM*(1+(2*0,21))
resistor, wirewound, through-hole mounting, at plant	card/board	BOM*(1+(2*0,21))
resistor, SMD type, surface mounting, at plant	card/board	BOM*(1+(2*0,21))
ferrite, at plant	card/board	BOM*(1+(2*0,21))
transformer, low voltage use, at plant	power supply	BOM*(1+(2*0,08))
plugs, inlet and outlet, for network cable, at plant		1
glass fibre reinforced plastic, polyamide, injection moulding, at plant		1
cable, ribbon cable, 20-pin, with plugs, at plant		1

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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS	EcoReport 2014: INPUTS Environmental Impact		Assessment of

Nr	1500 W inverter - 1 unit incl repair	Date	Author
	Products		Vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	5,86E-02	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	2,61E-03	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	2,35E-02	4-Non-ferro	31-Cu tube/sheet	
5	steel, low-alloyed, at plant	1,11E-02	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	1,08E-02	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	2,48E-03	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	1,61E-03	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	2,27E-02	8-Extra	111-Inductor, ring core choke type, at plant/GL	
10	integrated circuit, IC, logic type, at plant	8,12E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	4,29E-04	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	7,80E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	1,61E-03	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	5,75E-03	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	1,18E-04	8-Extra	109-Tin {GLO}| market for | Cut-off, U	
17	connector, clamp connection, at plant	4,26E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
18	inductor, ring core choke type, at plant	2,29E-03	8-Extra	111-Inductor, ring core choke type, at plant/GL	
19	inductor, miniature RF chip type, MRFI, at plant	1,92E-05	8-Extra	104-Inductor, miniature radio frequency chip {(	
20	integrated circuit, IC, logic type, at plant	2,70E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	3,26E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	2,83E-04	6-Electronics	48 - IC's avg., 1% Si	
23	transistor, SMD type, surface mounting, at plant	6,15E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
24	diode, glass-, SMD type, surface mounting, at plant	3,51E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
25	light emitting diode, LED, at plant	2,51E-07	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	2,90E-03	8-Extra	105-Capacitor, film type, for through-hole mou	
27	capacitor, electrolyte type, > 2cm height, at plant	3,47E-03	8-Extra	106-Capacitor, electrolyte type, > 2cm height {	
28	capacitor, electrolyte type, < 2cm height, at plant	9,07E-05	8-Extra	107-Capacitor, electrolyte type, < 2cm height {	
29	capacitor, SMD type, surface-mounting, at plant	2,32E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
30	resistor, wirewound, through-hole mounting, at plant	1,95E-05	8-Extra	108-Resistor, wirewound, through-hole mount	
31	resistor, SMD type, surface mounting, at plant	7,97E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
32	ferrite, at plant	4,45E-07	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	5,72E-04	8-Extra	111-Inductor, ring core choke type, at plant/GL	
34	plugs, inlet and outlet, for network cable, at plant	3,43E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	3,15E-04	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	2,95E-06	4-Non-ferro	30 - Cu wire	
37					
38					
39					
40					

BC2 – reference + efficient

As the Bill of materials are expressed per kWh they differ slightly per design option as the generated kWh are different per design option and a consequence also the number of inverters necessary per kWh. The BOM below is for the reference inverter.

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014				Document subject to a legal notice (see below)
ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS		EcoReport 2014: INPUTS Environmental Impact		Assessment of

Nr	20 kW inverter - 3 units Products	Date	Author Vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	8,08E-02	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	3,59E-03	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	3,24E-02	4-Non-ferro	31-Cu tube/sheet	
5	steel, low-alloyed, at plant	1,54E-02	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	1,50E-02	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	3,43E-03	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	2,23E-03	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	1,48E-02	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
10	integrated circuit, IC, logic type, at plant	1,12E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	5,94E-04	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	5,07E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	2,21E-03	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	5,59E-03	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	1,62E-04	8-Extra	109-Tin {GLO}| market for | Cut-off, U	
17	connector, clamp connection, at plant	4,12E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
18	inductor, ring core choke type, at plant	2,21E-03	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
19	inductor, miniature RF chip type, MRFI, at plant	1,87E-05	8-Extra	104-Inductor, miniature radio frequency chip {(	
20	integrated circuit, IC, logic type, at plant	2,64E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	3,18E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	3,25E-04	6-Electronics	48 - IC's avg., 1% Si	
23	transistor, SMD type, surface mounting, at plant	7,09E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
24	diode, glass-, SMD type, surface mounting, at plant	3,40E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
25	light emitting diode, LED, at plant	2,44E-07	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	2,82E-03	8-Extra	105-Capacitor, film type, for through-hole mou	
27	capacitor, electrolyte type, > 2cm height, at plant	4,37E-03	8-Extra	106-Capacitor, electrolyte type, > 2cm height {	
28	capacitor, electrolyte type, < 2cm height, at plant	1,14E-04	8-Extra	107-Capacitor, electrolyte type, < 2cm height {	
29	capacitor, SMD type, surface-mounting, at plant	2,26E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
30	resistor, wirewound, through-hole mounting, at plant	1,90E-05	8-Extra	108-Resistor, wirewound, through-hole mount	
31	resistor, SMD type, surface mounting, at plant	7,75E-05	8-Extra	110-Resistor, SMD type, surface mounting, at p	
32	ferrite, at plant	4,33E-07	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	6,80E-04	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
34	plugs, inlet and outlet, for network cable, at plant	4,74E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	4,33E-04	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	4,07E-06	4-Non-ferro	30 - Cu wire	
37					
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BC2 – repair

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014				Document subject to a legal notice (see below)
ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS		EcoReport 2014: INPUTS Environmental Impact		Assessment of

Nr	20 kW inverter - 1 unit incl repair Products	Date	Author Vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	2,69E-02	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	1,19E-03	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	1,08E-02	4-Non-ferro	31 - Cu tube/sheet	
5	steel, low-alloyed, at plant	5,12E-03	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	4,98E-03	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	1,14E-03	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	7,42E-04	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	1,04E-02	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
10	integrated circuit, IC, logic type, at plant	3,74E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	1,98E-04	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	3,58E-04	1-BlkPlastics	8 - PVC	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	7,37E-04	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	2,64E-03	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	5,41E-05	8-Extra	109-Tin {GLO}| market for | Cut-off, U	
17	connector, clamp connection, at plant	1,95E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
18	inductor, ring core choke type, at plant	1,05E-03	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
19	inductor, miniature RF chip type, MRFI, at plant	8,83E-06	8-Extra	104-Inductor, miniature radio frequency chip {(	
20	integrated circuit, IC, logic type, at plant	1,25E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	1,50E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	1,30E-04	6-Electronics	48 - IC's avg., 1% Si	
23	transistor, SMD type, surface mounting, at plant	2,83E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
24	diode, glass-, SMD type, surface mounting, at plant	1,61E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
25	light emitting diode, LED, at plant	1,15E-07	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	1,33E-03	8-Extra	105-Capacitor, film type, for through-hole mou	
27	capacitor, electrolyte type, > 2cm height, at plant	1,60E-03	8-Extra	106-Capacitor, electrolyte type, > 2cm height {	
28	capacitor, electrolyte type, < 2cm height, at plant	4,17E-05	8-Extra	107-Capacitor, electrolyte type, < 2cm height {	
29	capacitor, SMD type, surface-mounting, at plant	1,07E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
30	resistor, wirewound, through-hole mounting, at plant	8,97E-06	8-Extra	108-Resistor, wirewound, through-hole mount	
31	resistor, SMD type, surface mounting, at plant	3,67E-05	8-Extra	110-Resistor, SMD type, surface mounting, at p	
32	ferrite, at plant	2,05E-07	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	2,63E-04	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
34	plugs, inlet and outlet, for network cable, at plant	1,58E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	1,44E-04	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	1,35E-06	4-Non-ferro	30 - Cu wire	
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BC3 – reference + efficient + efficient string

As the Bill of materials are expressed per kWh they differ slightly per design option as the generated kWh are different per design option and a consequence also the number of inverters necessary per kWh. The BOM below is for the reference inverter.

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014			Document subject to a legal notice (see below)	
ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS		EcoReport 2014: INPUTS Environmental Impact		Assessment of
Nr	1500 kW inverter - 1 unit incl repair Products	Date	Author Vito	

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**individual components**				
2	Alkyd paint, white, without solvent, in 60% solution state	1,18E-03	8-Extra	103-Alkyd paint, white, without solvent, in 60%	
3	Aluminium, cast alloy	7,03E-03	4-Non-ferro	28 - Al diecast	
4	Capacitor, electrolyte type, > 2cm height	4,12E-05	8-Extra	109-Capacitor, electrolyte type, > 2cm height {	
5	Capacitor, film type, for through-hole mounting	5,49E-05	8-Extra	108-Capacitor, film type, for through-hole mou	
6	Capacitor, tantalum-, for through-hole mounting	3,70E-06	8-Extra	104-Capacitor, tantalum-, for through-hole mo	
7	Copper	1,80E-02	4-Non-ferro	31-Cu tube/sheet	
8	Diode, glass-, for through-hole mounting	7,57E-06	6-Electronics	49 - SMD/ LED's avg.	
9	Electric connector, wire clamp	7,64E-03	8-Extra	106-Plugs, inlet and outlet, for network cable, a	
10	Fleece, polyethylene	1,61E-05	1-BlkPlastics	2 - HDPE	
11	Glass fibre reinforced plastic, polyamide, injection moulded	3,81E-03	2-TecPlastics	12 - PA 6	
12	Glass fibre reinforced plastic, polyester resin, hand lay-up	2,36E-03	1-BlkPlastics	10 - PET	
13	Inductor, ring core choke type	5,65E-05	8-Extra	114-Inductor, ring core choke type {GLO}| mark	
14	Integrated circuit, logic type	4,51E-06	6-Electronics	47 - IC's avg., 5% Si, Au	
15	Lubricating oil	4,73E-02	8-Extra	102-Lubricating oil {GLO}| market for | Cut-off,	
16	Polyethylene, high density, granulate	1,18E-03	1-BlkPlastics	2 - HDPE	
17	Polystyrene foam slab	8,59E-05	1-BlkPlastics	5 - PS	
18	Printed wiring board, for through-hole mounting, Pb containing surface	5,90E-05	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
19	Printed wiring board, for through-hole mounting, Pb free surface	0,00E+00	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
20	Resistor, metal film type, through-hole mounting	8,05E-07	8-Extra	111-Resistor, wirewound, through-hole mountir	
21	Steel, low-alloyed, hot rolled	7,72E-02	3-Ferro	22 - St sheet galv.	
22	Transistor, wired, small size, through-hole mounting	6,12E-06	6-Electronics	48 - IC's avg., 1% Si	
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Annex 6C: Input data for LCC calculations at system level

Residential

System		Base Case - PO 1	PO 2	PO 3	PO 4	PO 5	PO 6	BC1-Reference	PO 7	PO 8	PO 9	PO 10	PO 11	PO 12	PO 13	SO 1	SO 2	SO 3
r (discount rate=interest - inflation)	%	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*		*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*
cost module (euro/Wp)	euro/Wp	0,48 €	0,52 €	0,56 €	0,53 €	0,60 €	0,62 €		0,48 €	0,48 €	0,48 €	0,48 €	0,48 €	0,48 €	0,48 €	0,52 €	0,52 €	0,52 €
cost inverter (euro/VA)	euro/VA	0,22 €	0,22 €	0,22 €	0,22 €	0,22 €	0,22 €		0,25 €	0,28 €	0,22 €	0,25 €	0,33 €	0,33 €	0,33 €	0,28 €	0,28 €	0,28 €
cost frames (euro/Wp)	euro/Wp	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €		0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €
cost cables+connectors (euro/Wp)	euro/Wp	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €		0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €
cost installation (euro/Wp)	euro/Wp	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €		0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €
cost design (euro/Wp)	euro/Wp	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €		0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €
CAPEX total installation	euro/installation	***3.826,86 €***	***3.946,86 €***	***4.066,86 €***	***3.976,86 €***	***4.186,86 €***	***4.235,50 €***		***3.908,46 €***	***3.982,86 €***	***3.826,86 €***	***3.916,19 €***	***4.107,86 €***	***4.098,86 €***	***4.098,86 €***	***4.102,86 €***	***4.102,86 €***	***4.102,86 €***
CAPEX scrap value at EOL	euro/Wp	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €		-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €
CAPEX uninstall labour	euro/Wp	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €		0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €
CAPEX recycle modules (€/module)	euro/module	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €		10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €
CAPEX total EOL	euro/installation	***1.029,46 €***	***1.008,45 €***	***997,10 €***	***1.026,88 €***	***1.003,43 €***	***995,81 €***		***1.029,46 €***	***1.029,46 €***	***1.029,46 €***	***1.029,46 €***	***1.029,46 €***	***1.029,46 €***	***1.029,46 €***	***1.008,45 €***	***1.008,45 €***	***1.008,45 €***
OPEX O&M	euro/service	150,00 €	150,00 €	150,00 €	150,00 €	150,00 €	151,00 €		150,00 €	150,00 €	250,00 €	150,00 €	150,00 €	150,00 €	150,00 €	150,00 €	150,00 €	150,00 €
OPEX total	euro/year/installation	***65,12 €***	***65,18 €***	***65,24 €***	***65,20 €***	***65,30 €***	***64,56 €***		***73,28 €***	***37,72 €***	***71,79 €***	***74,06 €***	***93,22 €***	***92,32 €***	***92,32 €***	***37,78 €***	***37,83 €***	***37,83 €***
PWF OPEX non elec		***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***		***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***
PWF CAPEX EOL		***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***		***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***
LCC	euro/installation	***5.186,01 €***	***5.300,49 €***	***5.417,95 €***	***5.336,41 €***	***5.540,86 €***	***5.575,25 €***		***5.398,14 €***	***4.903,67 €***	***5.292,65 €***	***5.418,24 €***	***5.916,51 €***	***5.893,11 €***	***5.893,11 €***	***5.018,15 €***	***5.018,95 €***	***5.018,95 €***
LCOE	EUR/kWh	***0,064 €***	***0,064 €***	***0,065 €***	***0,068 €***	***0,071 €***	***0,067 €***		***0,065 €***	***0,060 €***	***0,065 €***	***0,065 €***	***0,067 €***	***0,073 €***	***0,073 €***	***0,060 €***	***0,056 €***	***0,055 €***

Commercial

System		Base Case - PO 1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
r (discount rate=interest - inflation)	%	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*
cost module (euro/Wp)	euro/Wp	0,34 €	0,38 €	0,42 €	0,42 €	0,34 €	0,46 €	0,46 €	0,34 €	0,34 €	0,42 €
cost inverter (euro/VA)	euro/VA	0,15 €	0,15 €	0,15 €	0,15 €	0,15 €	0,15 €	0,15 €	0,18 €	0,15 €	0,15 €
cost frames (euro/Wp)	euro/Wp	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €
cost cables+connectors (euro/Wp)	euro/Wp	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €
cost installation (euro/Wp)	euro/Wp	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €
cost design (euro/Wp)	euro/Wp	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €
CAPEX total installation	euro/installation	***19.531,00 €***	***20.507,00 €***	***21.483,00 €***	***21.483,00 €***	***19.531,00 €***	***22.501,70 €***	***22.501,70 €***	***20.131,00 €***	***19.531,00 €***	***21.483,00 €***
CAPEX scrap value at EOL	euro/Wp	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €
CAPEX uninstall labour	euro/Wp	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €
CAPEX recycle modules (€/module)	euro/module	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €
CAPEX total EOL	euro/installation	***3.698,49 €***	***3.613,01 €***	***3.566,87 €***	***3.515,36 €***	***3.611,23 €***	***3.562,20 €***	***3.515,36 €***	***3.698,49 €***	***3.698,49 €***	***3.515,36 €***
OPEX O&M	euro/service	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	600,00 €	600,00 €
OPEX total	euro/year/installation	***337,45 €***	***337,94 €***	***338,43 €***	***338,43 €***	***337,45 €***	***334,45 €***	***338,94 €***	***397,45 €***	***344,12 €***	***345,09 €***
PWF OPEX non elec		***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***
PWF CAPEX EOL		***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***
LCC	euro/installation	***26.069,36 €***	***27.026,81 €***	***27.996,39 €***	***27.980,51 €***	***26.042,46 €***	***28.950,10 €***	***29.007,36 €***	***27.629,15 €***	***26.176,00 €***	***28.087,15 €***
LCOE	EUR/kWh	***0,036 €***	***0,037 €***	***0,037 €***	***0,037 €***	***0,035 €***	***0,039 €***	***0,039 €***	***0,038 €***	***0,036 €***	***0,035 €***

Utility

System		Base Case - PO 1	PO 2	PO 3	PO4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
r (discount rate=interest - inflation)	%	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*
cost module (euro/Wp)	euro/Wp	0,31 €	0,35 €	0,39 €	0,39 €	0,31 €	0,43 €	0,47 €	0,31 €	0,31 €	0,31 €
cost inverter (euro/VA)	euro/VA	0,10 €	0,10 €	0,10 €	0,10 €	0,10 €	0,10 €	0,10 €	0,12 €	0,15 €	0,15 €
cost frames (euro/Wp)	euro/Wp	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,20 €
cost cables+connectors (euro/Wp)	euro/Wp	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €
cost installation (euro/Wp)	euro/Wp	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €
cost design (euro/Wp)	euro/Wp	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €
CAPEX total installation	euro/installation	***1.115.625,00 €***	***1.190.625,00 €***	***1.265.625,00 €***	***1.265.625,00 €***	***1.115.625,00 €***	***1.338.750,00 €***	***1.419.187,50 €***	***1.145.625,00 €***	***1.190.625,00 €***	***1.503.125,00 €***
CAPEX scrap value at EOL	euro/Wp	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €
CAPEX uninstall labour	euro/Wp	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €
CAPEX recycle modules (€/module)	euro/module	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €
CAPEX total EOL	euro/installation	***115.457,59 €***	***108.889,44 €***	***105.343,19 €***	***102.584,72 €***	***108.752,16 €***	***106.688,46 €***	***102.584,72 €***	***115.457,59 €***	***115.457,59 €***	***108.752,16 €***
OPEX O&M	euro/service	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	3.125,00 €
OPEX total	euro/year/installation	***15.457,29 €***	***15.494,79 €***	***15.532,29 €***	***15.532,29 €***	***15.457,29 €***	***15.247,10 €***	***15.609,07 €***	***18.457,29 €***	***22.957,29 €***	***22.998,96 €***
PWF OPEX non elec		***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***
PWF CAPEX EOL		***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***
LCC	euro/installation	***1.398.485,93 €***	***1.472.060,71 €***	***1.546.567,21 €***	***1.545.716,72 €***	***1.396.418,52 €***	***1.615.544,97 €***	***1.700.507,45 €***	***1.476.475,55 €***	***1.593.459,98 €***	***1.904.559,09 €***
LCOE	EUR/kWh	***0,025 €***	***0,026 €***	***0,027 €***	***0,027 €***	***0,024 €***	***0,028 €***	***0,030 €***	***0,026 €***	***0,028 €***	***0,029 €***

Annex 7A: Forecast for the stock evolution for modelling purposes

year	Total stock additions scenario MWp/year	Stock installed residential	Stock MWp installed commercial	Stock MWp installed utility
2015	6021.66	*1298.025317*	*2462.239985*	*2261.398031*
2016	6021.66	*1298.025317*	*2462.239985*	*2261.398031*
2017	6021.66	1298.0	2462.2	2261.4
2018	8208	1769.3	3356.2	3082.5
2019	11589	2498.1	4738.7	4352.2
2020	13167	2838.3	5383.9	4944.8
2021	13717	2956.8	5608.8	5151.3
2022	14970	3226.9	6121.2	5621.9
2023	16258	3504.6	6647.8	6105.6
2024	16729	3606.1	6840.4	6282.5
2025	17215	3710.9	7039.2	6465.0
2026	17714	3818.4	7243.2	6652.4
2027	18228	3929.2	7453.4	6845.4
2028	18756	4043.0	7669.3	7043.7
2029	19300	4160.3	7891.7	7248.0
2030	19860	4281.0	8120.7	7458.3
2031	20356	4387.9	8323.5	7644.6
2032	20865	4497.6	8531.6	7835.7
2033	21387	4610.2	8745.1	8031.8
2034	21921	4725.3	8963.4	8232.3
2035	22470	4843.6	9187.9	8438.5
2036	23031	4964.5	9417.3	8649.1
2037	23607	5088.7	9652.8	8865.5
2038	24197	5215.9	9894.1	9087.0
2039	24802	5346.3	10141.5	9314.2
2040	25422	5479.9	10395.0	9547.1
2041	26058	5617.0	10655.0	9785.9
2042	26709	5757.4	10921.2	10030.4
2043	27377	5901.4	11194.4	10281.3
2044	28061	6048.8	11474.1	10538.1
2045	28763	6200.1	11761.1	10801.8
2046	29482	6355.1	12055.1	11071.8
2047	30219	6514.0	12356.5	11348.6
2048	30975	6676.9	12665.6	11632.5
2049	31749	6843.8	12982.1	11923.1
2050	32543	7014.9	13306.7	12221.3

Year	Additions low	Additions high	Stock Forecast	Stock forecast

	Scenario	scenario	High	Low
2016			101856	101856
2017	6022	6022	107878	107878
2018	9595	10212	117473	118090
2019	9705	11179	127178	129269
2020	8580	12237	135758	141506
2021	8885	13853	144643	155359
2022	9205	15209	153848	170568
2023	4482	16698	158330	187266
2024	4613	18333	162943	205599
2025	4747	20127	167690	225727
2026	4839	26404	172529	252131
2027	4979	29493	177508	281623
2028	5123	32942	182631	314565
2029	5271	36796	187901	351361
2030	5423	41100	193324	392461
2031	4780	9146	198104	401607
2032	4898	9359	203002	410965
2033	5019	9577	208021	420542
2034	5143	9800	213164	430342
2035	5270	10028	218435	440370
2036	5401	10262	223835	450632
2037	5534	10501	229370	461133
2038	5671	10746	235041	471879
2039	5811	10996	240852	482875
2040	5955	11252	246807	494128
2041	6102	11515	252909	505642
2042	6253	11783	259162	517425
2043	6408	12058	265570	529483

2044	6566	12339	272136	541822
2045	6728	12626	278865	554448
2046	6895	12920	285759	567368
2047	7065	13221	292825	580589
2048	7240	13530	300065	594119
2049	7419	13845	307484	607964
2050	7602	14167	315086	622131

Annex 7B: Proxies used in the scenario modelling tool. Note: high DR models also EL impact in part, EE = more efficient inverter; LL= long life inverter; R = repaired inverters, high DR = better system higher Performance Ratio, BOS: Balance of system.

BAU						
Base case 1						
proxy Task 6	**CIGS**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**BSF**
	2.04E+07	2.44E+07	2.42E+07	2.88E+07	2.38E+07	2.76E+07
Base case 2						
proxy Task 6	**CdTe**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**BSF**
	8.81E+06	2.19E+07	1.92E+07	2.63E+07	2.13E+07	2.51E+07
Base case 3						
proxy Task 6	**CdTe**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**BSF**
	7.24E+06	2.03E+07	1.83E+07	2.48E+07	1.97E+07	2.36E+07
BAT						
Base case 1						
proxy Task 6	**CIGS**	**BAT PERC2025+LL+EE**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**BAT PERC2025+LL+EE**
	2.04E+07	1.83E+07	2.42E+07	2.88E+07	2.38E+07	1.83E+07
Base case 2						
proxy Task 6	**CdTe**	**BNAT PERCbi 2025+EE+R+high DR (not bifac)**	**BNAT PERCbi 2025+EE+R+high DR (bifac)**	**BNAT kerfless new**	**SHJ**	**BNAT PERCbi 2025+EE+R+high DR (not bifac)**
	8.81E+06	1.78E+07	1.36E+07	2.63E+07	2.13E+07	1.78E+07
Base case 3						
proxy Task 6	**CdTe + tracking + EE string**	**BAT PERC 2025**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**CdTe + tracking + EE string**
	7.76E+06	1.82E+07	1.83E+07	2.48E+07	1.97E+07	7.76E+06

MOD 2.1 on module efficiency and life time yield scenario(Tier 2)						
Base case 1						
proxy Task 6	**CIGS**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**BAT PERC2019**
	2.04E+07	2.44E+07	2.42E+07	2.88E+07	2.38E+07	2.44E+07
Base case 2						
proxy Task 6	**CdTe**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**BAT PERC2019**
	8.81E+06	2.19E+07	1.92E+07	2.63E+07	2.13E+07	2.19E+07
Base case 3						
proxy Task 6	**CdTe**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**BAT PERC2019**
	7.24E+06	2.03E+07	1.83E+07	2.48E+07	1.97E+07	2.03E+07

MOD 2.2 on module performance on quality and durability						
Base case 1						
proxy Task 6	**CIGS**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**optimized PERC 2020**
	2.04E+07	2.44E+07	2.42E+07	2.88E+07	2.38E+07	2.63E+07
Base case 2						
proxy Task 6	**CdTe**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**optimized PERC 2020**
	8.81E+06	2.19E+07	1.92E+07	2.63E+07	2.13E+07	2.38E+07
Base case 3						
proxy Task 6	**CdTe**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**optimized PERC 2020**
	7.24E+06	2.03E+07	1.83E+07	2.48E+07	1.97E+07	2.23E+07

MOD 2.1+2 on module performance on quality and durability						
Base case 1						
proxy Task 6	**CIGS**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**BAT PERC 2019**	**optimized PERC 2020**
	2.04E+07	2.44E+07	2.42E+07	2.88E+07	2.44E+07	2.63E+07
Base case 2						
proxy Task 6	**CdTe**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**BAT PERC 2019**	**optimized PERC 2020**
	8.81E+06	2.19E+07	1.92E+07	2.63E+07	2.19E+07	2.38E+07
Base case 3						
proxy Task 6	**CdTe**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**BAT PERC 2019**	**optimized PERC 2020**
	7.24E+06	2.03E+07	1.83E+07	2.48E+07	2.03E+07	2.23E+07

INV 2.3 on inverters efficiency and life time electricity yield						
Base case 1						
proxy Task 6	**CIGS**	**PERC + EE**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**EE**
	2.04E+07	2.41E+07	2.42E+07	2.88E+07	2.38E+07	2.76E+07
Base case 2						
proxy Task 6	**CdTe**	**PERC + EE**	**PERC bifacial + EE**	**BNAT kerfless new**	**BSHJ**	**EE**
	8.81E+06	2.18E+07	1.91E+07	2.63E+07	2.13E+07	2.51E+07
Base case 3						
proxy Task 6	**CdTe**	**PERC + EE**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**EE +BOS**
	7.24E+06	2.03E+07	1.83E+07	2.48E+07	1.97E+07	2.33E+07

INV 2.4 on inverters on quality and durability						
Base case 1						
proxy Task 6	**CIGS**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**Longer life**
	2.04E+07	2.44E+07	2.42E+07	2.88E+07	2.38E+07	2.47E+07
Base case 2						
proxy Task 6	**CdTe**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**Repair**
	8.81E+06	2.19E+07	1.92E+07	2.63E+07	2.13E+07	2.39E+07
Base case 3						
proxy Task 6	**CdTe**	**BAT PERC 2019**	**BAT PERCbi 2019 (bifacial)**	**BNAT kerfless new**	**SHJ**	**EE+BOS**
	7.24E+06	2.03E+07	1.83E+07	2.48E+07	1.97E+07	2.36E+07

INV 2.3+4 on inverters on quality and durability						
Base case 1						
proxy Task 6	**CIGS**	**PERC + EE+LL**	**PERC bifacial**	**BNAT kerfless new**	**SHJ**	**EE**
	2.04E+07	2.12E+07	2.42E+07	2.88E+07	2.38E+07	2.76E+07
Base case 2						
proxy Task 6	**CdTe**	**PERC + EE+R**	**PERC bifacial + EE+R**	**BNAT kerfless new**	**SHJ**	**EE**
	8.81E+06	2.06E+07	1.78E+07	2.63E+07	2.13E+07	2.51E+07
Base case 3						
proxy Task 6	**CdTe**	**PERC + EE**	**PERC bifacial + EE**	**BNAT kerfless new**	**SHJ**	**BC3-EE +BOS**
	7.24E+06	2.03E+07	1.83E+07	2.48E+07	1.97E+07	2.33E+07

7.24E+06 2.03E+07 1.83E+07 2.48E+07 1.97E+07 2.33E+07

LAB 3.1 simple residential Energy label (Tier 2)						
Base case 1						
proxy Task 6	**CIGS**	**SHJ**	**PERC bifacial**	**BNAT kerfless new**	**SHJ**	**PERC**
	2.09E+07	2.53E+07	2.61E+07	2.95E+07	2.53E+07	2.56E+07

Annex 7C: Annual Yield and GER for modelled scenarios

	Annual yield (TWh)																	
	BAU BC1-3	**BAT**	**MOD2.1**	**MOD2.1++**	**MOD2.2**	**MOD2.1/2**	**INV2.3**	**INV2.4**	**INV2.3/4**	**BAU BC1**	**LAB3.1**	**LAB3.1-**	**LAB3.1+**	**LAB4.1**	**LAB4.1++**	**GPP5.1**	**COM 6.1**	**COM 6.2**
2015	6.484	6.484	6.484	6.484	6.484	6.484	6.484	6.484	6.484	1.294	1.294	1.294	1.294	1.294	1.294	2.706	6.484	6.484
2016	12.915	12.915	12.915	12.915	12.915	12.915	12.915	12.915	12.915	2.576	2.576	2.576	2.576	2.576	2.576	5.385	12.915	12.915
2017	19.295	19.295	19.295	19.295	19.295	19.295	19.295	19.295	19.295	3.844	3.844	3.844	3.844	3.844	3.844	8.037	19.295	19.295
2018	27.978	27.978	27.978	27.978	27.978	27.978	27.978	27.978	27.978	5.570	5.570	5.570	5.570	5.868	5.868	11.645	27.978	27.978
2019	40.234	40.234	40.234	40.234	40.234	40.234	40.234	40.234	40.234	8.005	8.005	8.005	8.005	7.896	7.896	16.738	40.234	40.234
2020	54.093	54.093	54.093	54.093	54.093	54.093	54.093	54.093	54.093	10.755	10.755	10.755	10.755	9.661	9.661	22.490	54.093	54.093
2021	68.433	68.433	68.433	68.433	68.433	68.433	68.433	68.433	68.433	13.596	13.596	13.596	13.596	11.474	11.474	28.432	68.433	68.433
2022	84.009	84.009	84.009	84.009	84.009	84.009	84.009	84.009	84.009	16.678	16.678	16.678	16.678	13.338	13.338	34.880	84.009	84.009
2023	100.849	101.822	100.864	102.617	100.856	100.856	101.032	100.853	101.032	20.006	20.204	20.045	20.573	14.168	14.168	41.853	102.363	101.901
2024	118.061	119.995	118.094	121.638	118.076	118.076	118.428	118.069	118.428	23.401	23.788	23.478	24.532	15.031	15.783	48.991	121.162	120.217
2025	135.660	138.546	135.711	141.083	135.681	135.681	136.210	135.671	136.210	26.867	27.433	26.980	28.558	15.913	16.709	56.266	140.424	138.974
2026	153.654	157.485	153.727	160.967	153.682	153.682	154.390	153.669	154.390	30.406	31.142	30.553	32.654	16.809	17.649	63.737	160.159	158.181
2027	172.058	176.824	172.155	181.302	172.092	172.092	172.980	172.076	172.980	34.020	34.916	34.199	36.821	17.730	18.616	71.333	180.381	177.851
2028	190.883	196.575	191.006	202.104	190.923	190.923	191.992	190.904	191.992	37.711	38.757	37.920	41.063	18.676	19.610	79.093	201.101	197.995
2029	210.142	216.752	210.296	223.387	210.188	210.188	211.441	210.166	211.441	41.483	42.668	41.719	45.380	19.649	20.631	87.020	222.335	218.626
2030	229.850	237.367	230.037	245.165	229.901	229.901	231.339	229.877	231.339	45.336	46.651	45.599	49.777	20.649	21.681	95.121	244.103	239.766
2031	249.934	258.343	250.155	267.359	249.990	249.990	251.613	249.963	251.613	49.258	50.690	49.544	54.235	21.503	22.578	103.365	266.339	261.347
2032	270.406	279.713	270.662	289.979	270.466	270.466	272.278	270.437	272.278	53.251	54.796	53.559	58.767	22.377	23.496	111.756	289.043	283.381
2033	291.276	301.483	291.568	313.038	291.340	291.340	293.343	291.310	293.343	57.315	58.970	57.645	63.374	23.274	24.437	120.300	312.229	305.880
2034	312.555	323.663	312.884	336.546	312.623	312.623	314.818	312.590	314.818	61.454	63.214	61.805	68.057	24.192	25.402	128.999	335.911	328.856
2035	334.254	346.265	334.622	360.519	334.327	334.327	336.717	334.292	336.717	65.669	67.529	66.040	72.819	25.113	26.369	137.859	360.102	352.322
2036	356.384	369.302	356.791	384.966	356.460	356.460	359.048	356.424	359.048	69.962	71.919	70.353	77.662	26.054	27.356	146.884	384.817	376.291
2037	378.957	392.787	379.404	409.901	379.036	379.036	381.825	378.998	381.825	74.337	76.385	74.746	82.589	27.015	28.366	156.078	410.069	400.777
2038	401.984	416.730	402.474	435.336	402.067	402.067	405.060	402.027	405.060	78.794	80.929	79.221	87.602	27.997	29.397	165.447	435.873	425.794
2039	425.478	441.144	426.011	461.286	425.565	425.565	428.764	425.523	428.764	83.337	85.554	83.780	92.704	29.001	30.451	174.995	462.243	451.356
2040	449.452	466.041	450.030	487.765	449.542	449.542	452.951	449.499	452.951	87.968	90.261	88.426	97.896	30.026	31.528	184.728	489.194	477.476
2041	473.919	491.436	474.543	514.788	474.012	474.012	477.633	473.967	477.633	92.689	95.054	93.161	103.181	31.075	32.628	194.650	516.743	504.170
2042	498.892	517.339	499.563	542.367	498.987	498.987	502.825	498.941	502.825	97.503	99.934	97.989	108.563	32.146	33.754	204.767	544.903	531.452
2043	524.384	543.770	525.104	570.519	524.482	524.482	528.539	524.434	528.539	102.413	104.905	102.910	114.045	33.242	34.904	215.084	573.688	559.337
2044	550.409	570.743	551.179	599.258	550.509	550.509	554.790	550.461	554.790	107.420	109.971	107.929	119.631	34.362	36.080	225.606	603.114	587.839
2045	571.886	593.177	572.708	623.505	571.989	571.989	576.497	571.939	576.497	111.571	114.177	112.091	124.367	34.549	36.276	234.339	628.101	611.880
2046	593.966	616.222	594.845	648.417	594.071	594.071	598.810	594.020	598.810	115.834	118.492	116.365	129.221	34.772	36.510	243.309	653.767	636.574
2047	616.663	639.892	617.605	674.009	616.770	616.770	621.744	616.718	621.744	120.214	122.918	120.754	134.197	35.030	36.782	252.522	680.124	661.937
2048	638.142	662.353	639.152	698.448	638.250	638.250	643.463	638.198	643.463	124.365	127.112	124.913	138.951	34.757	36.495	261.256	705.339	686.130
2049	657.419	682.621	658.505	720.754	657.529	657.529	662.986	657.476	662.986	128.103	130.888	128.659	143.298	34.510	36.235	269.128	728.428	708.171
2050	676.060	702.261	677.228	742.492	676.172	676.172	681.875	676.117	681.875	131.723	134.542	132.286	147.534	34.484	36.208	276.755	750.955	729.624

	GER (GJ)																	
	BAU BC 1-3	**BAT**	**MOD2.1**	**MOD2.1++**	**MOD2.2**	**MOD2.1/2**	**INV2.3**	**INV2.4**	**INV2.3/4**	**BAU BC3**	**LAB3.1**	**LAB3.1-**	**LAB3.1+**	**LAB4.1**	**LAB4.1++**	**GPP5.1**	**COM 6.1**	**COM 6.2**
2015	1.454E+08	1.454E+08	1.454E+08	1.454E+08	1.454E+08	1.454E+08	1.454E+08	3.479E+07	1.454E+08	3.479E+07	3.479E+07	3.479E+07	3.479E+07	3.583E+07	3.583E+07	5.965E+07	1.454E+08	1.454E+08
2016	1.455E+08	1.455E+08	1.455E+08	1.455E+08	1.455E+08	1.455E+08	1.455E+08	3.480E+07	1.455E+08	3.480E+07	3.480E+07	3.480E+07	3.480E+07	3.584E+07	3.584E+07	5.967E+07	1.455E+08	1.455E+08
2017	1.455E+08	1.455E+08	1.455E+08	1.455E+08	1.455E+08	1.455E+08	1.455E+08	3.481E+07	1.455E+08	3.481E+07	3.481E+07	3.481E+07	3.481E+07	3.586E+07	3.586E+07	5.969E+07	1.455E+08	1.455E+08
2018	1.971E+08	1.971E+08	1.971E+08	1.971E+08	1.971E+08	1.971E+08	1.971E+08	4.722E+07	1.971E+08	4.722E+07	4.722E+07	4.722E+07	4.722E+07	5.690E+07	5.690E+07	8.083E+07	1.971E+08	1.971E+08
2019	2.765E+08	2.765E+08	2.765E+08	2.765E+08	2.765E+08	2.765E+08	2.765E+08	6.634E+07	2.765E+08	6.634E+07	6.634E+07	6.634E+07	6.634E+07	5.735E+07	5.735E+07	1.133E+08	2.765E+08	2.765E+08
2020	3.121E+08	3.121E+08	3.121E+08	3.121E+08	3.121E+08	3.121E+08	3.121E+08	7.503E+07	3.121E+08	7.503E+07	7.503E+07	7.503E+07	7.503E+07	5.053E+07	5.053E+07	1.279E+08	3.121E+08	3.121E+08
2021	3.231E+08	3.231E+08	3.231E+08	3.231E+08	3.231E+08	3.231E+08	3.231E+08	7.781E+07	3.231E+08	7.781E+07	7.781E+07	7.781E+07	7.781E+07	5.215E+07	5.215E+07	1.323E+08	3.231E+08	3.231E+08
2022	3.502E+08	3.502E+08	3.502E+08	3.502E+08	3.502E+08	3.502E+08	3.502E+08	8.454E+07	3.502E+08	8.454E+07	8.454E+07	8.454E+07	8.454E+07	5.384E+07	5.384E+07	1.434E+08	3.502E+08	3.502E+08
2023	3.778E+08	2.581E+08	3.556E+08	3.911E+08	3.662E+08	3.663E+08	3.761E+08	8.581E+07	3.721E+08	9.141E+07	8.335E+07	7.376E+07	9.167E+07	2.619E+07	2.619E+07	1.536E+08	3.578E+08	3.002E+08
2024	3.861E+08	2.675E+08	3.647E+08	4.012E+08	3.749E+08	3.751E+08	3.844E+08	8.828E+07	3.799E+08	9.365E+07	8.591E+07	7.670E+07	9.449E+07	2.656E+07	2.788E+07	1.559E+08	3.663E+08	3.069E+08
2025	3.947E+08	2.767E+08	3.742E+08	4.115E+08	3.840E+08	3.841E+08	3.930E+08	9.083E+07	3.880E+08	9.601E+07	8.855E+07	7.969E+07	9.740E+07	2.719E+07	2.855E+07	1.593E+08	3.751E+08	3.136E+08
2026	4.035E+08	2.862E+08	3.837E+08	4.221E+08	3.932E+08	3.933E+08	4.017E+08	9.345E+07	3.961E+08	9.842E+07	9.127E+07	8.277E+07	1.004E+08	2.760E+07	2.898E+07	1.617E+08	3.840E+08	3.202E+08
2027	4.123E+08	2.958E+08	3.935E+08	4.328E+08	4.025E+08	4.026E+08	4.105E+08	9.615E+07	4.044E+08	1.009E+08	9.407E+07	8.596E+07	1.035E+08	2.826E+07	2.967E+07	1.650E+08	3.930E+08	3.268E+08
2028	4.213E+08	3.057E+08	4.034E+08	4.437E+08	4.119E+08	4.121E+08	4.194E+08	9.893E+07	4.127E+08	1.034E+08	9.695E+07	8.925E+07	1.066E+08	2.893E+07	3.037E+07	1.684E+08	4.021E+08	3.333E+08
2029	4.303E+08	3.157E+08	4.134E+08	4.547E+08	4.215E+08	4.216E+08	4.284E+08	1.018E+08	4.212E+08	1.060E+08	9.992E+07	9.266E+07	1.099E+08	2.962E+07	3.110E+07	1.718E+08	4.113E+08	3.398E+08
2030	4.398E+08	3.263E+08	4.240E+08	4.664E+08	4.316E+08	4.317E+08	4.379E+08	1.047E+08	4.300E+08	1.087E+08	1.030E+08	9.618E+07	1.133E+08	3.032E+07	3.184E+07	1.754E+08	4.211E+08	3.468E+08
2031	4.483E+08	3.362E+08	4.336E+08	4.770E+08	4.407E+08	4.408E+08	4.462E+08	1.073E+08	4.378E+08	1.110E+08	1.057E+08	9.943E+07	1.163E+08	2.662E+07	2.795E+07	1.786E+08	4.298E+08	3.534E+08
2032	4.587E+08	3.453E+08	4.442E+08	4.886E+08	4.512E+08	4.513E+08	4.566E+08	1.100E+08	4.478E+08	1.137E+08	1.084E+08	1.022E+08	1.193E+08	2.722E+07	2.858E+07	1.828E+08	4.401E+08	3.617E+08
2033	4.690E+08	3.549E+08	4.549E+08	5.004E+08	4.617E+08	4.618E+08	4.669E+08	1.128E+08	4.577E+08	1.163E+08	1.112E+08	1.052E+08	1.223E+08	2.783E+07	2.922E+07	1.868E+08	4.503E+08	3.699E+08
2034	4.796E+08	3.648E+08	4.659E+08	5.124E+08	4.725E+08	4.726E+08	4.774E+08	1.156E+08	4.677E+08	1.191E+08	1.141E+08	1.082E+08	1.255E+08	2.846E+07	2.988E+07	1.910E+08	4.608E+08	3.782E+08
2035	4.904E+08	3.748E+08	4.771E+08	5.248E+08	4.835E+08	4.836E+08	4.882E+08	1.185E+08	4.781E+08	1.219E+08	1.171E+08	1.113E+08	1.287E+08	2.916E+07	3.061E+07	1.953E+08	4.715E+08	3.867E+08
2036	5.015E+08	3.849E+08	4.886E+08	5.375E+08	4.948E+08	4.950E+08	4.993E+08	1.215E+08	4.887E+08	1.247E+08	1.201E+08	1.145E+08	1.321E+08	2.990E+07	3.140E+07	1.996E+08	4.825E+08	3.953E+08
2037	5.130E+08	3.953E+08	5.005E+08	5.504E+08	5.065E+08	5.066E+08	5.106E+08	1.245E+08	4.996E+08	1.277E+08	1.232E+08	1.178E+08	1.355E+08	3.064E+07	3.218E+07	2.041E+08	4.938E+08	4.041E+08
2038	5.246E+08	4.060E+08	5.125E+08	5.637E+08	5.183E+08	5.185E+08	5.222E+08	1.277E+08	5.107E+08	1.307E+08	1.263E+08	1.211E+08	1.390E+08	3.141E+07	3.298E+07	2.087E+08	5.053E+08	4.131E+08
2039	5.366E+08	4.169E+08	5.249E+08	5.774E+08	5.305E+08	5.306E+08	5.341E+08	1.309E+08	5.220E+08	1.338E+08	1.296E+08	1.246E+08	1.425E+08	3.219E+07	3.379E+07	2.134E+08	5.171E+08	4.223E+08
2040	5.487E+08	4.282E+08	5.376E+08	5.913E+08	5.430E+08	5.431E+08	5.462E+08	1.342E+08	5.336E+08	1.370E+08	1.329E+08	1.281E+08	1.462E+08	3.299E+07	3.464E+07	2.182E+08	5.292E+08	4.317E+08
2041	5.612E+08	4.397E+08	5.506E+08	6.056E+08	5.557E+08	5.558E+08	5.586E+08	1.375E+08	5.455E+08	1.402E+08	1.363E+08	1.318E+08	1.500E+08	3.380E+07	3.549E+07	2.231E+08	5.415E+08	4.413E+08
2042	5.740E+08	4.515E+08	5.639E+08	6.202E+08	5.687E+08	5.688E+08	5.713E+08	1.410E+08	5.576E+08	1.435E+08	1.399E+08	1.355E+08	1.538E+08	3.464E+07	3.638E+07	2.281E+08	5.541E+08	4.512E+08
2043	5.875E+08	4.634E+08	5.777E+08	6.354E+08	5.824E+08	5.825E+08	5.848E+08	1.445E+08	5.705E+08	1.470E+08	1.434E+08	1.392E+08	1.578E+08	3.551E+07	3.728E+07	2.334E+08	5.674E+08	4.616E+08
2044	6.013E+08	4.756E+08	5.918E+08	6.509E+08	5.964E+08	5.965E+08	5.985E+08	1.481E+08	5.837E+08	1.505E+08	1.471E+08	1.430E+08	1.618E+08	3.638E+07	3.820E+07	2.389E+08	5.810E+08	4.723E+08
2045	5.845E+08	4.573E+08	5.754E+08	6.360E+08	5.798E+08	5.799E+08	5.817E+08	1.447E+08	5.664E+08	1.470E+08	1.437E+08	1.398E+08	1.588E+08	2.984E+07	3.133E+07	2.320E+08	5.640E+08	4.524E+08
2046	5.973E+08	4.686E+08	5.886E+08	6.504E+08	5.928E+08	5.929E+08	5.944E+08	1.485E+08	5.785E+08	1.507E+08	1.476E+08	1.438E+08	1.630E+08	3.075E+07	3.229E+07	2.366E+08	5.764E+08	4.607E+08
2047	6.103E+08	4.801E+08	6.019E+08	6.652E+08	6.060E+08	6.060E+08	6.073E+08	1.524E+08	5.909E+08	1.545E+08	1.515E+08	1.479E+08	1.673E+08	3.169E+07	3.327E+07	2.413E+08	5.889E+08	4.690E+08
2048	6.125E+08	4.810E+08	6.046E+08	6.692E+08	6.085E+08	6.085E+08	6.095E+08	1.539E+08	5.925E+08	1.559E+08	1.530E+08	1.496E+08	1.692E+08	2.828E+07	2.969E+07	2.417E+08	5.908E+08	4.664E+08
2049	6.091E+08	4.761E+08	6.016E+08	6.676E+08	6.052E+08	6.053E+08	6.060E+08	1.540E+08	5.883E+08	1.559E+08	1.532E+08	1.500E+08	1.699E+08	2.917E+07	3.062E+07	2.397E+08	5.869E+08	4.580E+08
2050	6.151E+08	4.808E+08	6.081E+08	6.755E+08	6.115E+08	6.116E+08	6.119E+08	1.564E+08	5.936E+08	1.582E+08	1.557E+08	1.527E+08	1.728E+08	3.159E+07	3.317E+07	2.415E+08	5.925E+08	4.588E+08

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