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Preparatory study for solar photovoltaic modules, inverters and systems

Draft Report Task 5: Environmental and economic assessment of base cases

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Contents

List of figures iv

List of tables v

Annexes vii

Annex A. Materials added to the MEErP ecoreport tool vii

Annex B. External costs for society vii

Annex C. Overview of LCA literature vii

5. Task 5: Environmental and economic assessment of base case 8

5.0 General introduction 8

5.1 MEErP LCA and LCC assessments 8

5.1.1 Product specific inputs 8

5.1.1.1 Selection of base cases 8

5.1.1.2 Functional unit for the LCA 10

5.1.1.3 Life cycle cost and Levelised cost of electricity 11

5.1.1.4 Stock and/or sales 12

5.1.1.5 Product service life 12

5.1.1.6 Purchase price and repair and maintenance cost 12

5.1.1.7 Other economic parameters 13

5.1.2 Product life cycle information 14

5.1.2.1 Production phase 14

5.1.2.1.1 BOM multi Si module 14

5.1.2.1.2 BOM 2500 W inverter 16

5.1.2.1.3 BOM 20 kW inverter 18

5.1.2.1.4 BOM central inverter 19

5.1.2.2 Additional material loss in the manufacturing phase 20

5.1.2.3 Distribution phase 21

5.1.2.4 Use phase 21

5.1.2.5 End-of-life 22

5.2 Base Case Environmental Impact Assessment (using EcoReport 2014) 23

5.2.1 Scaling the EcoReport results to the functional unit 23

5.2.2 Results Base-Case for modules 23

5.2.2.1 Multicrystalline Silicon BSF 23

5.2.3 Results Base-Cases for inverters 26

5.2.3.1 String 1 phase inverter, 2500 W 26

5.2.3.2 String 3 phase inverter, 20 kW 27

5.2.3.3 Central inverter 29

5.2.4 Results Base-Cases for systems 31

5.2.4.1 Results Base-Case 1: 3 kW system (modules plus inverter) 31
5.2.4.2 Results Base-Case 2: 24.4 kW system (modules plus inverter) 32
5.2.4.3 Results Base-Case 3: 1875 kW system (modules plus inverter) 34
5.3 Base case life cycle cost for consumer 35
5.3.1 Introduction to Life Cycle Costing and the relationship with the Levelized Cost of electricity (LCOE) and functional unit of a PV system 35
5.3.2 LCC for individual components of the PV system 36
5.3.3 LCC and LCOE results base cases for systems 36
5.4 Base Case Life Cycle Costs for society 38
5.5 EU totals 38
5.5.1 Module stock estimates for the EU 38
5.5.2 Inverter stock estimates for the EU 39
5.5.3 System sales estimates for the EU 40
5.5.4 EU totals for systems 40
5.6 EU Ecolabel and GPP criteria 41
5.6.1 Systematic assessment of LCA related literature 41
5.6.1.1 Overview of LCA studies on solar photovoltaic modules, inverters and systems 41
5.6.1.2 Selection of LCA studies for further analysis 42
5.6.1.3 Detailed analysis of the selected LCA studies 42
5.6.1.3.1 Base parameters of the selected studies 43
5.6.1.3.2 Goal and scope 44
5.6.1.3.3 Functional unit, system boundaries and life time 45
5.6.1.3.4 Impact categories and impact assessment 47
5.6.1.3.5 Assumptions 49
5.6.1.3.6 Data quality requirements and data sources 50
5.6.1.3.7 Results of the selected LCA studies 54
5.6.2 Other environmental or non-environmental impacts of relevance for EU Ecolabel certification and GPP 60
5.6.2.1 Hazardous substances in solar photovoltaic products 60
5.6.2.1.1 REACH Candidate List substances 60
5.6.2.1.2 Substances classified with CLP hazards 61
5.6.2.1.3 Substances restricted by the RoHS Regulation 65
5.6.2.2 Hazardous substances in manufacturing processes 66
5.6.2.2.1 Use of Critical Raw Materials 66
5.6.2.3 Social and ethical issues 67
Annex A: Materials added to the MEErP ecoreport tool 1
Annex B: External costs for society 2
Annex C: Overview of LCA literature 4

List of figures

Figure 1: Environmental profile of a multi Si module per kWh 25

Figure 2: Environmental profile of 1 kWh by a 2500 W inverter 27

Figure 3: Environmental profile for 1 kWh by a 20 kW inverter 29

Figure 4: Environmental profile of 1 kWh by a 1500 kW central inverter 30

Figure 5: Environmental profile Base-Case 1, 3 kWp system 32

Figure 6: Environmental profile Base-Case 2, 24.4 kWp system....33

Figure 7: Environmental profile Base-Case 3, 1875 kWp system 35

Figure 8 (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. 55

Figure 9: (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). They were harmonized for 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. 56

Figure 10: (taken from UNEP 2016) Life-cycle GHG emissions of different energy technologies, in g CO_{2e}/kWh, reflecting application of technology in Europe 57

Figure 11: (taken from UNEP 2016) Human health impact in disability adjusted life years (DALY) per 1 TWh of electricity generated, for Europe 2010. 57

Figure 12: (taken from UNEP 2016): Ecosystem impacts in species-year affected per 1000 TWh of electricity following different damage pathways, reflecting Europe 2010. ..58

Figure 14: (taken from UNEP 2016) Bulk material and non-renewable energy requirements per unit power produced. 58

Figure 14 Share of CRMs used in wind and solar PV cell production 67

List of tables

Table 1: Overview of selected Base-Cases for systems 9

Table 2: System parameters for calculation of functional unit 10

Table 3: Calculation of functional unit for inverters 11

Table 4 Input data for Life Cycle Cost calculations 13

Table 5: BOM multi-Si module..15

Table 6: Energy inputs and emissions occurring during the manufacturing of the multi Si module...15

Table 7: BOM 2500 W inverter (1 unit)...17

Table 8: Energy inputs for manufacturing of 2500 W...17

Table 9: Energy inputs for manufacturing of 20 W 18

Table 10: BOM 20 kW inverter (1 unit)...19

Table 11: BOM 1500 kW inverter (1 unit consisting of 3 strings of 500 kW each) 20

Table 12: Energy inputs for manufacturing of 1500 kW 20

Table 13: Use phase input data 21

Table 14: End-of-life scenario's from EcoReport tool. Default values in red. 22

Table 15: EcoReport results for Multi Si module (per kWh) 24

Table 16: Results for production (material input) of 1 kWh by a multi Si module using EcoReport tool 25

Table 17: EcoReport results for 1 kWh by a 2500 W inverter.....................................26

Table 18: Results for production (material input) of 1 kWh by a 2500 W inverter using EcoReport tool 27

Table 19: EcoReport results for 20 kW inverter (per kWh) 28

Table 20: Results for production (material input) 20 kW inverter using EcoReport tool ..29

Table 21: EcoReport results for 1500 kW central inverter (per kWh) 30

Table 22: Results for production (material input) 1500 kW central inverter using EcoReport tool 31

Table 23: EcoReport results for Base-Case 1: 3 kW system with multi Si module and 2500 W inverter (per kWh) 32

Table 24: EcoReport results for Base-Case 2: 24.4 kWp system with multi Si module and 20 kW inverter (per kWh) 33

Table 25: EcoReport results for Base-Case 3: 1875 kW system with multi Si module and 1500 W inverter (per kWh) 34

Table 26 Calculated LCC and LCOE for BC 1 (residential system) 37

Table 27 Input data used for LCC and LCOE performance modelling..................37

Table 28 CAPEX and OPEX input data and calculated results 37

Table 29. Reference size in Wp of modules installed per segment and technology. 39

Table 30. Number of installed units (thousands) of modules per technology and segment estimated for the reference year 2016 39

Table 31. Reference size of inverters installed per segment and technology. 39

Table 32. Number of installed units (thousands) of modules per technology and segment estimated for the reference year 2016 40

Table 33. Number of installed units of systems per segment estimated for the reference year 2016....................40

Table 34. EU Total impacts for system market segments 40

Table 34: Description of the investigated studies 43

Table 35: Goal and scope of the studies 44

Table 36: Functional unit, System boundaries and considered life time....................46

Table 37: Impact categories, impact assessment method, database and software 47

Table 38: Assumptions....................49

Table 39: Time-related, geographical and technological representativeness of data and data sources of primary and secondary data 51

Table 40: Energy pay-back time calculated by Lecissi et al. 2016 59

Table 41: Restricted hazard classifications and their hazard categorisation 62

Table 42. Plasticiser alternatives that have been derogated for us in other EU Ecolabel product groups....................63

Table 43. Flame retardants alternatives for circuitry that have been derogated for us in other EU Ecolabel product groups 64

Table 44. Flame retardants alternatives for cables that have been derogated for us in other EU Ecolabel product groups 64

Annexes

Annex A. Materials added to the MEErP ecoreport tool

Annex B. External costs for society

Annex C. Overview of LCA literature

5. Task 5: Environmental and economic assessment of base case

5.0 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.

5.1 MEErP LCA and LCC assessments

5.1.1 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.

5.1.1.1 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[1]. 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 1. 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).[2]

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[1] See Task 4 for a description of back surface silicon cells

[2] 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 1: 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 life time	30 years	30 years	30 years
Inverter life time	10 years	10 years	30 years[3]
System life time	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
DC:AC 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	0.005-0.1	0.005-0.1	0.005-0.1
Inverter	10	Below 10	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			

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[3] The components of the inverter are progressively repaired and replaced along their lifetime

5.1.1.2 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 (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 life time 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 2.

Table 2: System parameters for calculation of functional unit

	Module parameters
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
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%
Yield (kWh/kWp) 30 year	926
Expected life time (years)	30
Module area per kWh energy produced (m^2)	**2.45E-04**

Inverters

Calculations of the number of inverters needed per functional unit are detailed below in Table 3**Error! Reference source not found.**. According to the IEA PVPS report on recent trends[4], 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.

Table 3: 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 kWh	3.69E-05	4.53E-06	1.97E-08	inverters per kWh

5.1.1.3 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)

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[4] IEA PVPS, *Technical Assumptions Used in PV Financial Models. Review of Current Practices and Recommendations*. 2017.

$WACC_{Nom}$ = 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

5.1.1.4 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.

5.1.1.5 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 life time of 10 years is assumed for an inverter (see Task 2, section 2.2.2.1).

5.1.1.6 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 4. 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 4 will be used (sample data only).

Table 4 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

5.1.1.7 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 5.3.

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[5] calculated the PV LCOE in 2014 for developing cost maps for unsubsidised photovoltaic electricity with a discount rate of 5 %.

5.1.2 Product life cycle information

5.1.2.1 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 A. The energy use and related emissions which occur during manufacturing have been added to the tool as well.

5.1.2.1.1 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[6]. 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. Annex A 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 6 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[6].

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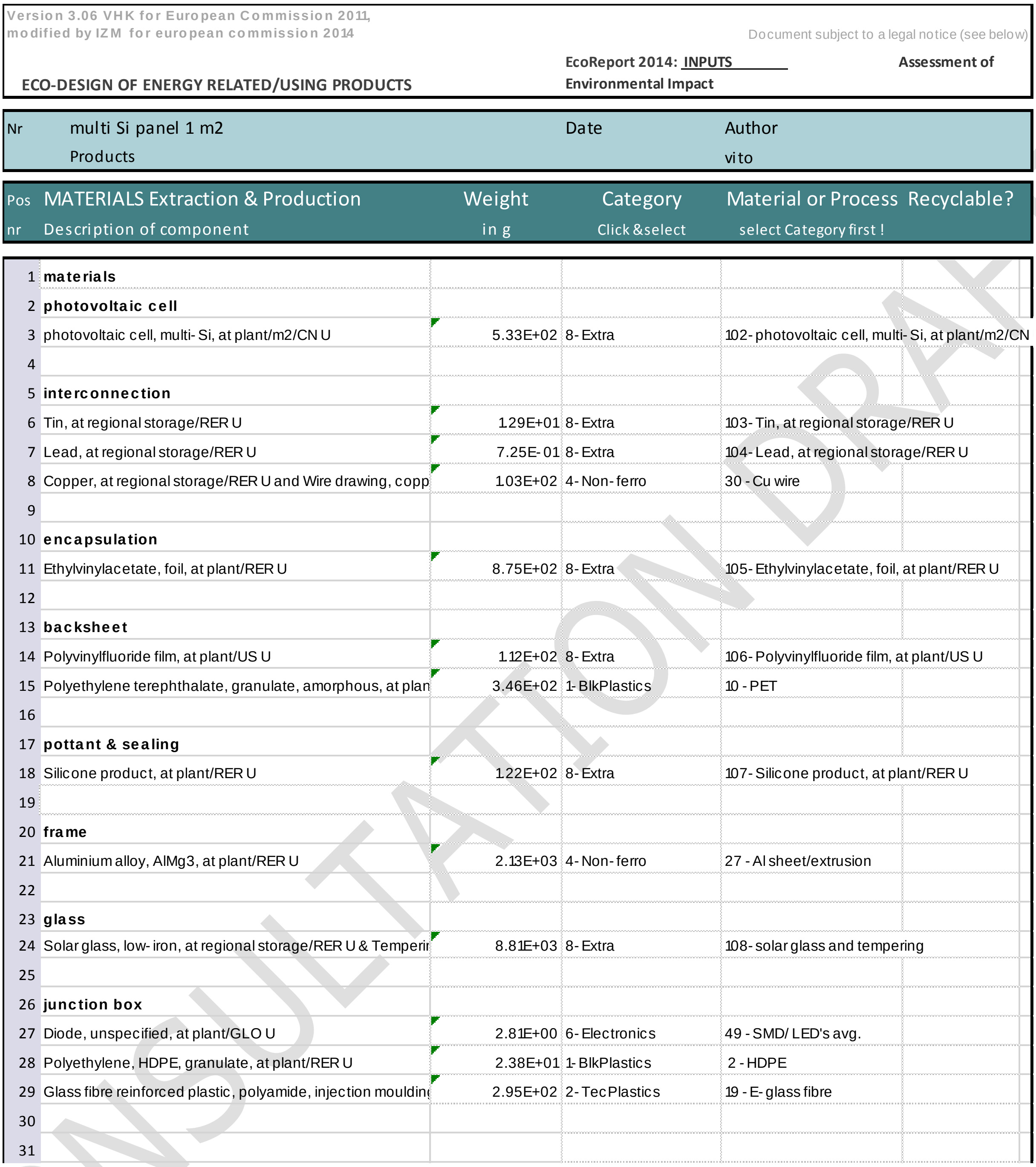
[5] https://setis.ec.europa.eu/related-jrc-activities/jrc-setis-reports/cost-maps-unsubsidised-photovoltaic-electricity

[6] 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 5: BOM multi-Si module



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EcoReport 2014: INPUTS

Assessment of Environmental Impact

ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

Nr	multi Si panel 1 m2 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, at plant/m2/CN U	5.33E+02	8-Extra	102-photovoltaic cell, multi-Si, at plant/m2/CN	
4					
5	**interconnection**				
6	Tin, at regional storage/RER U	1.29E+01	8-Extra	103-Tin, at regional storage/RER U	
7	Lead, at regional storage/RER U	7.25E-01	8-Extra	104-Lead, at regional storage/RER U	
8	Copper, at regional storage/RER U and Wire drawing, copp	1.03E+02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil, at plant/RER U	8.75E+02	8-Extra	105-Ethylvinylacetate, foil, at plant/RER U	
12					
13	**backsheet**				
14	Polyvinylfluoride film, at plant/US U	1.12E+02	8-Extra	106-Polyvinylfluoride film, at plant/US U	
15	Polyethylene terephthalate, granulate, amorphous, at plan	3.46E+02	1-BlkPlastics	10 -PET	
16					
17	**pottant & sealing**				
18	Silicone product, at plant/RER U	1.22E+02	8-Extra	107-Silicone product, at plant/RER U	
19					
20	**frame**				
21	Aluminium alloy, AlMg3, at plant/RER U	2.13E+03	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron, at regional storage/RER U & Temperi	8.81E+03	8-Extra	108-solar glass and tempering	
25					
26	**junction box**				
27	Diode, unspecified, at plant/GLO U	2.81E+00	6-Electronics	49 -SMD/ LED's avg.	
28	Polyethylene, HDPE, granulate, at plant/RER U	2.38E+01	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection mouldin	2.95E+02	2-TecPlastics	19 -E-glass fibre	
30					
31					

Table 6: Energy inputs and emissions occurring during the manufacturing of the multi Si module

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

5.1.2.1.2 BOM 2500 W inverter

Material input for the 2500 W inverter has been taken from a study made by Tschümperlin et al. (Treeze)[7]. 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. Annex A provides more details on the modelling of the additional materials.

Energy use for production has been added to the tool as well. Table 8 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)[7].

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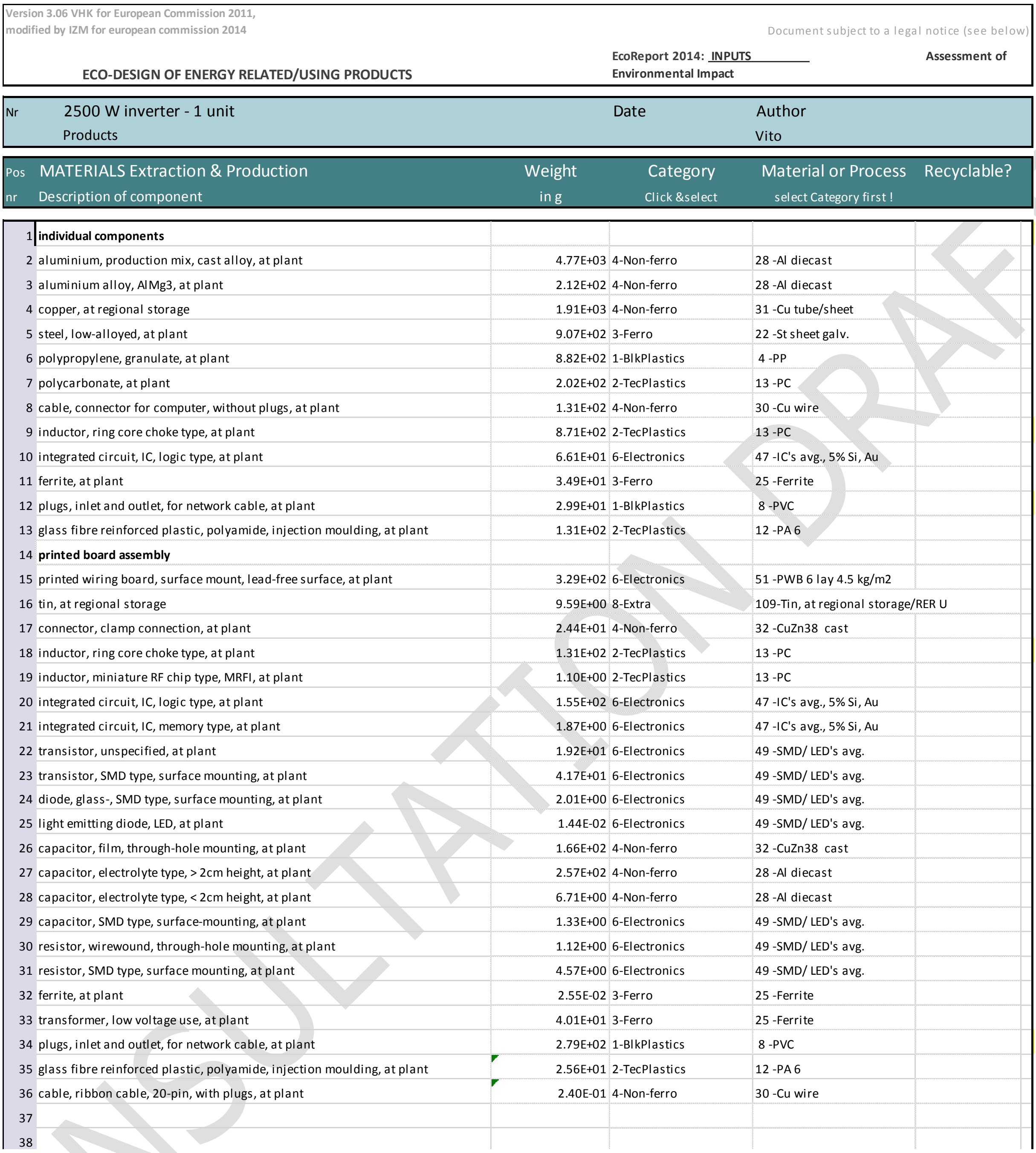
[7] Tschümperlin L, Stolz P., Frischknecht R. 2016. Life cycle assessment of low power solar inverters (2.5 to 20 kW). Available online: http://treeze.ch/fileadmin/user_upload/downloads/Publications/Case_Studies/Energy/174-Update_Inverter_IEA_PVPS_v1.1.pdf

Table 7: BOM 2500 W inverter (1 unit)



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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS
Environmental Impact

Assessment of

Nr	2500 W inverter - 1 unit	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	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					
38					

Table 8: 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

5.1.2.1.3 BOM 20 kW inverter

Material input for the 20 kW inverter have been taken from a study made by Tschümperlin et al. (Treeze)[7]. 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.

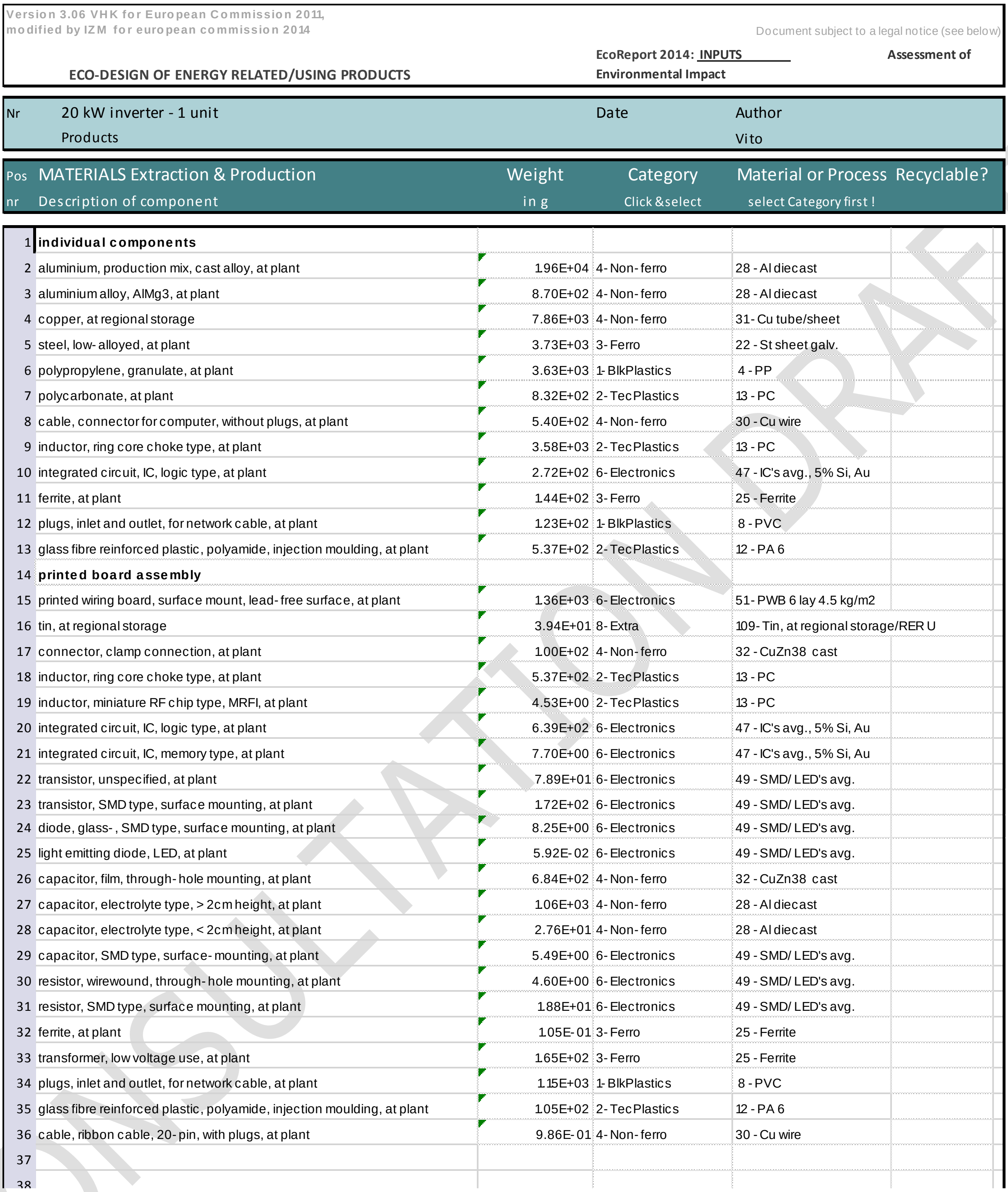
The inverter is replaced two times during the life span of the 30 years. The material that was not available and has been added to the EcoReport tool was tin. Annex A provides more details on the modelling of the additional materials.

Energy use for production has been added to the tool as well. Table 9 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)[7].

Table 9: 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

Table 10: BOM 20 kW inverter (1 unit)



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EcoReport 2014: INPUTS

Assessment of Environmental Impact

ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

Nr 20 kW inverter - 1 unit

Products

Date

Author

Vito

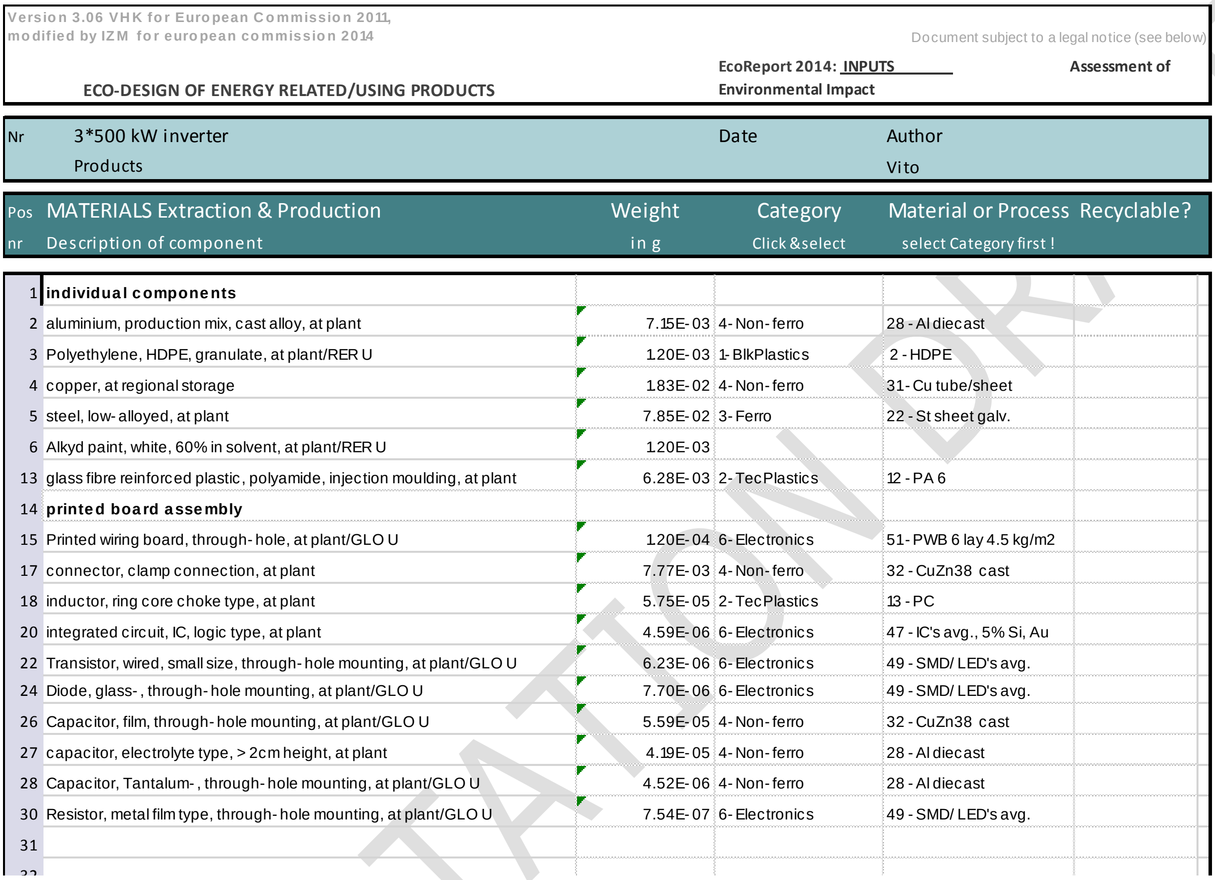
Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	1.96E+04	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, 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					

5.1.2.1.4 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 11: BOM 1500 kW inverter (1 unit consisting of 3 strings of 500 kW each)



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EcoReport 2014: INPUTS Assessment of Environmental Impact

ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

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.	
31					

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. **Error! Reference source not found.** provides an overview of the energy inputs for the manufacturing of a 1500 kW central inverter. The data have been taken from Ecoinvent.

Table 12: Energy inputs for manufacturing of 1500 kW

Input manufacturing	**Amount**	**Unit**
European medium voltage electricity	13733.4	kWh

5.1.2.2 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.

5.1.2.3 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? Yes
- ‘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? Yes.
- ‘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[8]).

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[9]).

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[10]).

The effect on the results of these answers is to be further analysed for representativeness given that answering 'Yes' introduces burdens associated air freight. This is one of the assumed modes of shipment for electronic products.

5.1.2.4 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 13 will be used.

Table 13: 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 1	See Table 1	See Table 1
Performance Ratio (in year 1)	See Table 1	See Table 1	See Table 1

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[8] 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

[9] http://www.sofarsolar.com/product-detail/406/Sofar%2020000TL

[10] https://library.e.abb.com/public/130d0dd62e4f47a992e1eaf9e4ee26e5/ULTRA-EN-Rev%20E.pdf

Performance degradation rate (% per year)	See Table 1	See Table 1	See Table 1
Number of maintenance operations during the lifetime	0	1	1
Travel distance for maintenance (km)	Not relevant	50	50

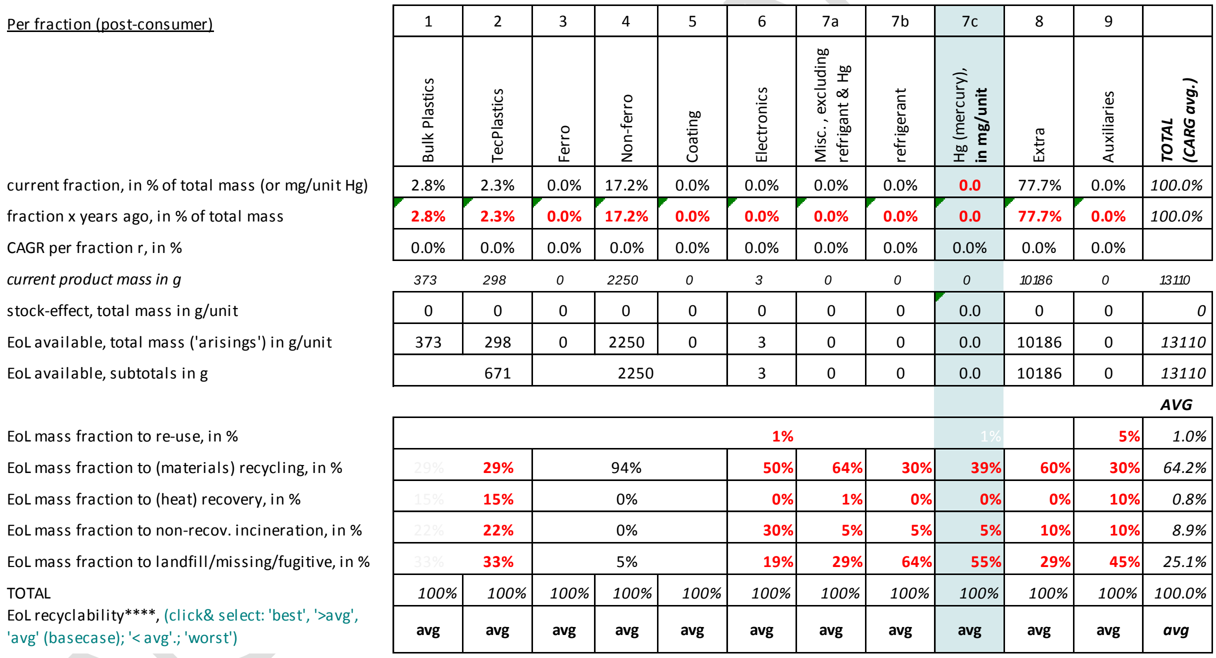
5.1.2.5 End-of-life

Default end-of-life values from the MEErP EcoReport tool have been used. They are provided in Table 14.

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)[11] gives additional insights into end-of-life treatment strategies of photovoltaic modules.

Table 14: 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***

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[11] 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

5.2 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 5.1).

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.

5.2.1 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 5.1.2.4.

5.2.2 Results Base-Case for modules

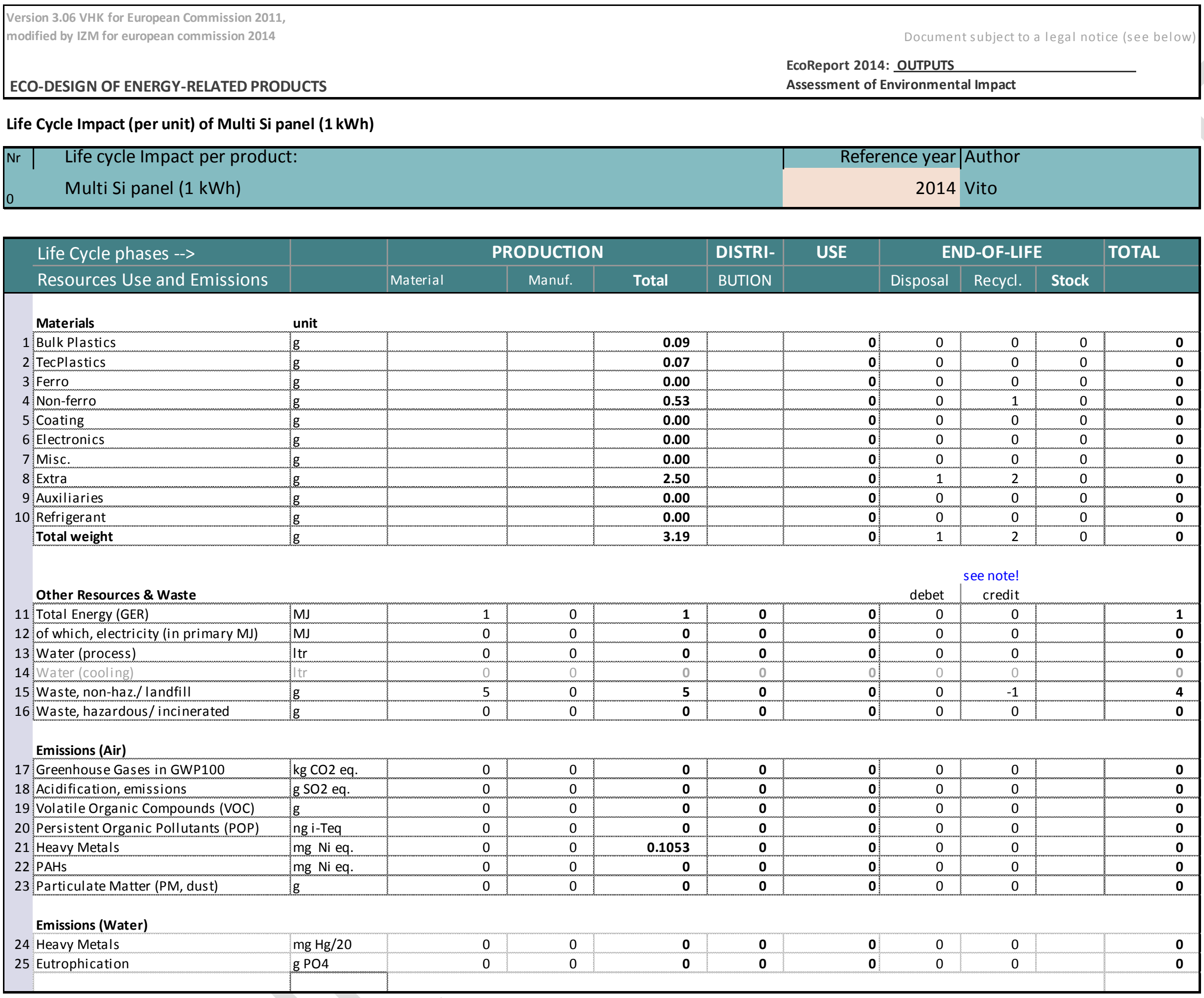
The bill of materials for a multi Si module is available in section 5.1.2.1. Modules are not assumed to be replaced during the lifespan.

5.2.2.1 Multicrystalline Silicon BSF

This section discusses the LCA results for the multicrystalline Si module. Table 15 provides the LCIA results in absolute values for 1 kWh produced by a multi Si BSF PV module. Figure 1 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 15: EcoReport results for Multi Si module (per kWh)



Version 3.06 VHK for European Commission 2011,
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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			**0.09**		**0**	0	0	0	**0**
2	TecPlastics	g			**0.07**		**0**	0	0	0	**0**
3	Ferro	g			**0.00**		**0**	0	0	0	**0**
4	Non-ferro	g			**0.53**		**0**	0	1	0	**0**
5	Coating	g			**0.00**		**0**	0	0	0	**0**
6	Electronics	g			**0.00**		**0**	0	0	0	**0**
7	Misc.	g			**0.00**		**0**	0	0	0	**0**
8	Extra	g			**2.50**		**0**	1	2	0	**0**
9	Auxiliaries	g			**0.00**		**0**	0	0	0	**0**
10	Refrigerant	g			**0.00**		**0**	0	0	0	**0**
	Total weight	g			**3.19**		**0**	1	2	0	**0**
									see note!		
	Other Resources & Waste							debet	credit		
11	Total Energy (GER)	MJ	1	0	**1**	**0**	**0**	0	0		**1**
12	of which, electricity (in primary MJ)	MJ	0	0	**0**	**0**	**0**	0	0		**0**
13	Water (process)	ltr	0	0	**0**	**0**	**0**	0	0		**0**
14	Water (cooling)	ltr	0	0	0	0	0	0	0		0
15	Waste, non-haz./ landfill	g	5	0	**5**	**0**	**0**	0	-1		**4**
16	Waste, hazardous/ incinerated	g	0	0	**0**	**0**	**0**	0	0		**0**
	Emissions (Air)										
17	Greenhouse Gases in GWP100	kg CO2 eq.	0	0	**0**	**0**	**0**	0	0		**0**
18	Acidification, emissions	g SO2 eq.	0	0	**0**	**0**	**0**	0	0		**0**
19	Volatile Organic Compounds (VOC)	g	0	0	**0**	**0**	**0**	0	0		**0**
20	Persistent Organic Pollutants (POP)	ng i-Teq	0	0	**0**	**0**	**0**	0	0		**0**
21	Heavy Metals	mg Ni eq.	0	0	**0.1053**	**0**	**0**	0	0		**0**
22	PAHs	mg Ni eq.	0	0	**0**	**0**	**0**	0	0		**0**
23	Particulate Matter (PM, dust)	g	0	0	**0**	**0**	**0**	0	0		**0**
	Emissions (Water)										
24	Heavy Metals	mg Hg/20	0	0	**0**	**0**	**0**	0	0		**0**
25	Eutrophication	g PO4	0	0	**0**	**0**	**0**	0	0		**0**

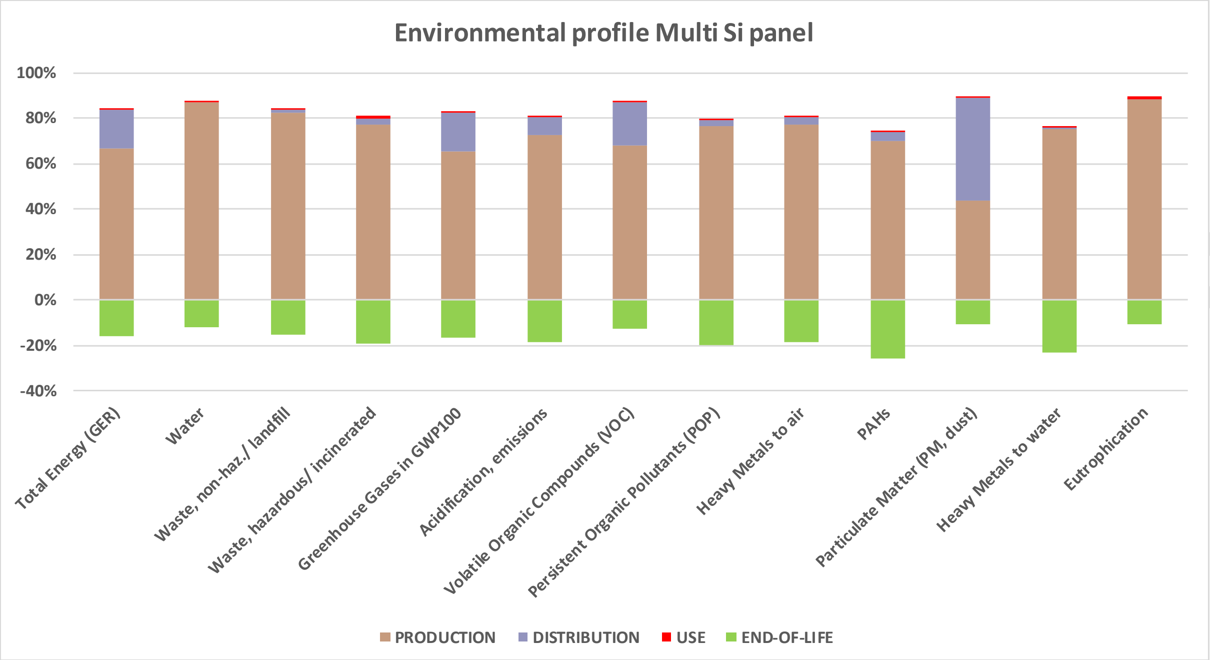


Figure 1: Environmental profile of a multi Si module per kWh

Table 16 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 16: 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%

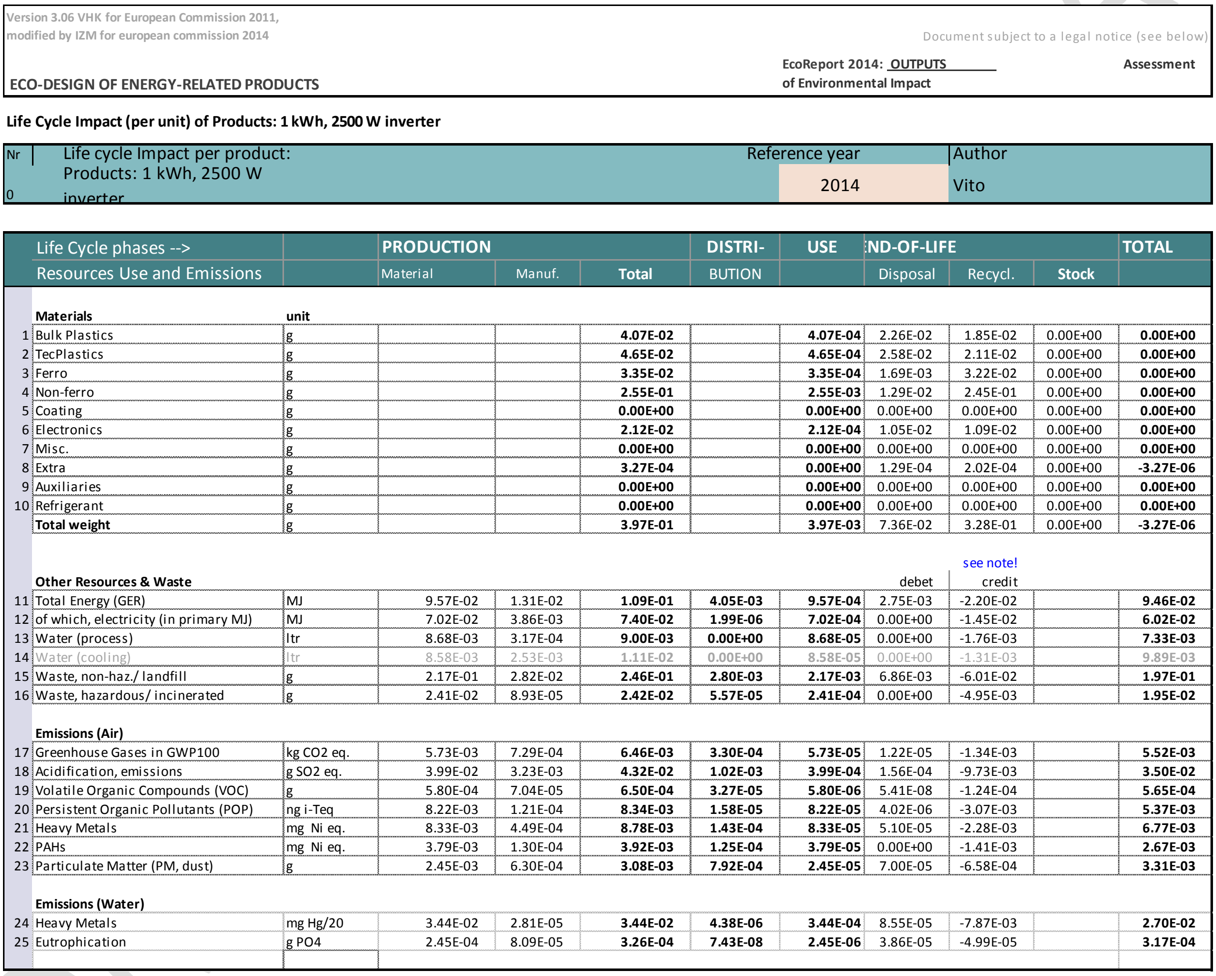
5.2.3 Results Base-Cases for inverters

The bill of materials for inverters are available in 5.1.2.1.

5.2.3.1 String 1 phase inverter, 2500 W

This section discusses the LCA results for the 2500 W inverter. Table 17 provides the LCIA results in absolute value for the production of 1 kWh by an inverter of 2500 W. Figure 2 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 17: EcoReport results for 1 kWh by a 2500 W inverter



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EcoReport 2014: OUTPUTS Assessment
of Environmental Impact

ECO-DESIGN OF ENERGY-RELATED PRODUCTS

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

	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			**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**

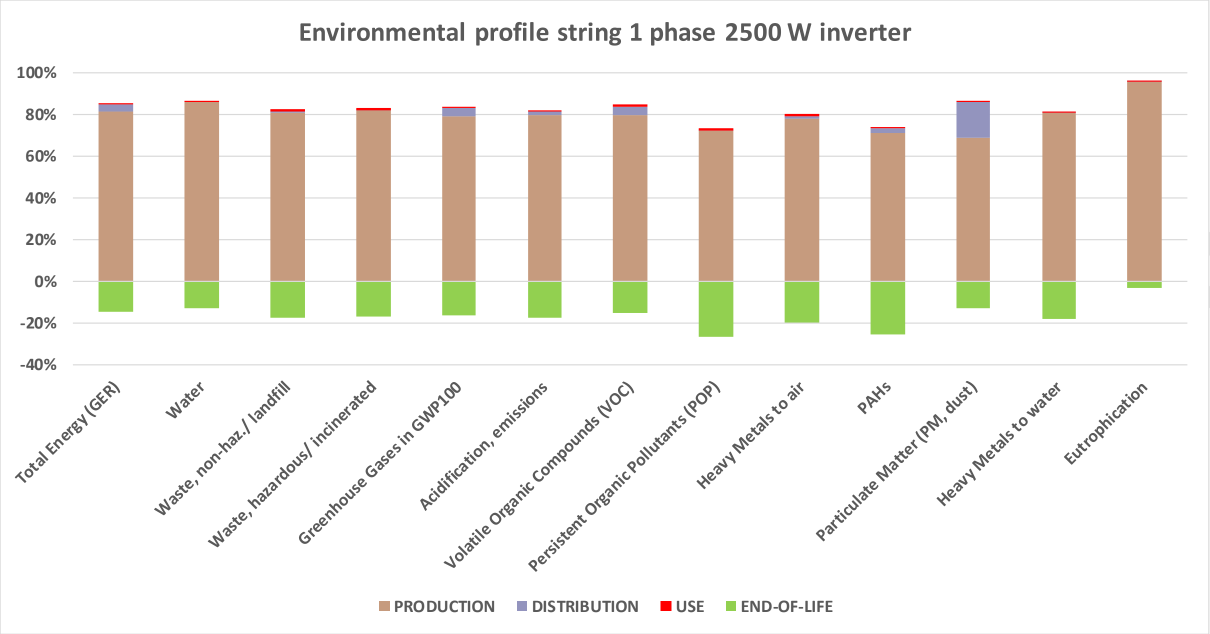

Figure 2: Environmental profile of 1 kWh by a 2500 W inverter

Table 18 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 18: 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%

5.2.3.2 String 3 phase inverter, 20 kW

This section discusses the LCA results for the 20 kW inverter. Table 19 provides the LCIA results in absolute value for the production of 1 kWh by an inverter of 20 kW. Figure 3 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 19: EcoReport results for 20 kW inverter (per kWh)

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EcoReport 2014: OUTPUTS
Environmental Impact

Assessment of

ECO-DESIGN OF ENERGY-RELATED PRODUCTS

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

	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**

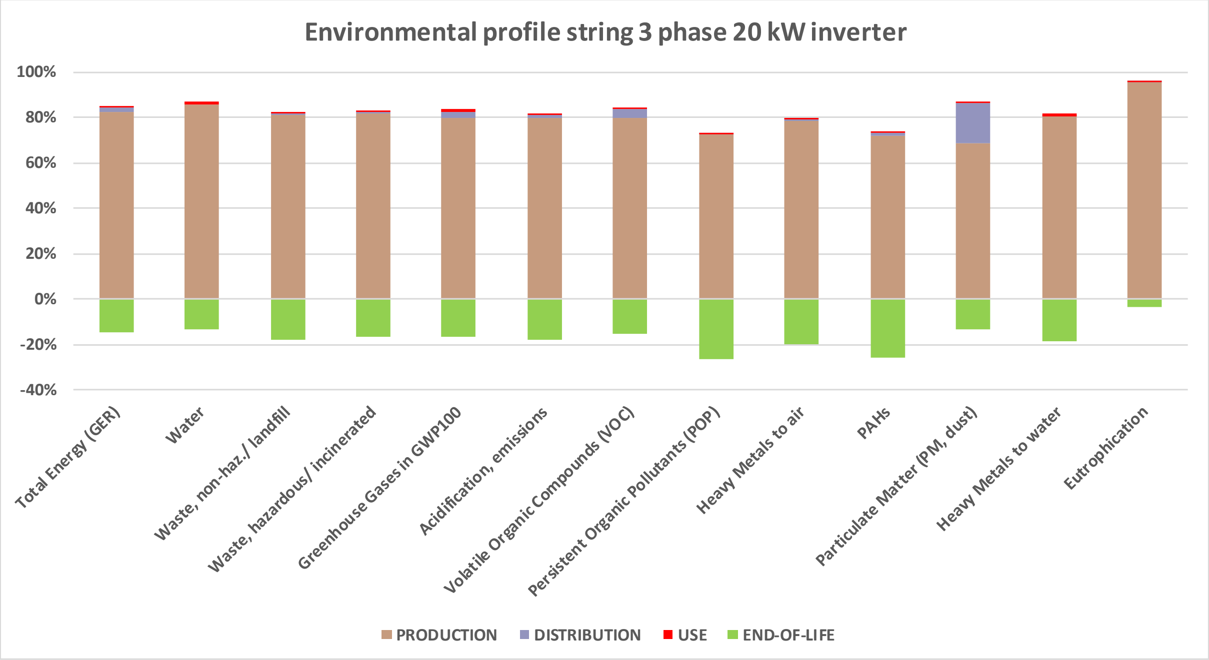

Figure 3: Environmental profile for 1 kWh by a 20 kW inverter

Table 20 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 18).

Table 20: 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%

5.2.3.3 Central inverter

This section discusses the LCA results for the 1500 kW central inverter. Table 21 provides the LCIA results in absolute value for the production of 1 kWh by an inverter of 1500 kW. Figure 4 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 21: 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

	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**

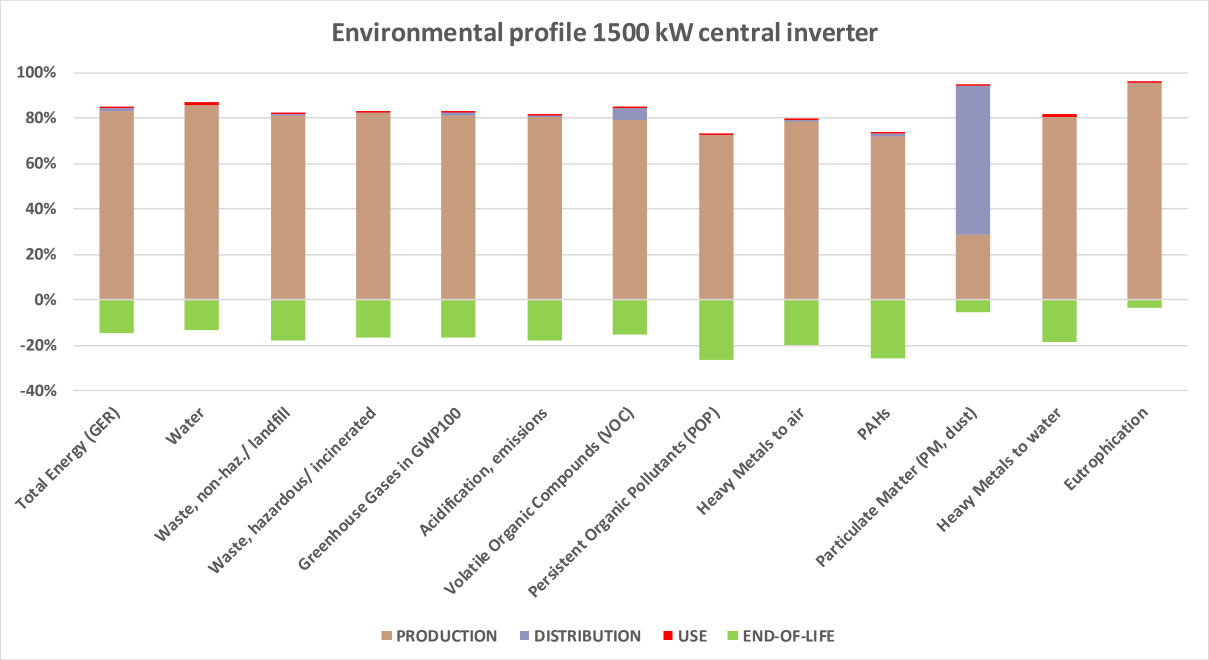

Figure 4: Environmental profile of 1 kWh by a 1500 kW central inverter

Table 22 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 22: 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%

5.2.4 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 5.1.1.1. Parameters for the calculation of the functional unit are available in Table 2 (modules) and Table 3 (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.

5.2.4.1 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 23 provides the LCIA results in absolute values for a 3 kW system. Figure 5 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 23: 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 --> Resources Use and Emissions		PRODUCTION Material	 Manuf.	 Total	DISTRI- BUTION	USE	END-OF-LIFE Disposal	 Recycl.	 Stock	TOTAL
	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

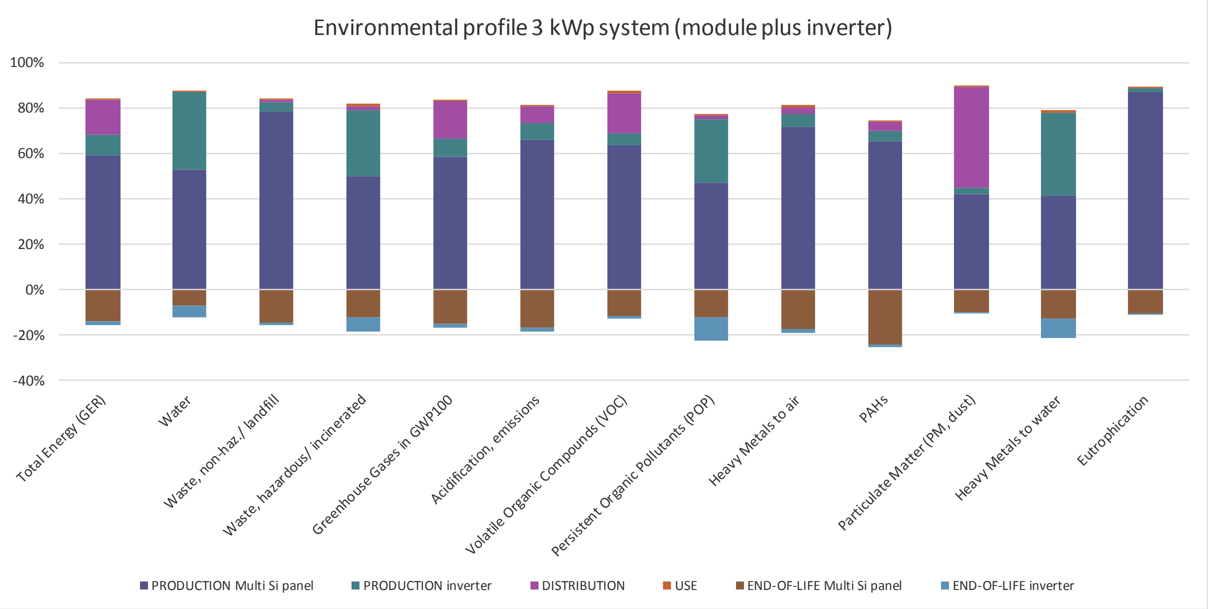

Figure 5: Environmental profile Base-Case 1, 3 kW system

5.2.4.2 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 24 provides the LCIA results in absolute values for a 24.4 kW system. Figure 6 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 24: 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

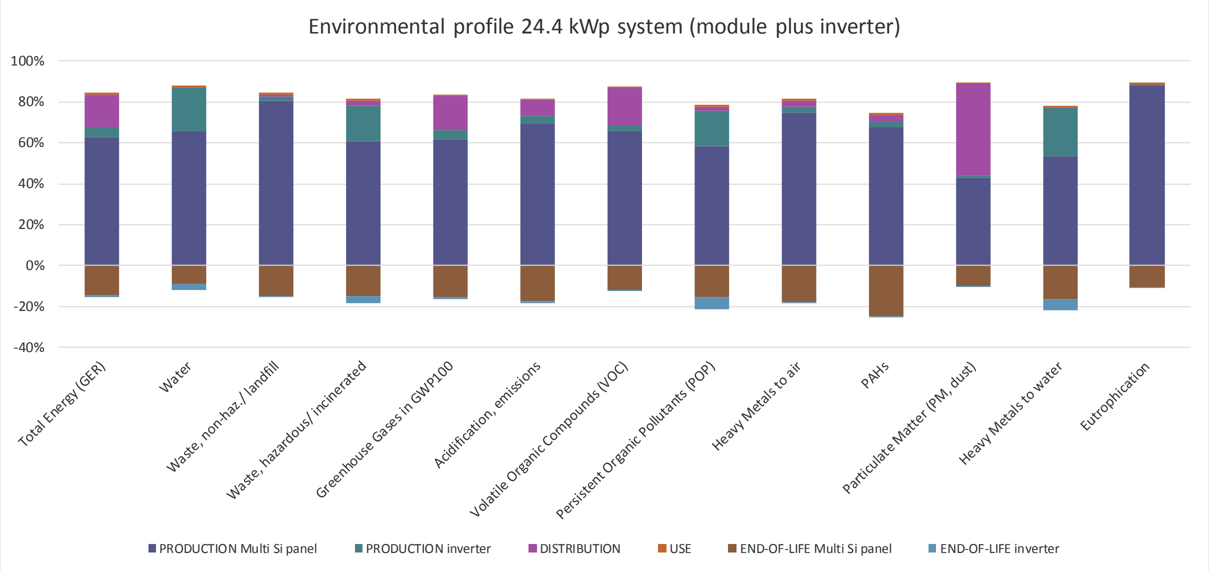

Figure 6: Environmental profile Base-Case 2, 24.4 kWp system

5.2.4.3 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 25 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 7 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.

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 25: 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

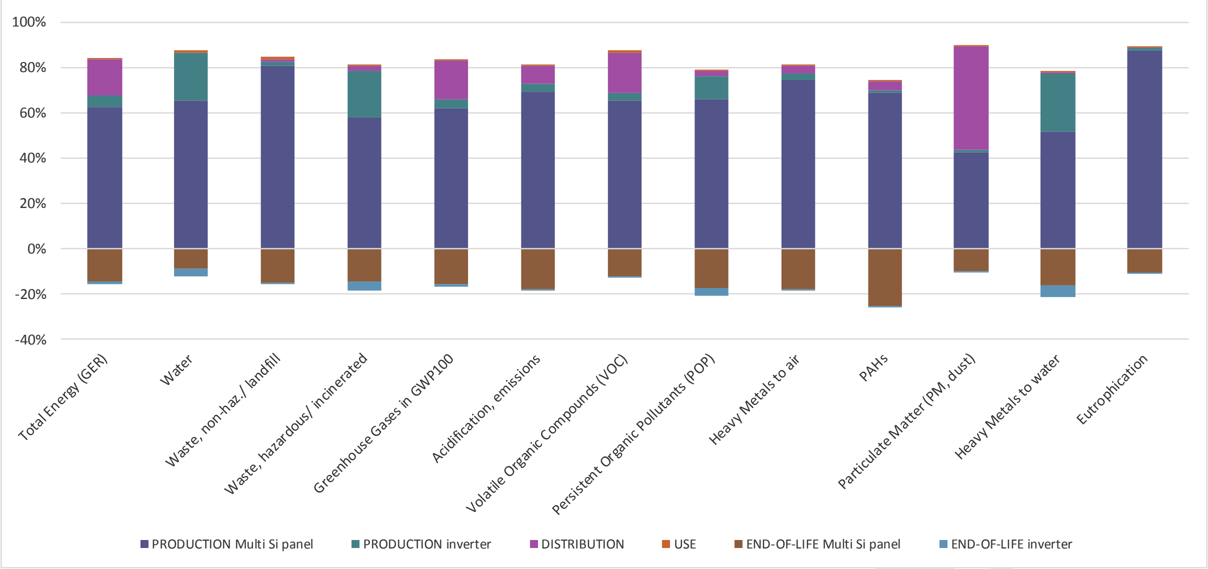

Figure 7: Environmental profile Base-Case 3, 1875 kW system

5.3 Base case life cycle cost for consumer

5.3.1 Introduction to Life Cycle Costing and the relationship with the Levelized Cost of electricity (LCOE) 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 following 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 5.1.1.7).

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[12]. The Levelized cost of electricity (LCOE) is defined for the purpose of these calculations as:

$$\mathrm{LCOE}[€/\mathrm{kWh}] = \frac{\text{net present value of sum of costs of generation over its life time}}{sum\ of\ electrical\ energy\ produced\ over\ its\ life\ time}$$

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 life time 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 life time).
- When **PV systems** are **scaled according to their 'functional unit'** their **Life Cycle Cost(LCC) is the Levelized cost of electricity(LCOE)**.

5.3.2 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.

5.3.3 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 26 based on the input from Table 27 and Table 28. All data has been sourced from previous sections. All module and inverter replacements in the system over its life time are modelled in cost at 1 year after midlife of the system, see 'average all repairs' in Table 27.

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[12] https://setis.ec.europa.eu/sites/default/files/reports/Cost-Maps-for-Unsubsidised-Photovoltaic-Electricity.pdf

Table 26 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 life time	81379.43	kWh

Table 27 Input data used for LCC and LCOE performance modelling

reference Yield, Yr(hours) (in year 1)	1331.00
PR	0.75
Life time (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	2500
Average module repairs/life	0.9%
Average inverter repair/life	300.0%

Table 28 CAPEX and OPEX input data and calculated results

OPEX and CAPEX processing based on LCCinputdata							
event	**Year**	**PWF**	**CAPEX**	**OPEX**	**Y**	**NPV**	**Electricity**
		ratio	**euro**	**euro**	**h**	**euro**	**kWh/year**
installation	1	1	4,832.00 €		998.3	4,832.00 €	2994.75
O&M	2	0.925			991.3	0.00 €	2973.79
O&M	3	0.889			984.3	0.00 €	2952.97
O&M	4	0.855			977.4	0.00 €	2932.30
O&M	5	0.822			970.6	0.00 €	2911.77
O&M	6	0.790			963.8	0.00 €	2891.39
O&M	7	0.760			957.1	0.00 €	2871.15
O&M	8	0.731			950.4	0.00 €	2851.05
O&M	9	0.703			943.7	0.00 €	2831.10
Replace	10	0.676		1,239.99 €	937.1	837.69 €	2811.28
O&M	11	0.650			930.5	0.00 €	2791.60
O&M	12	0.625			924.0	0.00 €	2772.06
O&M	13	0.601			917.6	0.00 €	2752.65
O&M	14	0.577			911.1	0.00 €	2733.38
O&M	15	0.555			904.8	0.00 €	2714.25
O&M	16	0.534			898.4	0.00 €	2695.25
O&M	17	0.513			892.1	0.00 €	2676.38
O&M	18	0.494			885.9	0.00 €	2657.65
O&M	19	0.475			879.7	0.00 €	2639.05

Replace	20	0.456		1,239.99 €	873.5	565.91 €	2620.57
O&M	21	0.439			867.4	0.00 €	2602.23
O&M	22	0.422			861.3	0.00 €	2584.01
O&M	23	0.406			855.3	0.00 €	2565.93
O&M	24	0.390			849.3	0.00 €	2547.96
O&M	25	0.375			843.4	0.00 €	2530.13
O&M	26	0.361			837.5	0.00 €	2512.42
O&M	27	0.347			831.6	0.00 €	2494.83
O&M	28	0.333			825.8	0.00 €	2477.37
O&M	29	0.321			820.0	0.00 €	2460.03
EoL	30	0.308	481.50 €	0.00 €	843.4	148.46 €	2530.13
Total					904.2	6384.06	81379.43

5.4 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 26). 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.

5.5 EU totals

For the energy impact of the current stock of PV systems has been estimated.

5.5.1 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 29. The values have been taken from the ITRPV Roadmap[13], which tracks the module rated power for different cell technologies.

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[13] http://www.itrpv.net/Reports/Downloads/

Table 29. Reference size in Wp of modules installed per segment and technology.

	Multi	Mono	CdTe	aSi	CIGS	HighEff
Rated power residential	270	285	-	-	145	245
Rated power commercial	325	340	-	-	145	375
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 30)

Table 30. 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

5.5.2 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 29. The values have been taken from the market research by GTM and Becquerel Institute[14], which tracks the inverter capacities for different technologies.

Table 31. Reference size of inverters installed per segment and technology.

	Micro	String 1 phase	String 3 phase	Central
Rated power residential (W)	250	3,000	3000.00	-
Rated power commercial (kW)	-	-	25.00	-
Rated power utility (kW)	-	-	-	1,500

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 30)

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[14] http://www.itrpv.net/Reports/Downloads/

Table 32. 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

5.5.3 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 33. 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

5.5.4 EU totals for systems

EU totals have been calculated for the system Base-Cases using the sales in the reference year 2016.

EU totals are calculated using the sales estimates from Table 30, the reference yield (1311 kWh/kW before PR) provided in Table 1 and the calculated environmental impacts for the different Base-Cases. The calculated environmental impacts for the residential Base-Case are available in Table 23, for the commercial Base-Case in Table 24 and for the Utility scale Base Case in Table 25.

Table 34. 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 CO2 eq.	7.35E+07	1.45E+08	1.26E+08	3.45E+08

Acidification, emissions	g SO2 eq.	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

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).

5.6 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.

5.6.1 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.

5.6.1.1 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.

5.6.1.2 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)

5.6.1.3 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 life time. 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.

5.6.1.3.1 Base parameters of the selected studies

Some details of the products investigated in the selected studies are outlined in Table 35.

Table 35: Description of the investigated studies

Study	**Products investigated**	**Type of system/capacity**
Wyss et al. 2015	CdTe, CIS, microcrystalline -Si[15], 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
Chatzisderis 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 Chatzisderis 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 Chatzisderis et al.

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[15] Microcrystalline Silicon is amorphous Silicon, but also contains small crystals

(2016) looked at different thin-film applications. The study from Tschümperlin et al. (2016) looked only at inverters.

5.6.1.3.2 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 Chatzisderis 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 36 below.

Table 36: 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,	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.

	module and BOS.	
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.
Chatzisderis 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.

5.6.1.3.3 Functional unit, system boundaries and life time

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 Chatzisderis 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 Chatzisderis 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 37 provides an overview of the functional unit, system boundaries and life time considered in the selected LCA studies.

Table 37: Functional unit, System boundaries and considered life time

Study	Functional unit	System boundaries	Life time
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)
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
Chatzisderis 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	Review paper: depends on the paper

		studies cover production and use stage; 13 studies cover only the production and 2 cover production and end-of-life	
Tschümperlin et al. 2016	One solar inverter of a given power output with a life time 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

5.6.1.3.4 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 Chatzisderis et al. (2016) report many different environmental impacts (see Table 38). 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[16]): 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 38.

Table 38: 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,	Impact assessment methods according to PEF Guide	Ecoinvent 2.2 – with some	SimaPro 7.3.3

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[16] 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.

	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		adaptations	
Frischknecht et al. 2015	Primary energy demand, Energy payback time, Greenhouse Gas emissions	For GHG: IPCC method (Fthenakis, 2011)	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
Chatzisderis 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, onising radiation, Land use, Agricultural land occupation, urban land occupation, natural land transformation, resource depletion water, Abiotic depletion non fossil,	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

	Abiotic depletion fossil, Solid waste, Cumulative energy demand			
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

5.6.1.3.5 Assumptions

Table 39 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. Lecessi 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 39 are not relevant for inverters.

Table 39: Assumptions

Study	Average yield	Degradation rate	Irradiation	Performance ratio	Average efficiency
Wyss et al. 2015	975 kWh/kWp	0.7% per year	1090 kWh/m^2/yr	/	CdTe: 14% CIS: 10.8% Micro-Si: 10% Multi-Si: 14.7% Mono-Si: 15.1%
Frischknecht et al. 2015	/	/	1700 kWh/m^2/yr	0.75	Multi-Si: 14.2% Mono-Si: 14.5% CdTe: 11.3%

UNEP. 2016	/	/	/	/	/
Lecissi et al. 2016	/	/	1000 $kWh/m^2/yr$; 1700 $kWh/m^2/yr$ 2300 $kWh/m^2/yr$	0.8	Sc-Si PV: 17% mc-Si: 16% CdTe PV: 15.6% CIGS PV: 14%
Chatzisderis et al. 2016	/	/	/	/	/
Tschümperlin et al. 2016	Not relevant, inverters	Not relevant, inverters	Not relevant, inverters	Not relevant, inverters	Not relevant, inverters

5.6.1.3.6 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 40. This table also contains information on data sources of primary and secondary data.

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 40: 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
Chatzisderis 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) from three European manufacturers. 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)[17]: $M = 6.03 * P^{0.68}$ (where M = Mass and P = Power output)	Primary data collected from three European manufacturers. 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

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[17] 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.

5.6.1.3.7 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 CdTe 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 8). 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.

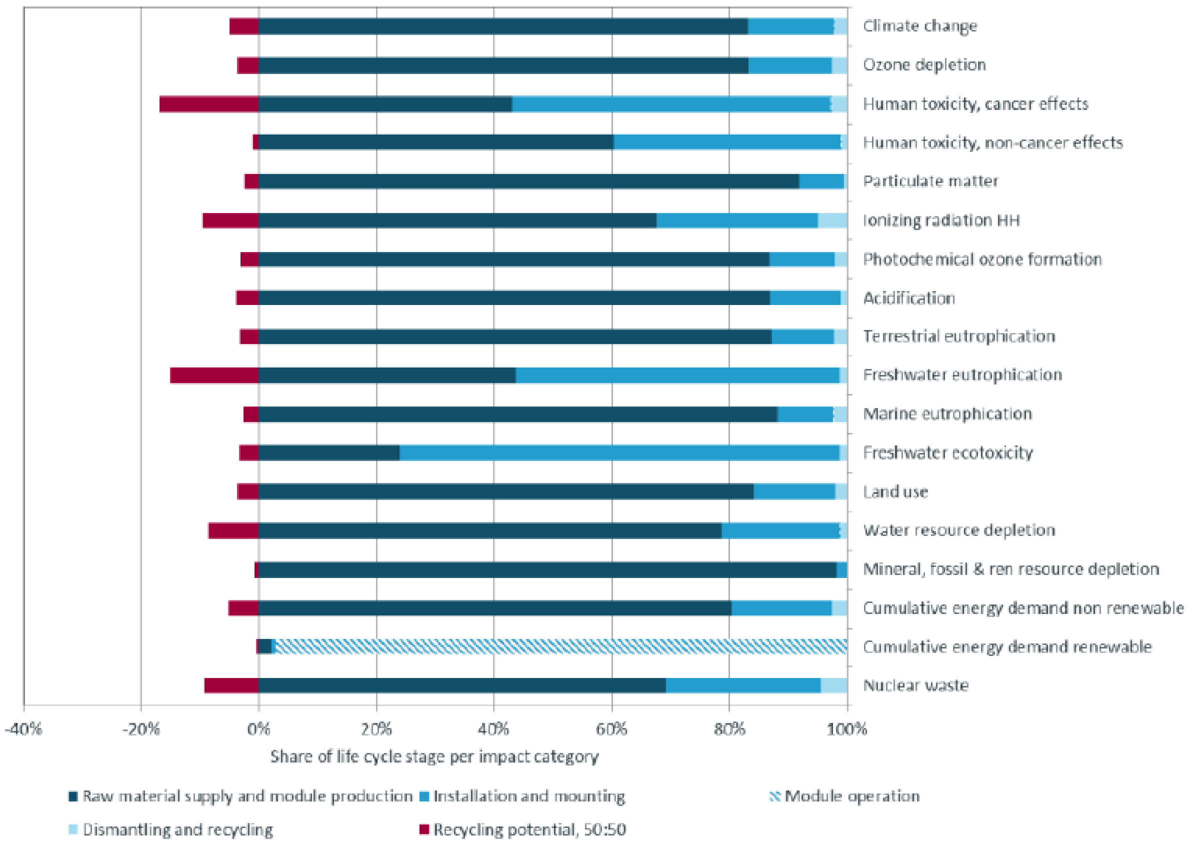


Figure 8 (taken from Wyss et al., 2015): Environmental impact results (characterized, indexed to 100 %) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with average PV modules mounted on a slanted roof. The potential benefits due to recycling are illustrated relative to the overall environmental impacts from production to end-of-life.

IEA, PVPS task 12 (Frischknecht et al., 2015)

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 9 gives the energy payback time (EPBT) estimates of three major commercial PV module types, i.e. mono-Si, multi-Si, and cadmium telluride (CdTe). 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.

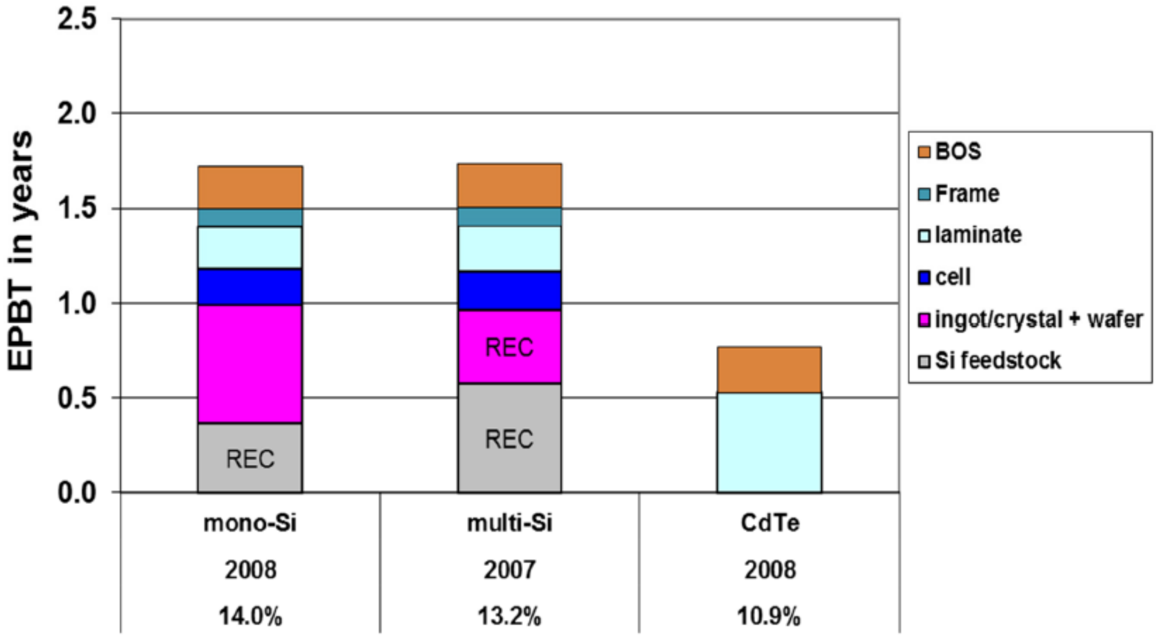


Figure 9: (taken from Frischknecht et al. 2015) Energy payback time (EPBT) of rooftop mounted PV systems for European production and installation under Southern European irradiation of 1700 kWh/m2/yr and performance ratio of 0.75. Data adapted from de Wild Scholten (2009) and Fthenakis et al. (2009). They were harmonized for 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.

UNEP (2016)

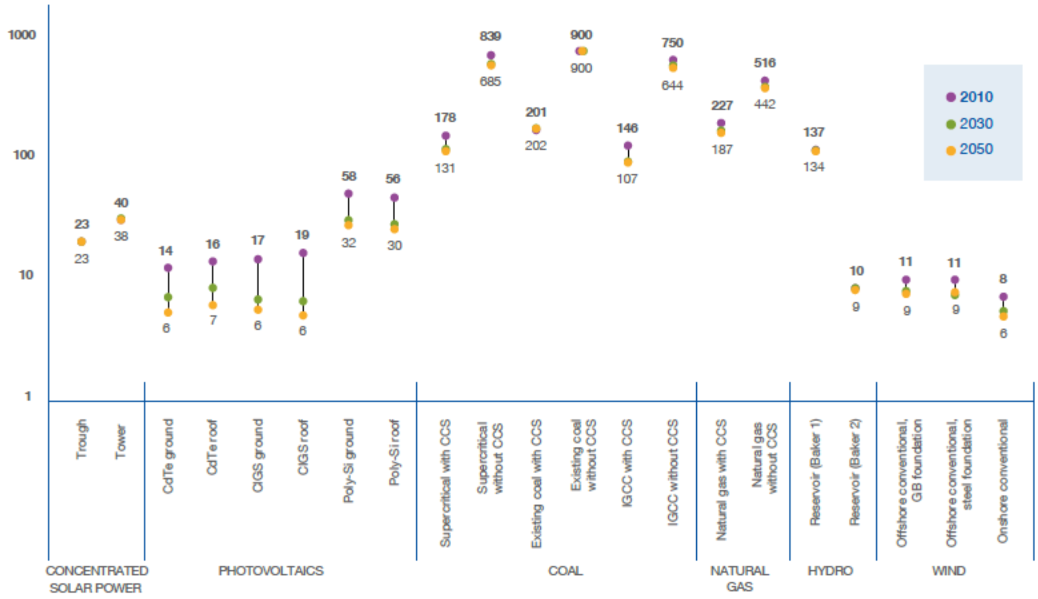
This report compares PV technologies with other energy technologies. It concludes that PV technologies show clear environmental benefits in terms of climate change, particulates, ecotoxicity, human health and eutrophication relative to fossil fuel technologies. However, PV electricity requires a greater 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.

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.



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[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 10: (taken from UNEP 2016) Life-cycle GHG emissions of different energy technologies, in g CO_{2e}/kWh, reflecting application of technology in Europe

Figure 2: Human health impact in disability adjusted life years (DALY) per 1TWh of electricity generated, for Europe 2010 [20].

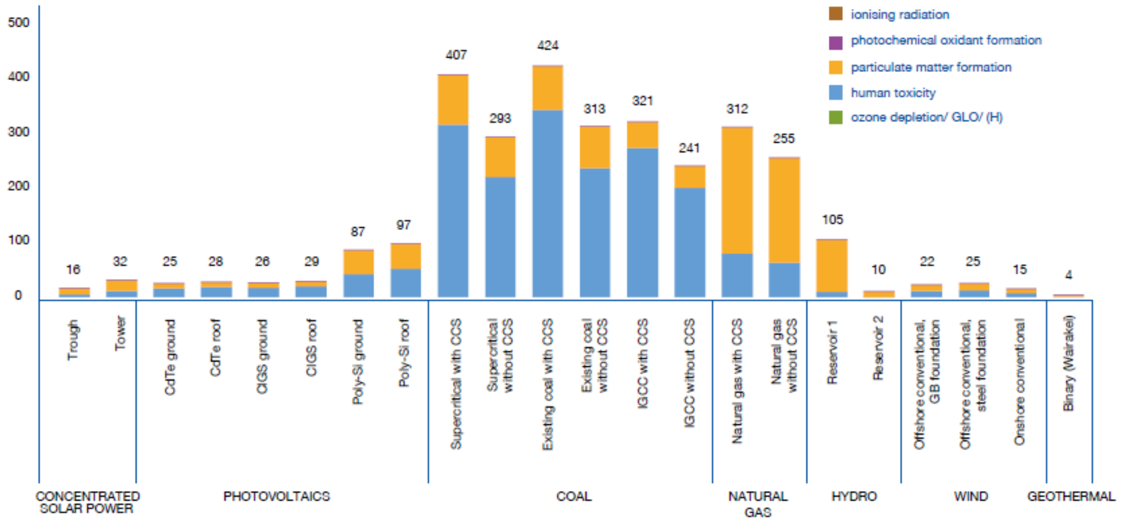

Figure 11: (taken from UNEP 2016) Human health impact in disability adjusted life years (DALY) per 1 TWh of electricity generated, for Europe 2010.

Figure 3: Ecosystem impacts in species-year affected per 1000 TWh of electricity following different damage pathways, reflecting Europe 2010 [23].

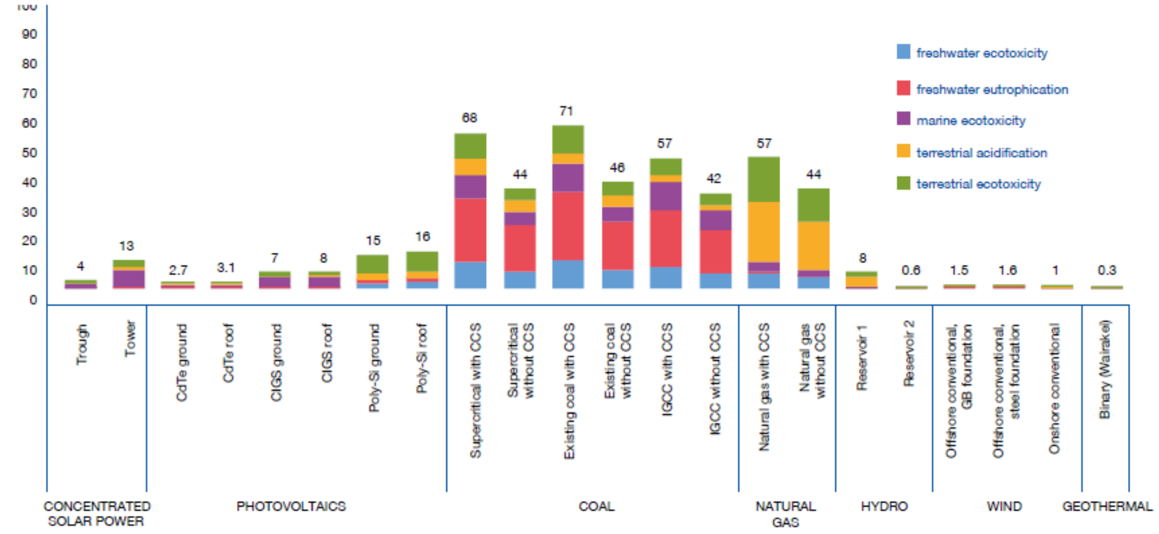

Figure 12: (taken from UNEP 2016): Ecosystem impacts in species-year affected per 1000 TWh of electricity following different damage pathways, reflecting Europe 2010.

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.

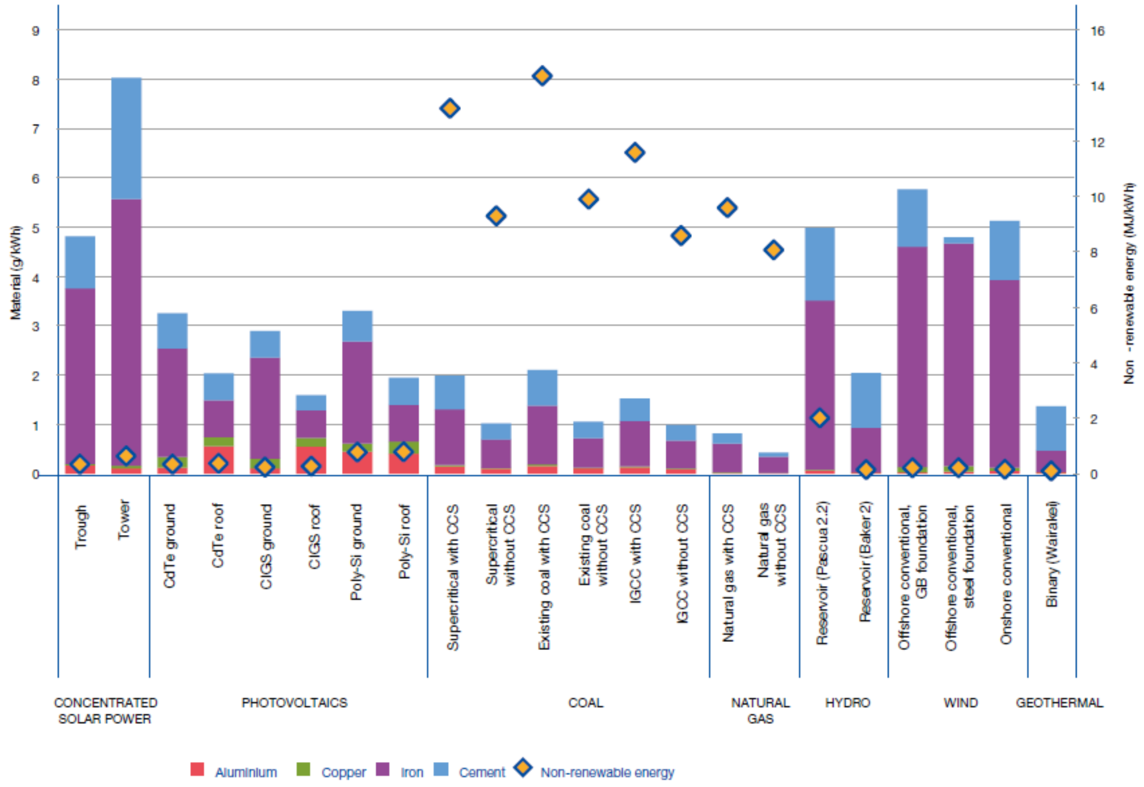

Figure 13: (taken from UNEP 2016) Bulk material and non-renewable energy requirements per unit power produced.

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 41). 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 a remarkable improvement 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 41: Energy pay-back time calculated by Lecissi et al. 2016

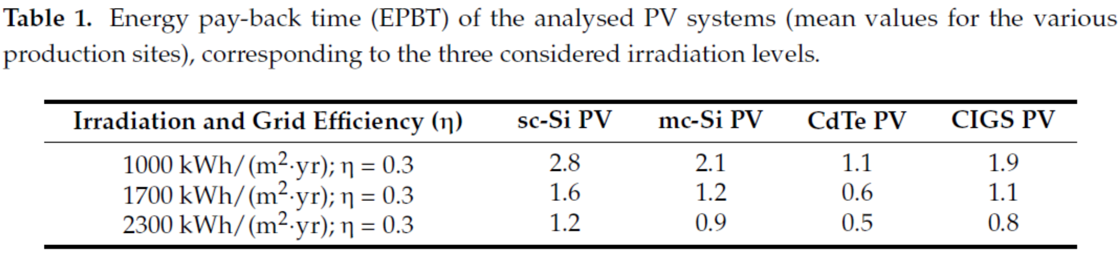

Table 1. Energy pay-back time (EPBT) of the analysed PV systems (mean values for the various production sites), corresponding to the three considered irradiation levels.

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.

5.6.2 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.

5.6.2.1 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.

5.6.2.1.1 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[18].

The IEC 62474 substance declaration list[19] 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 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.

A further revised screening will be necessary in order to identify if any subsequent new additions to the Candidate List in 2016-2018 are of relevance.

5.6.2.1.2 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 42.

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

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[18] ECHA, Candidate List of substances of very high concern for Authorisation, Accessed November 2018, https://echa.europa.eu/candidate-list-table

[19] International Electrotechnical Commission (IEC), IEC 62474: Material declaration for products of and for the electrotechnical industry, http://std.iec.ch/iec62474

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.

Table 42: 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)	

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 43.

Table 43. 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.

In relation to back sheet materials, 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, PVDF), 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 44 and Table 45. These flame retardants are potentially relevant for internal electrical components of an inverter and for a module junction box.

The type of flame retardants 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 a polymer back sheet.

Table 44. 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 45. 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

As was identified in Task 2, the application of repellent coatings to module glass can reduce the accumulation of dust and dirt on the surface, thereby reducing performance losses[20]. 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 degradation or 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, although it is not clear whether anti-soiling properties require additional more complex chemistries.

The substitution of repellents in other sectors 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. 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[21].

5.6.2.1.3 Substances restricted by the RoHS Regulation

Despite solar photovoltaic products being exempted from the requirements of the RoHS Regulation it is understood that manufacturers in the sector differentiate themselves by claiming 'RoHS compliance' for substances 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 useage:

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%.

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[22]. 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.

Cadmium

The thin film technologies CdTe and CIGS both contain cadmium in their semi-conductor layers. CdTe modules contains cadmium telluride and 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. CIGS modules contain cadmium sulphide but data could not be found on the concentration. Two CIGS manufacturers - Solar Frontier and Steon - claim that they manufacture modules with 'RoHS compliant' cadmium concentrations of less than 0.01%.

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[20] Voicu et al, Anti-soiling coatings for PV applications, Presentation made by DSM at PV Module Technology & Applications Forum 2018, 29th January 2018.

[21] 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.

[22] 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

5.6.2.2 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 23. 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[24] is a byproduct of crystalline silicon production[25] 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 [26]. It is also understood that it can be used as a raw material for further polysilicon production and also to manufacturer fibre optics [27]. Further information is required on the abatement strategies adopted by the sector.

5.6.2.2.1 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.

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 x for end-use shares). A high potential (95%) for economically feasible recycling has been identified.

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.

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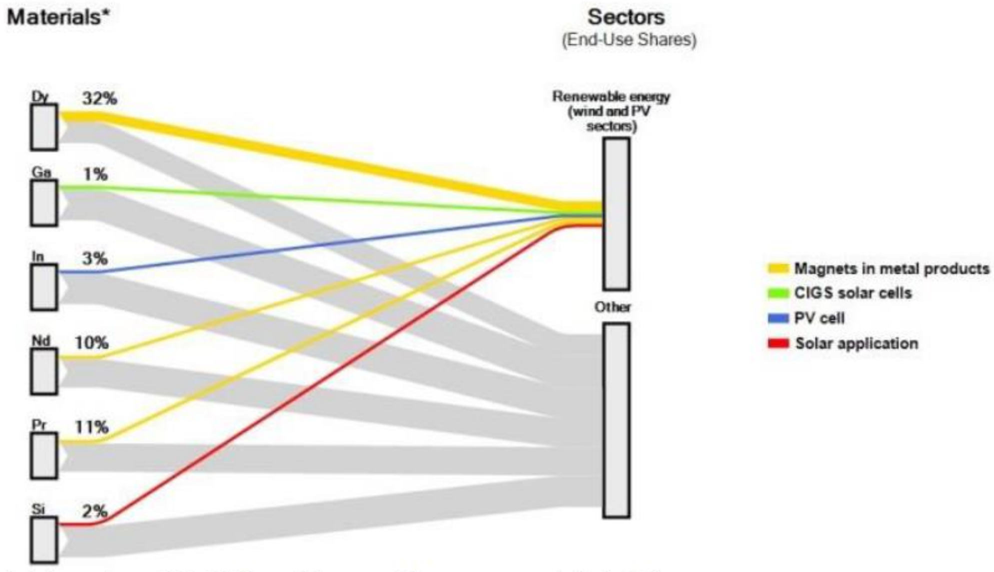
[23] Wild-Schoten,M.J. et al, *Fluorinated greenhouse gases in photovoltaic module manufacturing: potential emissions and abatement strategies*, 22nd European Photovoltaic Solar Energy Conference, Milano, Italy, 3-7 September 2007

[24] https://pubchem.ncbi.nlm.nih.gov/compound/Tetrachlorosilane#section=2D-Structure

[25] Dustin Mulvaney et al., 2009, 'Toward a Just and Sustainable Solar Energy Industry - A Silicon Valley Toxics Coalition White Paper'

[26] Yanh.H, Huang.X and J.R.Thompson, *Tackle pollution from solar panels*, Nature, 2014/05/28/online

[27] 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



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

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

Source: European Commission (2018)

5.6.2.3 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*.'

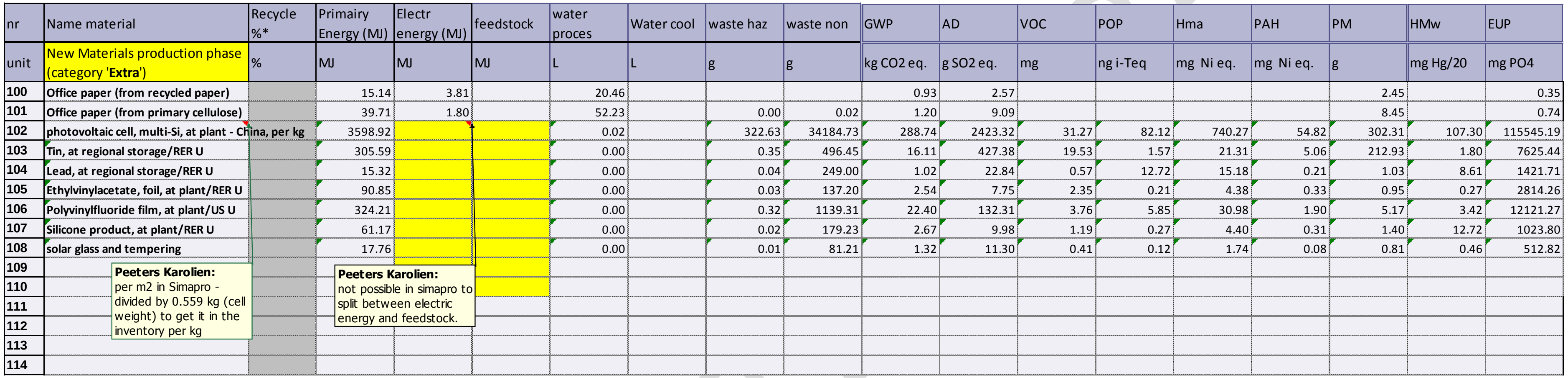
Mining in the Great Lakes region of Africa, a conflict area, is recognised as a major source of minerals and according to sources under dangerous conditions, and without sufficient maintenance of health and safety standards and in some cases by children.

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.

Annex A: 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			0.02		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			0.00		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			0.00		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			0.00		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			0.00		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			0.00		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			0.00		0.01	81.21	1.32	11.30	0.41	0.12	1.74	0.08	0.81	0.46	512.82
109																		
110																		
111																		
112																		
113																		
114																		

Peeters Karolien:
per m2 in Simapro - divided by 0.559 kg (cell weight) to get it in the inventory per kg

Peeters Karolien:
not possible in simapro to split between electric energy and feedstock.

Annex B: 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 C: 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 heterojur	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 Env	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 Environme	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/r		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 m	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 of	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 ecoto	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,	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													

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