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Draft Report Task 6: Assessment of BAT, design options and improvement potential

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List of abbreviations and acronyms

Abbreviations	Descriptions
AC	Alternating Current
AD	Acidification
AR	Anti-reflection
BAT	Best Available Technology
BNAT	Best Not yet Available Technology
BOM	Bill-of-Materials
BOS	Balance of System
BSF	Back-surface field
CAPEX	Capital Expenditure
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide solar cells
CRM	Critical Raw Material
DC	Direct Current
DQR	Data Quality Rating
DR	Derating
EEG	Erneuerbare-Energien-Gesetz
EF	Environmental Footprint
EoL	End-of-Life
Eq.	equivalent
EU	European Union
EUP	Eutrophication Potential
EVA	Ethylene vinyl acetate
FU	Functional Unit
GER	Gross Energy Requirement
GLO	Global
GWP	Global Warming Potential
HDPE	High Density Polyethylene
Hma	Heavy metals to air
HMw	Heavy metals to water
IBC	Interdigitated Back-contact
IEC	International Electrotechnical Commission
IGBT	Insulated-gate bipolar transistor
IRTPV	International Technology Roadmap for Photovoltaic
JRC	Joint Research Centre
LAN	Local Area Network
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
LCOE	Levelised Cost Of Energy
LeTID	Light and elevated Temperature Induced Degradation
LLCC	Least Life Cycle Cost
MEErP	Methodology for Ecodesign of Energy related Products
MLI	Module Level Inverter
MOSFET	Metal oxide semiconductor field effect transistor
MTBF	Mean Time Between Failure

Abbreviations	Descriptions
O&M	Operation and Maintenance
OPEX	Operational Expenditure
PA	Polyamide
PAH	Polycyclic Aromatic Hydrocarbons
PEF	Product Environmental Footprint
PERC	Passivated Emitter and Rear Contact cell
PERCbi	Passivated Emitter and Rear Cell bifacial
PERL	Passivated Emitter with Rear Locally diffused cells
PERT	Passivated Emitter with Rear Totally diffused cells
PERx	Passivated Emitter with Rear X (Contact, Locally diffused, Totally diffused)
PET	Polyethylene Terephthalate
PM	Particulate Matter
PO	Package Option
POP	Persistent Organic Pollutants
PV	Photovoltaics
PVDF	Polyvinylidene fluoride
PVGIS	Photovoltaic Geographical Information System
PWF	Present Worth Factor
RER	Europe
SHJ	Silicon Heterojunction
SO	System Option
VDMA	Verband Deutscher Maschinen- und Anlagenbau
VOC	Volatile Organic Compounds
WBG	Wide Band Gab inverter

6. Task 6: Assessment of BAT, design options and improvement potential

6.0 General introduction

This task aims at identifying the design options of the photovoltaic product group, their monetary consequences in terms of Life Cycle Cost for the user, their economic and possible social impacts, and pinpointing the solution with the Least Life Cycle Costs (LLCC) and the Best Available Technology (BAT).

The assessment of monetary Life Cycle Costs is relevant to indicate whether design solutions might impact the total user's expenditure over the total product life (purchase, operating, end-of-life costs, etc.). The distance between the LLCC and the BAT indicates — in a case a LLCC solution is set as a minimum target— the remaining space for product-differentiation (competition).

The BAT indicates a target in the shorter term that would probably be more subject to promotion measures than to restrictive action. The BNAT indicates possibilities in the longer term and helps to define the exact scope and definition of possible measures. Any intermediate options between the LLCC and the BAT have to be described, and their impacts assessed.

The scope of the photovoltaic product group ~~is~~was determined in Task 1 and the ~~sectors~~market segments that have been analysed are the following:

- Residential: up to 10 kW
- Commercial: from 10 to 100 kW
- Utility: above 100 kW

6.0.1 Identification of design options and assessment of their impacts

Available design options will be identified by investigating and assessing the environmental impact and LCC of each suggested design option against each Base-Case (using the MEErP EcoReport 2014):

- The design option should not have a significant variation in the functionality, the quality ~~of the produced products~~ and in the primary or secondary performance parameters compared to the Base-Case and in the product-specific inputs. In fact the improvements in eco-design parameters may be realised by achieving improvements in quality.
- The design option must have a significant potential for improvement regarding at least one of the following ecodesign parameters and without deteriorating others:
  - the consumption of energy, water and other resources,
  - use of hazardous substances,
  - emissions to air, water or soil,
  - weight and volume of the product,
  - use of recycled material,
  - quantity and nature of consumables needed for proper use and maintenance,
  - ease for reuse and recycling,
  - extension of lifetime or amounts of waste generated.

- The design option should not entail excessive costs. Impacts on the manufacturer must be investigated regarding redesign, testing, investment and/or production costs, including economy of scale, sector-specific margins and market structure, and required time periods for market entrance of the design option and market decline of the current product. The assessment of the monetary impact for categories of users includes the estimation of the possible price increase due to implementation of the design option, either by looking at prices of the product on the market and/ or by applying a production cost model with sector-specific margins.

For each of the identified design options, it ~~must~~ shall be described:

- if Member State, Community or Third Country legislation and/or standards are available regarding the design option;
- how market forces may address the design option;
- how large the disparity is in the environmental performance of the product available on the market with equivalent functionality compared to the design option.

The analysis carried out in task 5.2 also has the intention of identifying environmental 'hotspots'., If these hotspots differ from the findings of Ecoreport tool they may then also be taken into account, if relevant~~ to the extent of Ecodesign/Energy Labelling~~, in the analysis under tasks 6 and 7, provided that the life cycle cost is properly assessed.

6.0.2 Summary of how the functional unit for LCA and LCOE results has been calculated

The functional unit used for the calculation of environmental impacts and levelis~~z~~ed cost of energy is '1 kWh of electricity generated~~ in one year~~' taking into account the total electricity generated during a notional 30 year lifetime. The environmental impacts are expressed per kWh of electricity generated. The lead impact category according to the conclusions in Task 5 is the C~~c~~umulative E~~e~~nergy D~~d~~emand (CED), also referred to as~~ or~~ primary energy consumption.~~ ~~At module level, the primary energy results do not include the electricity generated by the module. Instead the primary energy is a function of the life time energy yield. To get the results per kWh produced, environmental impacts are first calculated per m^2 of module and per inverter. Then the area of modules and amount of inverters needed to generate 1 kWh electricity is calculated using module and inverter efficiencies and derate factors. Area and amount necessary per kWh are then multiplied with the environmental impact per m^2 of module

PV system yield over years is calculated in line with the transitional method under development by JRC unit C2. However, in this part of the study more derate factors have been used. The additional derate factors made possible a more detailed differentiation between the package and system options.

The task 5 report includes an introduction to Life Cycle Costing and Levelis~~z~~ed Cost of electricity (LCOE) (section 5.3.1). LCOE is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment (including module and inverter costs), operations and maintenance, cost of fuel and cost of capital. It is commonly applied to evaluate PV system costs[1]. The Levelis~~z~~ed cost of electricity (LCOE) is defined for the purpose of these calculations as:

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

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

The LCOE calculation of costs per kWh generated aligns with the functional unit defined in Task 1. In this definition the life cycle environmental impacts of the PV system or component are normalized to 1 kWh of electricity produced by the system/component.

The LCOE results present the cost of supplying each kWh to the grid. ~~They~~ It does not present revenue~~s~~ streams for PV owners. Revenues for PV owners depend on the market/subsidy prices.

Table 1. Overview of design options for photovoltaic modules (the options selected for further analyses are highlighted in grey).

Design options	**Description**	**Rationale for the selection of design options for further analyses**
Option 1: Optimised ~~multi~~ PERC~~BSF~~ Si 2020	Optimized ~~BSF~~ PERC modules as of today (2020~~19~~): - Mono crystalline PERC - white EVA - more busbars (6) - better glass (AR properties) - factory quality control measures - thinner wafer Note: ~~this is not PERC~~ See ~~F~~further details in Table 4.	Expected to become the 2020 mainstream module product ~~PERC~~ which can substitute ~~Within BSF modules also some progress is expected compared to~~ the base case of Task 5
Option 2: BAT PERC 2019	The 2019 best m~~M~~ono Si PERC cells with also thinner wafers	The best PERC (BAT) as found on the market Q2/2019~~Expected mainstream improvement option~~
Option 3: BAT PERCbi 2019 (~~B~~bifacial)	Bifacial PERC cells ~~and~~ with a glass backsheet	Expected to have a higher yield when applied at utility scale and moreover they do not have a halogenated back sheet . It can also model mono-facial glass on glass modules.
Option 4: CdTe	Thin film CdTe	Showed lower carbon footprint and GER in the LCA review in Task 5
Option 5: CIGS	Thin film CIGS	Showed lower carbon footprint and GER in the LCA review in Task 5
~~Option 6: Kerfless old~~	~~Epitaxial Si/Ribbon Si~~	~~Could reduce energy intensive wafer manufacturing~~

Option 76: SHJ	Silicon heterojunction	Silicon heterojunction (SHJ) cells offer high efficiencies, yield and several advantages in the production process compared to conventional crystalline silicon solar cells (Louwen et al, 20152) SHJ could minimisze the use of silicon raw material that hasd an important GWP/Primary energy impact.
Option 78: BAT PERC 2025	BAT PERC 2019 with further improvements in the BOM, e.g.including: – kerf loss recycling, – halogen free backsheet, – factory quality inspections, – reduced glass thickness (2mm), – reduced wafer thickness (120 µm) and kerf losses (50 µm). – BetterLow factory defect rate (all other options 1,5%, here 0%)MSi base case module	Could reduce energy intensive Metallurgical grade Silicon wafer manufacturing due to recycling within the manufacturing process, also some other bill of material improvements are added. Module manufactured with a more favourable grid emissions factor for electricity (EU average and best performing Member State- Sweeden)
Option 9: BNAT PERCbi 2025 incl. Wafer recycling	PERC bifacial cells (PERC 2019) + BNAT option for wafer recycling *Recycle wafers for new cells (BNAT):* this is an ambitious recycling route. It will require additional process steps such as etching to recover wafers but is considered technically feasible. Amongst others it will also require to remove the backsheet. Likely this can only be applied to ain a closed loop circular economy model where modules return to their original manufacturer for recycling [3].	*Partially modelled:* Could reduce energy intensive Metallurgical grade Silicon wafer manufacturing due to the extended life time of cells as a component of modules, (*e.g. via cell or wafer recyclingreuse/remanufacturing or recycling*).,

[2] Louwen A., van Sark W.G.J.H.M., Schropp R.E.I., Turkenburg W.C., Faaij A.P.C. 2015. Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs. Progress in photovoltaics: research and application. 23:1406-1428. Doi: 10.1002/pip.2540

[3] Note that also weaker options for cell recycling exist, e.g. refurbishing second hand modules with less invasive steps such as inspection, glass cleaning and coating, replace the bypass diode, etc. These can extend the insitu cell life time beyond the 30 years.

Option 10: Interdigitated Back-contact (IBC)t	Compared to solar cells with two contact sides, back-contact solar cells have both contact polarities on the rear side which significantly reduces shading losses from contacts optical losses at the illuminated front side both from cell metallization and cell-to-cell interconnection (task 4 report), such improvements relies on interdigitated Back Contact (IBC) Technology, some manufacturers have already placed these products this on the market and itthey can provide the highest commercial modules efficiencies.	*Not selectedpossible to model:* The benefits of the higher module effiency can easily be modelled but there is no reliaaible quantitatiave data available to model the negative impacts from this increased manufacturing complexity and no manufacturer providedbecause of propietory processes it was not possible to obtain time representative sufficient data for thismodelling purposes.. Therefore this option is not further modelled
Option 11: BNAT Perovskite	Perovskite based thin film PV is not yet in production, but this technology has made remarkable progress in the past few years. Because of its potential of very low-cost production, and its suitable bandgap for tandem formation with crystalline silicon, it could be (or pave the way for) a significant and disruptive technology PV energy generation (task 4 report)	Not selectedpossible to model: BNAT and a lack of sufficient and suitable LCA data to model.
Option 12: BNAT Perovskite/Si-tandem	The start-up Oxford PV showed that the tandem configuration has the potential to outperform single junction Si PV with efficiencies over 22%. They have acquired a production facility in Germany targeting tandem pilot production by 2019-2020 (task 4 report).	*Not selectedpossible to model*: BNAT and a lack of sufficient and suitable LCA data to model.
Option 13: BNAT kerfless silicon	Kerfless wafer production which eliminates the need for the slicing of silicon blocks or ingots to obtain the wafer substrate.	It is anticipated to reduce the energy intensive wafer manufacturing step.

Table 2. Overview of design options for inverters (the options selected for further analyses are highlighted in grey).

Design options	Description	Rationale for the selection of design options for further analyses
Residential		
Option 1: more efficient	This design option represents the potential for improvement on the Euro efficiency of the base case	The focus of Ecodesign and Energy label is on the energy efficiency during the use phase
Option 2: longer life time	This design option represents the potential for extension of the design lifetime of the base case	Reducing the number of inverter replacements during the PV system lifetime will minimise environmental impacts and improve material efficiency
Option 3: repair (repaired)	This design option represents the extent to which a product is designed for repair along its lifetime	Repairing and replacing components to achieve a longer design life will minimise the environmental impacts and improve material efficiency
Option 4: monitor/smart	This design option represents the potential for monitoring to diagnose and react to faults related to firmware or hardware. It can help additionally the consumer to adjust their demand to increase self-consumption	Early fault detection and reaction can reduce downtime and maximise energy efficiency during the use phase
Option 5: Module Level I~~Co~~nverter (MLI)	This design option represents the installation of module level inverters that may increase yield in mismatch conditions	Shifting to inversion at the module level may bring system level benefits, such as maximising energy efficiency during the use phase
Option 6: Hybrid storage worst performer (peak shaving)	These design options represent the installation of inverter with integrated storage to either: - provide peak shaving in feed in (German EEG case). - increase hourly and quarterly self-consumption	A trend has been observed for households to want to increase~~ing~~ their self-consumption by integrating battery storage. However, this may introduce losses in the total amount of renewable electricity generated which should be avoided or minimised. There is also the potential to achieve marginal emissions reduction by displacing peak power generating plants in the evening
Option 7: Hybrid storage best performer (load following)		
Commercial		
Option 8: More efficient	This design option represents the potential for improvement on the Euro efficiency of the base case	The focus of Ecodesign and Energy label is on the energy efficiency during the use phase

Option 9: Repair (repaired)	This design option represents the extent to which a product is designed for repair along its lifetime	Repairing and replacing components to achieve a longer design life will minimise the environmental impacts and improve material efficiency
Option 10: Wide band gap iconverter (WBG)	This design option represents the installation of inverters which transistors are completely based on new semiconductor materials with a wide band gap	Not selected possible to model/not selected: – cConsultation of with manufacturers revealed that the benefits and possible trade-offs of this design option are not apparent at this stage
Utility		
Option 11: More efficient	This design option represents the potential for improvement on the system level efficiency of the base case	The focus of Ecodesign and Energy label is on the energy efficiency during the use phase
Option 12: More efficient plus combiner strings	This design option represents the potential for improvement on the Euro efficiency of the base case	Shifting to inversion up the string level may bring system level benefits, such as maximising energy efficiency during the use phase. However, there may be a trade-off in material efficiency
Option 13: Wide band gap coinverter (WBG)	This design option represents the installation of inverters which transistors are completely based on new semiconductor materials with a wide band gap	Not selected – consultation of manufacturers revealed that the benefits and possible tradeoffs of this design option are not apparent at this stage.

Table 3. Overview of design options for systems (the options selected for further analyses are highlighted in grey).

Design options	Description	Rationale for the selection of design options for further analyses
Residential		
System Options		
System Option 1: Multi Optimiszed PERC 2020 Si optimised + best inverter (SO 1)	This option combines the best module with the best inverter (longer life and monitoring)	An obvious combination of all the best at component level in a system to be compared to a standard design with base case components
System Option 2: Multi Si oOptimised PERC 2020 + best inverter + better design (SO 2)	This system combines the best module with the best inverter (longer life and monitoring) and includes a better design by installer	An obvious combination of all the best at component level in a system to be compared to a standard design with base case components Derating factors are adapted to reflect the better design
System Option 3: Multi SiOptimizsed PERC 2020 optimised + best inverter + optimised O&M (SO 3)	This system combines the best module with the best inverter and includes optimized operation and maintenance routine.	This would introduce practices from the large-–scale segment including remote monitoring, repair response or early failure detection and cleaning routines.
Package option 1 (PO 1)	Multi Si module and reference inverter	
Package option 2 (PO 2)	Multi Si optimisedOptimiszed PERC 2020 module and reference inverter	
Package option 3 (PO 3)	BAT PERC 2019 module and reference inverter	
Package option 4 (PO 4)	CIGS module and reference inverter	
Package option 5 (PO 5)	Kerfless (old) module and reference inverter	
Package option 56 (PO 65)	Silicion heterojunction module and reference inverter	
Package option 6 (PO 6)	BAT PERC 2025 module and reference inverter	
Package option 7 (PO 7)	BNAT kerfless (new) module and reference inverter	

Package option 78 (PO 87)	Multi Si module and more efficient inverter	
Package option 97 (PO 97)	Multi Si module and longer life inverter	
Package option 190 (PO 109)	Multi Si Module and inverter with repair	
Package option 110 (PO 110)	Multi Si module and inverter including monitoring	
Package option 121 (PO 121)	Multi Si module and multi-level inverter	
Package option 132 (PO 132)	Multi Si module and inverter including storage (worst case)	
Package option 143 (PO 143)	Multi Si module and inverter including storage (best case)	
Commercial		
System Options		
System Option 1: best combination and design (SO 1)	Improved design, this is a combination of all the best options at component level in a system including bifacial modules (BAT PERCbi 2019) with a more with reflective roof surface. This option also assumes higher derating factors due to lower cable losses, shading and module mismatch losses because of a tailored design	This is an all best combination to be compared to a standard design with base case components. PERC bifacial + higher derating factors due to lower cable losses, shading and module mismatch because of a tailored design
Package option 1 (PO 1)	Multi Si module and reference inverter	
Package option 2 (PO 2)	OMulti Si optimised PERC 2020 module and reference inverter	
Package option 3 (PO 3)	BAT PERC 2019 module and reference inverter	
Package option 4 (PO 4)	BAT PERC bifacial 2019 module and reference inverter	
Package option 5 (PO 5)	CdTe module and reference inverter	
Package option 6 (PO 6)	BAT PERC 2025 module and reference inverter	

Package option 7 (PO 7)	BNAT PERCbi 2025 + recycled wafer module and reference inverter	
Package option ~~6~~8 (PO ~~6~~8)	Multi Si module and more efficient inverter	
Package option ~~7~~9 (PO 9~~7~~)	Multi Si module and inverter with repair	
Utility		
System Options		
System Option 1: best combination and design including single axis tracker (SO 1)	System with single axis tracker, CdTe modules and energy efficient string inverter	Single axis trackers can provide higher yield at the expense of a slewing drive worm gear and motor for a series of modules
Package option 1 (PO 1)	Multi Si module and reference inverter and reference BOS	
Package option 2 (PO 2)	~~Multi Si o~~Optimised PERC 2020 module and reference inverter and reference BOS	
Package option 3 (PO 3)	BAT PERC 2019 module and reference inverter and reference BOS	
Package option 4 (PO 4)	BAT PERC~~-~~bi~~facial~~ 2019 module and reference inverter and reference BOS	
Package option 5 (PO 5)	CdTe module and reference inverter and reference BOS	
Package option 6 (PO 6)	BAT PERC 2025 module and reference inverter and reference BOS	
Package option 7 (PO 7)	BNAT PERCbi 2025 + recycled wafer module and reference inverter and reference BOS	
Package option ~~6~~8 (PO 8~~6~~)	Multi Si module and more efficient inverter and reference BOS	
Package option 9~~7~~ (PO ~~7~~9)	Multi Si module and more efficient string inverter and reference BOS	

6.1 Overview of the selection of single design options

6.1.1 PV modules

6.1.1.1 Assumptions regarding the selected selected fundamental cell and module design optionsdesign options

Table 4Table 5 below provides the assumptions for the selected design options. The modules can be used for residential, commercial and utility scale applications. The design parameters remain identical. Table 4Table 5 also provides the estimated additional costs per Wp. A notional life-time of 30 years has been assumed for all modules, reflecting the point in time where, according to most commercial power guarantees, the performance would drop to below 80-85% of the initial performance as measured under STC.

The Base-Case as defined in Task 5 represents a multi Si BSF module with reference year 2016. The technology of the multi Si base case has been improved since 2016. This has been considered in the Base-Case 'optimiszed sSilicon design multi-Si'. It is assumed that technology will further improve, following the innovations described in the according to the VDMA IRTPV roadmap., BSF will no longer have a relevant market share and will be replaced by mainstream PERC type cells by as early as 2020. The expected improvement measures are provided in Table 4.

Table 4: Expected improvement of the multi Si modules (year 2020 and 2025)

Production step	Selected improvement measures	
	Optimised BSF process and materials 2020	Optimised Further optimisations in BoMBSF 2025
Wafer production	MultiMono crystalline with diamond wire sawing with larger wafer size than>156x156 mm² 170 um wafer thickness and 80 75 µm of kerf loess	Epitaxial Wwafer production with larger wafer size than>156x156 mm² and wafer thickness of 120 µm and no50 µm of kerf loess with recycling (85% of kerfloss remelted)
Semi-conductor preparation e.g. passivation	Bifacial PERC p-type mono wafer cell without passivation	SHJ PERC on np-type mono Si wafer
Cell metallisation	Reduced Ag to 850 mg/cell and Al to < 200 mg/cell	Reduced Ag (70 mg/cell) and Pb-free cell metallization paste with ≤ 0.1% module weight90 mg/ml and Al< 200 mg/cell
Cell stringing	Full-cells and 5BB interconnection	Half-cell, busbarless cells with copper interconnection with Pb-free soldering
Cell encapsulation	GlassReduced front glass-glass withickness 3.2 mm glass	Front gGlass-non fluorinated backsheet glass Glass with AR and anti-soiling coating with and < 3.2.5 mm glass thickness
Module power	340 Wp for 72-cell modules	44380 Wp for 72-cell modules
Degradation rate	0.67%	0.5%

~~Performance warranty~~	~~25 years~~	~~30 years~~
~~Factory quality inspection~~	~~Infrared + Electroluminescence/ Lock in thermography~~	~~Infrared + high-resolution Electroluminescence/Lock in thermography~~ ~~Light/Potential Induced Degradation assessment~~

Table 4~~Table 5~~ contains the performance assumptions for the different module technologies, including the degradation rates that have been used for further modelling. Degradation rates cannot in practice be ~~simply put into~~expressed as a ~~"~~'single~~"~~' number, even for the same technology. There are ~~high~~significant possible variations depending on the case, the climate/site conditions, etc. ~~We chose to use t~~The 0.5%-0.7% range has been selected based on the two most extensive and largely cited studies: Jordan et al (2012)[4] and Ishii et al. (2017)[5].

For bifacial PV, there is not yet enough feedback from the field ~~feedback~~ made publicly available so assumptions have had to be~~en~~ made for this technology options.

For the degradation rate~~s~~ of CIGS, the ~~degradation rates~~rate used represents field observed rates and is based on Ishii et al. (2017).

For CdTe the degradation rate is taken from the Series 6 product data sheet (NREL)[6] (0.5%). This long term rate is complemented by an initial, burn-in degradation of 2%.

The costs specified in Table 4~~Table 5~~ are applicable to mid 2018. The cost for the last two BAT and BNAT options has a higher degree of uncertainty because they are 'composite' products that do not exist in this form on the market.

[4] D.C. Jordan and S.R. Kurtz in NREL/JA-5200-51664 (2012)
[5] T. Ishii et al. Prog. Photovolt: Res. Appl. 2017; 25:953–967

[6] First Solar, *Series 6 data sheet*, http://www.firstsolar.com/en-EMEA/-/media/First-Solar/Technical-Documents/Series-6-Datasheets/Series-6-Datasheet.ashx

Table 4~~5~~: Design option parameters

Acronym	Multi Si – Base Case	~~Multi Si optimized~~Optimis~~z~~ed PERC 2020	BAT PERC 2019	BAT PERCbi ~~bifacial~~2019	CdTe	CIGS	SHJ	~~SHJ~~BAT PERC 2025	BNAT ~~kerfless new~~PERCbi 2019 + recycled wafer
Module type	Multi crystalline Si	Mono~~ulti crystalline~~ Si PERC (Passivated Emitter and Rear Cell) – optimized design	Passivated Emitter and Rear Cell (PERC), mono Si	PERC + bifacial glass backsheet	Thin film - Cadmium Telluride	Thin film – Copper Indium Gallium Selenide	Silicon heterojunction mono Si cells	~~Silicon heterojunction mono Si cells~~BAT PERC 2019 with further improvements in BOM and kerf loss recycling	~~Kerfless manufacturing~~PERC bifacial + 50% recycled wafer
Performance degradation rate (% per year)	0.7%	0.~~7~~6%	0.5%	0.5%	0.5~~1~~% + 2% in first year	1%	1%[1]	0.5~~1~~%~~[1]~~	0.5%
Failure rate modules (%/year)	0.2	0.~~2~~05	0.~~2~~05	0.~~2~~05	0.~~2~~05	0.~~2~~05	0.05	0.~~2~~01	0.~~2~~05
Cells per module	60	60	60	60	/	/	60	60	60
Module power density (Wp/m²)	147	175~~4~~	196	196	180	150	184	196~~7~~	196
Wafer thickness/Active layer thickness (µm)	200	170	180	180	/	/	150	120~~80~~	180~~25~~
Kerf thickness (µm)	100	75~~80~~	75~~100~~	75~~100~~	/	/	75	150~~30~~	75~~0~~
Total silicon use (wafer + kerf) in kg per m²	0.638	0.521~~31~~	0.5~~9~~542	0.5~~9~~425	/	/	0.478	0.3~~83~~61	0.~~266~~542

Economic life time for the FU (years)	30	30	30	30	30	30	30	30	30
Cost (EUR/Wp) – ref year 2018	0.48	0.52~~48~~	0.56	0.56	0.48	0.53	0.60	0.62~~0~~	0.62~~39~~

6.1.1.2 Assumptions regarding the selected BoM module design options

Two module designs have been introduced as design options that reflect combinations of material and quality improvements that are being achieved or specified in the global market. The expected improvement measures are ~~provided~~presented in Table 5~~Table 4~~ as two design options – the first, an update of the 2016 base case and the second a hypothetical further improvement of this case, albeit still based on the same cell technology.

Table 5~~4~~: Expected improvement of the multi Si modules (year 2020 and 2025)

Production step	**Selected improvement measures**	
	Optimised PERC Si 2020 (optimised process and materials)	**Further optimisations in BoM (BAT 2025)**
Wafer production	Mono-crystalline with diamond wire sawing with larger wafer size than>156x156 mm² 170 um wafer thickness and 75 µm of kerf loss	Wafer production with larger wafer size than>156x156 mm² and wafer thickness of 120 µm and 50µm of kerf loss with recycling (30% recycled content of kerf)
Semi-conductor preparation e.g. passivation	PERC p-type mono wafer	PERC on p-type mono Si wafer
Cell metallisation	Reduced Ag to 80 mg/cell	Reduced Ag (70 mg/cell) and Pb-free cell metallization paste with < 0.1% module weight
Cell stringing	Full-cells and 5BB interconnection	Half-cell, busbarless cells with copper interconnection with Pb-free soldering
Cell encapsulation	Reduced front glass thickness 3.2 mm	Front glass-non fluorinated backsheet Glass with AR and anti-soiling coating and < 2.5 mm thickness
Module power	281.6 Wp for 60-cell modules	313.6 Wp for 60-cell modules
Degradation rate	0.6%	0.5%
Performance warranty	25 years (modelled for 30 years)	30 years
Factory quality inspection	Infrared + Electroluminescence/ Lock in thermography – <1,5% factory ~~defect~~reject rate assumed	Infrared + high-resolution Electroluminescence/Lock in thermography L~~ighte~~TID/Potential Induced Degradation assessment <0,5% factory ~~defect~~reject rate assumed

6.1.1.3 Improvement option: thinner wafers

Improved wafer production technologies ha~~s~~ve resulted in thinner wafers that use less silicon.

The multi Si base case has a wafer thickness of 200 micrometers. This decreases to 120 micrometers in the BAT PERC 2025 option. Wafer thicknesses used in the different intermediate design options are ~~available~~presented in Table 4~~Table 2~~ which summarises the design option parameters.

6.1.1.4 Improvement option: increased silicon recycling

Two design options contain recycled ~~content~~silicon material. Option 8 (BAT PERC 2025) contains recycled kerf losses from wafer slicing and option 9 (BNAT PERCbi 2025 + recycled wafer) contains ~~recycled~~reused wafers recovered from old modules.

Two ~~kerfloss~~ potential recycling routes have been identified for kerf waste from silicon wafer slicing [7] and are considered possible:

1. Recycle as MG Si for Si-steel (BAT). Solar Grade Silicon kerf loss waste is contaminated from the tools used (e.g. SiC), but it remains a useful alloy compound for Si-steel manufacturing to substitute Metallurgical Grade silicon.
2. Recycle as solar grade silicon (BNAT): this is a more ambitious recycling route. Because of the contaminants it is still a challenge and part of research. NorSun has conducted pilot scale tests and will in 2020 introduce such waste into full scale production of silicon blocks. ~~set up a plant which can recycle kerf waste from wafer cutting and reuses this kerf waste in new modules.~~ They ~~are~~claim to be able ~~able~~ to reprocess 85% of the kerf waste that arises from wafer ~~cutting~~slicing~~,~~ and can tolerate in the production of new ~~silicon for ingot production~~ a 30% reprocessed content (~~at the moment, in~~claimed for full scale production) [8].

In option 8 (BAT PERC 2025) ~~we have included~~ the second option has been included, being considered as commercially available from 2021 onwards and allowing for 30% recycled kerf waste in new ~~ingot~~poli-Si block production.

In regard to option 9 and wafer reuse, Tsanakas et al. (2019)[9] recently published a review ~~ppare~~paper on recycling challenges in the PV sector. This paper mentions to relevant innovations – the first, a module design for recycling by the French manufacturer Apollon, and the second processes to reuse wafers of the type that could be recovered from such a module product at the end of life. The module design of Apollon was also described in Task 4 and is at pilot scale production.

The paper ~~mentioned~~refers to SolarWorld~~, as another pioneer and key actor in PV recycling that~~as having ~~has~~ a well-established c-Si recycling program and process, based on a thermal processing method, with which EVA is eliminated through burning, followed by manual separation of metals, silicon and glass. Then, Si cells are re-etched and at the end of such process clean wafers can be re-used. SolarWorld's recovery ratios typically

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[7] Eco-solar project (2018) *Eco-solar factory*, http://ecosolar.eu.com/wp-content/uploads/2018/11/D6.4-Scientific-Workshop.pdf

[8] Personal communication with Elkem/Norsun

[9] J.A. Tsanakas, A. van der Heide, T. Radavičius, J. Denafas, E. Lemaire, K. Wang, Jef Poortmans, E.Voroshazi. 2019. *Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification. Progress in Photovoltaics.*

exceed 84% of the module weight, namely 90% of the glass and 95% of the semiconductor materials (Lunardi et al., 2018)[10].

In option 9 ~~we have attempted to incorporate~~ an attempt has been made to incorporate wafer ~~recycling~~reuse into a design option. Data was not possible to obtain from Apollon, despite approaches, due to confidentiality issues. Little data was therefore available and ~~we have assumed~~an assumption has instead been made that 50% ~~recycled~~reused wafers can be tolerated and this reuse would be facilitated by improved future glass-glass module designs, reflecting the approach adopted by Apollon. Life cycle inventory data on possible processing steps were not, however, available. As a consequence ~~we had to neglect the~~these additional processing steps have had to be omitted and the simulation of this option ~~should be~~can only be seen as a very ~~rough~~limited first attempt to model the potential benefits.

A short description on the data used for life cycle assessment for each of the options is available in paragraph 6.1.1.10~~6.1.1.9~~.

6.1.1.5 Improvement option: solar glass

Light transmittance of glass can be improved (coatings, iron content, thickness, etc..) in combination with a trend towards manufacturing thinner tempered glass especially for bifacial glass on glass modules. Currently 2 mm for bifacial is possible. Also, when considering the Antimony content it is possible to recycle glass for solar glass, instead of other glass applications.

The ~~A~~assumptions used were as follows:~~are:~~

- Default 3.5 mm and 2x2 mm for bifacial
- Base case (multi Si) is 3.5 mm
- Optimised PERC 2020 is 3.2 mm
- BAT PERC 2025 is 2.5 mm

6.1.1.6 Improvement option: halogen free backsheet

Halogen containing backsheets can be responsible for ~~the~~ emissions of air pollutants such as hydrogen fluoride potentially released ~~from t~~during~~he combustion~~thermal processing of modules [11]. H~~h~~alogen free backsheets can therefore simplify ~~the~~ recycling via thermal and mechanical processing routes.

In the bifacial design option the polymer backsheet ~~has been~~is eliminated and replaced with a glass backsheet. In the BAT PERC 2025 a halogen-free polymer back sheet has been used. The chosen solution is a three layer, polyolefin (HDPE) backsheet.

6.1.1.7 Improvement option: increased manufacturing quality

~~This~~Evidence from audit programmes suggests that improvements can be obtained by more stringent factory quality control of~~on~~ materials supplied and manufacturing processes. This can ~~that will~~both reduce defects, for example those related to cells (poor handling resulting in cracking), ~~and~~ tabbing (~~material purity +~~ resulting in mis-

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[10] Lunardi MM, Alvarez-Gaitan JP, Bilbao JI, Corkish R. A Review of Recycling Processes for Photovoltaic Modules. Book Chapter in Solar Panels and Photovoltaic Materials. Intechopen, 2018; DOI: 10.5772/intechopen.74390.

[11] ~~https://doi.org/10.1016/j.wasman.2019.04.059~~Ardente et al, *Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling*, Waste Management 91 (2019) 156–167

alignment of cells) and material purity (e.g. silver purity). This can in turn reduce rejects and the waste in the factory.

This can also contribute to bring modules on the market with narrower efficiency tolerances ~~or~~on bins of rated power that comes out of the factory.

Feedback from factory inspections suggests that there is currently an overall 1.5% reject rate for all modules (no variance provided). For the design option BAT PERC 2025 an improved factory ~~defect~~reject rate of 0,5% has been assumed.

Feedback from factory ~~inspections~~audits suggests that the~~-~~ compound implementation of a series of quality measures can result in between 1-7% uplift in the Wp output from modules upon flash testing. This has been taken into account in the increased efficiency of the design options, with uplifts of 1, 3.5 and 7% used as increments.

A module failure rate of 0,05% has been assumed for all design options except for the BAT PERC 2025 option where an improved failure rate of 0,01% has been assumed.

6.1.1.8 Improvement option: back contact (IBC)

Compared to ~~two-sides contacted~~ solar cells with two contact sides, back-contact solar cells have both contact polarities on the rear side which significantly reduces optical losses at the illuminated front side both from cell metallis~~z~~ation and cell-to-cell interconnection (see the task 4 report).

The most promising technology is Interdigitated back contact solar cells (IBC). Their key features are as follows:~~;~~

- ~~Uses~~They use a complex diode structure with both positive and negative contacts on the back side.
- They ~~R~~require~~s~~ both n-type(Phosphor) and p-type (Boron) difussion material to used.
- Paste with phophor/boron compound needs to be added before diffusion, e.g. inject printing, silk screen
- They ~~C~~can require various ~~more~~additional ~~-~~production steps and ~~is~~these form part of the intellectual property related to the cell/module products.

Note: The benefits of the higher efficiency can easily be modelled but there is no relia~~i~~ble and up to date ~~quantitave~~quantitative LCI data to model the ~~negative~~ impacts from the~~is~~ increased manufacturing complexity. Therefore this option ~~is not be further modelled~~has not been possible to model.

6.1.1.9 Improvement option SHJ yield improvement

Silicon heterojunction (SHJ) cells offer high efficiencies and several advantages in the production process compared to conventional crystalline silicon solar cells (Louwen et al, 2015[12]).

SHJ technology could also minimi~~z~~se the use of silicon raw material that ha~~d~~s an important GWP/Primary energy impact.

~~The~~A further benefit of the cell design is a yield improvement because the cells have a lower temperature co-efficient (-0.258 %/°C) and a broader spectral response. This will confer a yield increase in locations with intense solar irradiation and at higher altitudes with clear skies. This improvement has been taken into account in design option 7 (SHJ), which has a conservative adjustment of DR temp of 102% instead of 100%.

[12] Louwen A., van Sark W.G.J.H.M., Schropp R.E.I., Turkenburg W.C., Faaij A.P.C. 2015. Life-cycle greenhouse gas emissions and energy payback time of current and prospective silicon heterojunction solar cell designs. Progress in photovoltaics: research and application. 23:1406-1428. Doi: 10.1002/pip.2540

6.1.1.26.1.1.10 Life cycle information – Bill of Materials: Modules

6.1.1.2.16.1.1.10.1 Multi Si (BSF)

Material input for the multi Si module production has been taken from the data collection exercise carried out for the PEF[13]. This is considered to provide the most up to date and representative dataset for the silicon wafer-based cells, as validated by the data quality rating (DQR) contained within the PEF pilot. For this assessment, packaging materials and the end of life treatment of the production waste have been omitted.

Data for the solar cell production has been taken from the ecoinvent 3.4 database. The global dataset has been used. This dataset contained an input of both solar and electronic grade Si. The input of electronic grade Si has been changed into solar grade Si, which better resembles reality.

The PEF data provided the input of photovoltaic cells per m^2, not per kg. The weight of the photovoltaic cells has been calculated based on the wafer thickness. The wafer has a thickness of 200 micrometer. The specific weight cell weight is 0.530 kg/m^{2}cell (including wafer+kerf losses). The cell area per m^2 module is 93,5% (PEF), which results in a cell weight of 0.496 kg/m^2 module.

The materials which were not available and have been added to the EcoReport tool are: multi Si photovoltaic cell, tin, lead, ethylenvinylacetate, polyvinylfluoride, silicone, solar glass and tempering, tap water, hydrogen fluoride, potassium hydroxide, 1-propanol, isopropanol. The ecoinvent version 3.4 global datasets have been used to model these materials.

Energy use for module manufacturing has been added to the tool as well. The input data have been taken from the PEF life cycle inventory (LCI) file. Data from the EcoReport tool have been used to calculate the environmental impact of the energy use during module manufacturing.

The BOM is available in annex A.

6.1.1.10.2 BAT PERC 2019

The LCI for module production has been taken from the PEF LCI table for Monocrystalline silicon solar modules.

For the photovoltaic cell again the 'PERC rear passivation layer' process and 'PERC dielectric openings' process have been added based on the LCI information provided in Lunardi et al. (2018) (see paragraph **Error! Reference source not found.**6.1.1.10.2).

BOM of PERC 2019. It includes a reduction of silicon use for the wafer (180 micrometer wafer thickness and 75 micrometer kerf losses). The glass thickness is 3.5 mm.

The BOM in EcoReport tool format is available in annex A.

6.1.1.10.3 BAT PERC bifacial 2019

For this design option, we started from the PERC 2019 inventory. The PVF/PET backsheet has been replaced with a glass backsheet. The thickness of the frontsheet has been adapted to 2 mm. The backsheet has the same thickness, being 2 mm. No other changes have been made to the BOM compared to the PERC 2019 design option.

The BOM in EcoReport tool format is available in annex A.

[13] 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

6.1.1.10.4 Optimised PERC 2020

The LCI for module production has been taken from the PEF LCI table for Monocrystalline silicon solar modules.

The photovoltaic cell has been taken from the ecoinvent 3.4 database. To this dataset the 'PERC rear passivation layer' process and 'PERC dielectric openings' process has been added based on the LCI information provided in Lunardi et al. (2018). Some minor modifications have been made to the report inventory because some of the inputs or outputs were not available in the ecoinvent database. In addition, electronic grade silicon has been changed into solar grade silicon, like in the multi Si cell. The considered cells are n-type cells.

It includes a reduction of silicon use for the wafer (170 micrometer wafer and 75 micrometer kerf losses). The glass thickness of the backsheet is reduced to 3.2 mm.

The BOM in EcoReport tool format is available in annex A.

~~6.1.1.2.2~~6.1.1.10.5 CdTe

The life cycle inventory for the CdTe module production has been taken from PEF. Data for the materials which were not available in the EcoReport Tool have been taken from Ecoinvent 3.4.

The BOM in EcoReport tool format is available in annex A.

~~6.1.1.2.3~~6.1.1.10.6 CIGS

The life cycle inventory for the CIGS module production has been taken from PEF. Data for the materials which were not available in the EcoReport Tool have been taken from Ecoinvent 3.4.

The BOM in EcoReport tool format is available in annex A.

~~6.1.1.2.4~~6.1.1.10.7 SHJ

The life cycle inventory for the SHJ module is a combination of data available in ecoinvent and the life cycle inventory published by Louwen et al. (2015)[25]. Data for the materials which were not available in the EcoReport Tool have been taken from Ecoinvent 3.4. The wafer thickness is adapted to 150 micrometer, the kerf thickness to 75 micrometer.

The BOM in EcoReport tool format is available in annex A.

6.1.1.10.8 BAT PERC 2025

This option models further expected improvements on the BAT PERC 2019 option related to BOM and manufacturing. To model this design option, ~~we started from~~ the BOM of the PERC module has been used as a starting point (see 6.1.1.1.1~~6.1.1.9.2~~). The wafer thickness has been adapted to 120 micrometers. Of ~~T~~the kerf losses, 50 micrometer, ~~consist for~~ 85% ~~out of~~are –recycled ~~kerf material~~to manufacture new wafers. The input data for the recycling process have been provided by NorSun. Wafers can be manufactured with 30% recycled content. The input of virgin kerf material is ~~15~~70%.

This option also contains a different backsheet with HDPE, PA and TiO_2 used instead of PVDF and PET.

Composition backsheet in the PERC 2025 option:

- 349 g HDPE/m^2
- 56,5 g/m^2 PA
- 37,8 g/m^2 TiO_2

For the BOM ~~we refer~~reference is made to the BOM of the PERC module which is available in Annex A. Only the solar cell input has been changed compared to the PERC module.

The BOM in EcoReport tool format is available in annex A.

6.1.1.10.9 BNAT PERC bifacial 2025 incl. wafer recycling

This option relates to the new possibilities to reduce environmental impact through recycling of the wafer and/or by achieving an extended cell or wafer life in a new product. Several new recycling and cell reuse routes during production and at the end of life are currently under investigation[14],[15]. A recent study**Error! Bookmark not defined.**~~[12]~~ concluded that the '*Assessment of the resource efficiency of PV recycling remains largely unexplored, especially concerning the benefits of increasing recovery rates for different materials in PV waste'*. Accordingly, this option is still denoted as a 'Best Not yet Available' (BNAT) technology. This option also addresses an important topic of Task 4, which was the consumption of ultrapure quartz that is being is considered a critical raw material(CRM) for Si cell manufacturing.

Herein it is worth noting that some proposed recycling schemes aim to recover silicon only as metallurgical grade silicon suitable for the steel industry while others also aim to recover the cells ~~them self~~ or in part a fraction that can be added to the solar grade silicon manufacturing. Future research in this area is highly recommended. Of course, it is also possible to extend the life-time of the modules through repair and repurposinge.

As a relative simplifiede proxy to model ~~all this tThis~~these optionss, ~~starts from~~ the bifacial module has been used as a starting point ~~option~~ and ~~assumesincludes~~only —wafer ~~recycling~~re-use introduced. Included in this option is therefore the direct re-use of wafers without any additional processing. An ~~As an educated guess, wWe've assumed~~assumed conservative estimate that ultimately 50% of the wafers can come from re-use has been used as a proxy for this ~~various recycle/reuse options cited~~option.

~~6.1.1.2.5 Multi Si optimised design~~

~~To model this design option, we started from the BOM of the multi Si base case module. The wafer thickness has been adapted to 170 micrometers (200 micrometers in the base case). This means less cast silicon is needed.~~

~~For the BOM we refer to the BOM of the multi Si base case which is available in Annex A. Only the solar cell input has been changed compared to the base case.~~

~~6.1.1.2.6 PERC~~

~~The LCI for module production has been taken from the PEF LCI table for Monocrystalline silicon solar modules.~~

~~The photovoltaic cell has been taken from the ecoinvent 3.4 database. To this dataset the 'PERC rear passivation layer' process and 'PERC dielectric openings' process has been added based on the LCI information provided in Lunardi et al. (2018). Some minor modifications have been made to the report inventory because some of the inputs or outputs were not available in the ecoinvent database. In addition, electronic grade silicon has been changed into solar grade silicon, like in the multi Si cell. The considered cells are n-type cells.~~

~~The BOM in EcoReport tool format is available in annex A.~~

~~6.1.1.2.7 PERC+bifacial~~

~~For this design option, we started from the PERC inventory. The PVF/PET backsheet has been replaced with a glass backsheet. The same weight as the front sheet has been assumed. No other changes have been made to the BOM compared to the PERC only design option.~~

[14] http://ecosolar.eu.com/wp-content/uploads/2018/11/D6.4-Scientific-Workshop.pdf
[15] https://doi.org/10.1016/j.wasman.2019.04.059

The BOM in EcoReport tool format is available in annex A.

6.1.1.2.8 CdTe

The life cycle inventory for the CdTe module production has been taken from PEF. Data for the materials which were not available in the EcoReport Tool have been taken from Ecoinvent 3.4.

The BOM in EcoReport tool format is available in annex A.

6.1.1.2.9 CIGS

The life cycle inventory for the CIGS module production has been taken from PEF. Data for the materials which were not available in the EcoReport Tool have been taken from Ecoinvent 3.4.

The BOM in EcoReport tool format is available in annex A.

6.1.1.2.10 Kerfless old

This design option has been modelled using the ecoinvent record 'photovoltaic panel production, ribbon-Si RER' which is based on primary data of the production of ,modules by Evergreen's string ribbon process (ca. 2011)

The BOM in EcoReport tool format is available in annex A.

6.1.1.2.11 SHJ

The life cycle inventory for the SHJ module is a combination of data available in ecoinvent and the life cycle inventory published by Louwen et al. (2015)Error! Bookmark not defined.[2]. Data for the materials which were not available in the EcoReport Tool have been taken from Ecoinvent 3.4.

The BOM in EcoReport tool format is available in annex A.

6.1.1.2.12 BNAT kerfless new

To model this design option, we started from the BOM of the PERC module (see 6.1.1.2.3). The wafer thickness has been adapted to 125 micrometers. There are no kerf losses.

For the BOM we refer to the BOM of the PERC module which is available in Annex A. Only the solar cell input has been changed compared to the PERC module.

The BOM in EcoReport tool format is available in annex A.

6.1.2 PV inverters

6.1.2.1 Assumptions regarding the selected design options for residential use

Table 6 below provides the assumptions for the selected design options. The modules can be used for residential applications.

Life time assumptions for inverters:

More background on inverter failure is given in Task 3, section 3.3.1.5 and Task 4, section 4.1.4.3.~~,~~ ~~as a reminder,~~ The failure rate of an inverter was defined as the linear average failure rate per year of an inverter relative to its technical life time (= 1/MTBFinv).

In electronics the common method applied for reliability prediction of electronic equipment are metrics, methods and data from MIL-HDBK-217, published by the US Department of Defense. It allows to calculate the failure rates [%/y] and the reciprocal value Mean Time Between Failure (MTBF). They are referred as 'MTBF random' failures in Table 6~~Table 6~~. Note that these computed values in the failure rate bathtub curve (Figure 23, Task 3) relate to the constant failure rate phase only, which excludes premature failures covered under first year warranty. In the Tasks 5 and 6 modelling we assume that premature warranty failures are part of the manufacturing drop out and waste. This does not cover wear out failures or inverters taken out of service due to the economic life time of the installation, which are the 'Wear out & economic system life failures' included in Table 6~~Table 6~~.

Based on literature[16] a 10 years average life time was proposed for the base case (see Tasks 2), hence the failure rate of 10 % was established in Task 5 as a minimum reference. This was based on assumptions relating to warranty provisions and indications of a high replacement rate by year 10 However, it is understood that, at least for commercial scale inverters, design lifetimes of manufacturers are now ~~up to~~targeted at 20-25 years with accompanying recommendations as to repair and replacement cycles to achieve ~~the~~ a longer design lifetime. In the residential sector manufacturers have the objective of making inverters maintenance-free, so as to minimise call-outs.

Clearly as a circular economy improvement option the failure rates of products can be improved using the MIL-HDBK 217 as reference. Task 4 already reported that manufacturers today already offer inverter warranty up to 10 years and input from manufacturers together with the findings from field analysis suggest a constant failure rate of as low as 0,50 % per annum. This is added as a separate improvement option 'longer life time'.

Note that 'longer life time' is an alternative to repairing low life time products, which for residential inverters ~~repair cost~~ can be expensive, hence a market shift to longer life time products is likely more economic. For larger units service costs aren't a barrier and servicing is common practice.

[16] See sources cited in Task 3 and 4 but also high amount of inverter failures reported by consumer organisations: https://www.which.co.uk/news/2017/08/top-five-solar-panel-problems/

Table 6: Design option residential inverters (BC 1)

Acronym	Base Case - Reference	Efficient	Longer life	Repair	Monitoring	MLI (microinverter)	Storage (worst case)	Storage (best case)
Inverter type	String 1 phase reference inverter Transformerless	More efficient inverter	Longer life time	Repair/repaired	Monitor/Smart BC1 reference plus monitoring	Module level coinverter transformerless	Hybrid storage worst performer	Hybrid storage best performer
Rated power (kVA) AC power	2.5	2.5	2.5	2.5	2.5	2.5 (for all inverters or 10x250 VA)	2.5	2.5
Euro Efficiency η_{conv}[%]	96	98	96	96	96	9796	96	96
Wear out & economic system life failures	3.3 % (= 1/30y)	3.3 %	3.3 %	3.3 %	3.3 %	3.3 %	3.3 %	3.3 %
MTBF random failures (constant failures, e.g. defined in e.g. MIL-HDBK-217)	6,.67% (=1/15 y)	6.,67% (=1/15 y)	0.,52% (=1/191 y)	6.,67% (=1/15 y) (+10 % of BOM replaced)	6.,67% (=1/15 y)	6.,67% (for a set of 10 inverters or 0,.67 % per inverter)	6.,67% (=1/15 y)	6,.67% (=1/15 y)
Failure rate inverters (% / year] = 1/(average life time)	10%	10%	3.86%	10% - repairs, not a full inverter being replaced	10%	10%	10%	10%
Cost (EUR/VA)	0.22	0.25	0.28	0.22	0.25	0.33	0.33	0.33

	BC 1 residential	BC 2 Commercial	BC 3
EOL (years)	30	30	30
proxy replacement rate for EoL (%/y)	3,33%	3,33%	3,33%
MTBF BAU (years)	15	15	15
constant failure rate BAU (%/y)	6,67%	6,67%	6,67%
MTBF BAT LL (years)	191	50	30
constant failure rate BAU (%/y)	0,52%	2,00%	3,33%
BAU total failure rate (%/y)	10,00%	10,00%	10,00%
BAT total failure rate (%/y)	3,86%	5,33%	6,67%
BAU inverter needed over 30 y life	3,00	3,00	3,00
BAT inverter needed over 30 y life	1,16	1,60	2,00
Notes: wear out failures = wear out + economic life time of installation premature failures = warranty replacements (assumed in BOM) random failures = constant failure rate phase			

6.1.2.2 Life cycle information – Bill of Materials: Inverters for Residential use

6.1.2.2.1 More efficient inverter

No change in the BOM compared to the base case (see Task 5 report).

6.1.2.2.2 Longer life time inverter

The reference case BOM for 1 inverter has been used as a starting point. The base case inverter is replaced 2 times during the life span of the system. The inverter used in this design option has a failure rate of 3.76% while the reference inverter has a failure rate of 10%.

The BOM in Ecoreport tool format is available in annex B.

6.1.2.2.3 Repair

Based on the information contained in Table 4 of the Task 4 report, the main repair events for an inverter are derived. Note that this is related to BC 1 (residential) and BC 2 (commercial) in particular.

The base case inverter is replaced 2 times during the life span of the system. For this design option, it is assumed that inverters are repaired and the damaged components are replaced proportionally to their failure rate and this occurs two times during the 30 year life span of the inverter (after 10 years and after 20 years). The most replaced components during on-site repairs are fuses and circuit boards. However, in the case of other significant failures occurring, then a common practice is that the faulty inverter is taken off site and replaced by refurbished units.

Table 7~~Ta~~Table 7~~Table 7ble 8~~ provides a proxy LCA estimate for inverter failures that have an impact on Bill-of-Materials. Based on this information the BOM for this design option has been established. The BOM of the base case has been taken from Tschumperlin et al (2016). This BOM contains several proxies and to establish the modelling of this design option further proxies have been added to it (e.g. link between BOM and the failed component), our repair estimate is accordingly.

This estimate excludes software failures. Software failures have no impact on the BOM, only on the derate factor.

Fans are excluded as well, as the best inverter designs are designed without fans.

Table 7~~78~~: Proxy bill of material estimate to model smaller fanless inverter failures. Source: based on table 4 from the ~~t~~Task 4 report[17]

Inverter failure area	Percentage of occurrence
Fuse/contactor	56%
Card/board	21%
Matrix/IGBT	10%
Capacitors	5%
Power supply	8%

The bill of materials is adjusted accordingly. A more detailed BOM in EcoReport format is available in annex B.

6.1.2.2.4 Monitor/smart ready

The impact of this design option, which would likely require a coms port and circuit board to support LAN communication using Mod/Fieldbus, on the BOM is unknown and therefore the BOM of the reference inverter has been used per similar rated power.

The BOM in Ecoreport tool format is available in annex B.

6.1.2.2.5 Module level inverter

The impact of this design option on the BOM is unknown and therefore the BOM of the reference inverter has been used per similar rated power. A Bill of Materials was not possible to obtain as this information is proprietary to the market leading manufacturer.

The BOM in Ecoreport tool format is available in annex B.

6.1.2.2.6 Hybrid storage worst performer

This design option has an impact on the BOM.~~,~~ ~~b~~Based on the weight of commercially available products, the impact has been estimated at +20 %. ~~based on total weight of commercial available solutions~~ The BOM of the reference inverter has been used and upscaled.

[17] Reference table 4, taks 4 report: T. J. Formica, H. A. Khan, and M. G. Pecht, "*The Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems*," *IEEE Access*, vol. 5, pp. 21336–21343, Sep. 2017.

The external battery is excluded from the BOM as the focus is on the performance of the power conditioning equipment and it is not the intention to set battery performance criteria.

The BOM in Ecoreport tool format is available in annex B.

6.1.2.2.7 Hybrid storage best performer

Due to a~~By~~ lack of accurate LCA modelling data apart from efficiency parameters, ~~Due to lack of accurate data,~~ the same bill of materials as the worst performer storage inverter was assumed. Likely the difference between the two cases is more a cost, design and quality issue.

The BOM in Ecoreport tool format is available in annex B.

6.1.2.3 Assumptions regarding the selected design options for commercial use

This BC 2 ~~is done~~has been put together in line with the BC 1 options.

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Table 889: Design option inverters for commercial use (BC 2)

Acronym	**Reference**	**Efficient**	**Repair**
Inverter type	3 phase reference inverter Transformerless	More efficient inverter	Repair/repaired
Rated power (kVA) AC	20	20	20
Euro Efficiency η_{conv}[%]	97	98	97
Wear out & economic system life failures	3.3 % (= 1/30y)	3.3 % (= 1/30y)	3.3 % (= 1/30y)
MTBF random failures **(constant failures, e.g. defined in e.g. MIL-HDBK-217)**	6.~~,~~67% (=1/15 y)	6.~~,~~67% (=1/15 y)	6~~,~~.67% (=1/15 y) (+10 % of BOM replaced)
~~**Failure rate inverters (% / year]**~~ ~~**= 1/(average life time)**~~	~~10%~~	~~10%~~	~~10%~~
Cost (EUR/VA)	0.15	0.18	0.12

6.1.2.4 Life cycle information – Bill of Materials: Inverters for commercial use

6.1.2.4.1 More efficient inverter

The impact of this design option on the BOM is unknown and therefore the BOM of the reference inverter has been used per similar rated power.

The BOM in Ecoreport tool format is available in annex B.

6.1.2.4.2 Repair

To model this scenario, the BOM of the reference inverter has been modified in a similar way as in the residential case (see 6.1.2.2.3).

The BOM in Ecoreport tool format is available in annex B.

6.1.2.5 Assumptions regarding the selected design options for utility scale

Larger utility scale systems (BC 3)~~,~~ have already the servicing of inverters in the base case.~~,~~ ~~o~~Amongst~~ne~~ of the most replaced components are fans and filters of the cooling system (in utility scale systems). Operation and Maintenance (O&M), including the replacement of fans, is modelled in the base case (Task 5) of BC3 (utility scale). In BC 3 we consider therefore inverter O&M as a prerequisite and not an improvement option.

Table 99~~10~~: Design option inverters for utility scale (BC 3)

Acronym	**Reference**	**Efficient**	**Efficient String**
Inverter type	3 phase reference inverter Transformerless	More efficient inverter	More efficient inverter with string level inverters
Rated power (kVA) AC	1500 kW central inverter	1500 kW central inverter	10 string inverters of 150 kW each
Euro Efficiency η_{conv}[%]	97	98	98
Wear out & economic system life failures	3.3 % (= 1/30y)	3.3 % (= 1/30y)	3.3 % (= 1/30y)
MTBF random failures **(constant failures, e.g. defined in e.g. MIL-HDBK-217)**	6.~~,~~67% (=1/15 y)	6.~~,~~67% (=1/15 y)	6.~~,~~67% (=1/15 y)
~~**Failure rate inverters (%/year = 1/(average life time)**~~	~~10%~~	~~10%~~	~~10%~~
Cost (EUR/VA)	0.10	0.12	0.15

6.1.2.6 Life cycle information – Bill of Materials: Inverters for utility scale

6.1.2.6.1 More efficient inverter

The impact of this design option on the BOM is unknown and therefore the BOM of the reference inverter has been used per similar rated power.

The BOM in Ecoreport tool format is available in annex B.

6.1.2.6.2 Efficient string inverter

The impact of this design option on the BOM is unknown and therefore the BOM of the reference inverter has been used per similar rated power. More inverter units are required to serve the PV array.

The BOM in Ecoreport tool format is available in annex B.

6.1.3 PV Systems

At system level, modules are combined with inverters. Also, the balance of systems and mounting systems haves been added at system level.

6.1.3.1 Assumptions regarding the selected design options at residential scale

All the design options at residential scale include a reference balance of system, except for some of the design options in which the inverter is different.

Table 10Table 10Table 11 provides an overview of the considered design options for systems at residential scale.

6.1.3.1.1 Multi Si module and reference inverter (PO 1)
In this design option, a multi Si module has been combined with the reference inverter and a reference BOS.

6.1.3.1.2 Multi Si oOptimised PERC 2020 module and reference inverter (PO 2)
This design option combines the multi Si oOptimized PERC 2020 module with the reference inverter and reference BOS.

6.1.3.1.3 BAT PERC 2019 module and reference inverter (PO 3)
This design option combines the PERC 2019 module with the reference inverter and a reference BOS.

6.1.3.1.4 CIGS module and reference inverter (PO 4)
This design option combines a CIGS module with a reference inverter and BOS.

6.1.3.1.5 Kerfless (old) module and reference inverter (PO 5)
This design option combines the kerfless (old) module with a reference inverter and BOS.

6.1.3.1.66.1.3.1.5 Silicon Heterojunction and reference inverter (PO 65)
This design option combines a silicon heterojunction module with the reference inverter and BOS.

6.1.3.1.76.1.3.1.6 BNAT kerfless (new)PERC 2025 module and reference inverter (PO 67)
This design option combines the BNAT kerflessPERC 2025 module with a reference inverter and BOS.

6.1.3.1.86.1.3.1.7 Multi Si module and more efficient inverter (PO 87)
This design option makes uses a more efficient inverter. The Euro Efficiency of the inverter is 98%, while 96% was assumed for the reference inverter. This more efficient inverter is combined with the reference multi Si module and a reference BOS.

~~6.1.3.1.9~~6.1.3.1.8 Multi Si module and longer life inverter (PO ~~9~~8)

In this design option the inverter failure rate has been changed from 10% to 0.5%. The inverter with a longer life has been combined with the reference multi Si module and a reference BOS.

~~6.1.3.1.10~~6.1.3.1.9 Multi Si module and inverter with repair (PO ~~10~~9)

This design option makes use of an inverter with an increased repair. The failure rate is 10%, but the failure does not lead to a full replacement of the inverter, rather a repair of the broken component has been assumed. The inverter with increased repair has been combined with the reference Si module and a reference BOS.

~~6.1.3.1.11~~6.1.3.1.10 Multi Si module and inverter including monitoring (PO 1~~1~~0)

This design option represents a situation with improved monitoring. Derate soiling factor has been increased to 98% (compared to 96% in the reference case) and derate inverter failure downtime has been increased to 99.9% (compared to 99% in the reference case). The inverter including monitoring has been combined with the reference multi Si module and reference BOS.

~~6.1.3.1.12~~6.1.3.1.11 Multi Si module and multi-level inverter (PO 1~~2~~1)

In this design option a multi-level inverter is combined with a multi Si module and reference BOM. The multi-level inverter has a higher Euro Efficiency (97%) compared to the reference inverter (96%). Also, the derate shading is increased to 98% (compared to 90% for the reference inverter). The multi-level inverter is combined with the reference multi Si module and reference BOS.

~~6.1.3.1.13~~6.1.3.1.12 Multi Si module and inverter including storage (worst case) (PO 1~~3~~2)

In this design option the Euro Efficiency of the derate module mismatch has been increased from 97% in the reference case to 98.5%. The inverter including storage is combined with a reference multi Si module and reference BOS. The extra system loss storage changes from 5% in the reference case to 30% in this design option including storage. System losses are however not modelled in the Ecoreport tool.

~~6.1.3.1.14~~6.1.3.1.13 Multi Si module and inverter including storage (best case) (PO 1~~4~~3)

In this design option the Euro Efficiency of the derate module mismatch has been increased from 97% in the reference case to 98.5%. The inverter including storage is combined with a reference multi Si module and reference BOS. The extra system loss storage changes from 5% in the reference case to 10% in this design option including storage. System losses are however not modelled in the Ecoreport tool.

~~6.1.3.1.15~~6.1.3.1.14 ~~Multi Si o~~Optimized PERC 2020 module and best of best inverters (SO 1)

This design option combines the best performing cost effective module with an inverter design combining the best of all the ~~-~~investigated inverters. The optimised PERC 2020 module combines a low life cycle cost with a lower GER (compared to the multi Si module) and is therefore selected as the best performing module. ~~The multi Si optimized module is the best performing module. CIGS performs better but it was not selected due to its higher life cycle cost.~~ This option has a derate soiling factor of 9~~6~~8%, the best of best inverter has a Euro Efficiency of 98%, and a derate inverter failure factor of 99.9%. The other derate factors are equal to the reference inverter. A reference BOS is added to this design option.

~~6.1.3.1.16~~6.1.3.1.15 O~~Multi Si o~~ptimized PERC 2020 module, best of best inverters and better design (SO 2)

This design option adds a better design to the pervious design option. The better design is reflected in the ~~higher derate module mismatch factor (98.5%), the~~ higher derate shading factor (96%) and the higher derate cable losses (99.5%) compared to the previous design option (O~~multi Si o~~ptimized PERC 2020 + best of best inverter 6.1.3.1.14~~6.1.3.1.15~~).

~~6.1.3.1.17~~6.1.3.1.16 O~~Multi Si o~~ptimised PERC 2020+ best inverter + optimised O&M (SO 3)

This system combines the best module with the best inverter and includes optimized operation and maintenance routine. This introduces practices from the large scale segment including remote monitoring, repair response or early failure detection and cleaning routines. This affects the downtime, repair cycles for the modules and inverter and the derate soiling factor.

6.1.3.2 Assumptions regarding the selected design options at commercial scale

All the design options at ~~utility~~ commercial scale include a reference BOS (except for the inverter which changes in some of the design options).

Table 11~~Table 12~~ provides an overview of the considered design options for both modules and inverters at commercial scale.

6.1.3.2.1 Multi Si module and reference inverter (Base Case PO 1)

In this design option, a multi Si module has been combined with the reference inverter and a reference BOS.

6.1.3.2.2 O~~Multi Si o~~ptimized PERC 2020 module and reference inverter (PO 2)

This design option combines the ~~multi Si o~~Optimized PERC 2020 module with the reference inverter and reference BOS.

6.1.3.2.3 BAT PERC 2019 module and reference inverter (PO 3)

This design option combines the PERC 2019 module with the reference inverter and a reference BOS.

6.1.3.2.4 BAT PERC bifacial 2019 module and reference inverter (PO 4)

This design option combines the BAT PERC bifacial 2019 module with the reference inverter and reference BOS. The power gain due to the bifacial surface is set at 115%.

6.1.3.2.5 CdTe module and reference inverter (PO 5)

This design option combines a CdTe module with a reference inverter and reference BOS.

6.1.3.2.6 BAT PERC 2025 module and reference inverter (PO 6)

This design option combines the PERC 2025 module with a reference inverter and reference BOS.

6.1.3.2.7 BNAT PERC bifacial 2025 + recycled wafer and reference inverter (PO 7)

This design option combines the *BNAT* PERC 2025 bifacial module with a reference inverter and reference BOS.

~~6.1.3.2.6~~6.1.3.2.8 Multi Si module and more efficient inverter (PO ~~6~~8)
This design option makes use~~s~~ of a more efficient inverter. The Euro Efficiency of the inverter is 98%, while 96~~7~~% was assumed for the reference inverter. This more efficient inverter is combined with the reference multi Si module and a reference BOS.

~~6.1.3.2.7~~6.1.3.2.9 Multi Si module and inverter with repair (PO 9~~7~~)
This design option makes use of an inverter with an increased repair. The failure rate is 10%, but the failure does not lead to a full replacement of the inverter, rather a repair of the broken component has been assumed. The inverter with increased repair has been combined with the reference Si module and a reference BOS.

~~6.1.3.2.8~~6.1.3.2.10 BAT PERC bifacial 2019 and higher derating factors (SO 1)
This design option combines a the BAT PERC bifacial 2019 module with higher derating factors due to lower cable losses, shading and module mismatch because of a tailored design. The Euro Efficiency of the inverter is set at 98%, the derate shading is 98~~,5~~%, ~~the derate temperature effect is 98%~~ the derate module mismatch is 98% and the derate cable losses are~~is~~ 99.5%.

6.1.3.3 Assumptions regarding the selected design options at utility scale

Table 12~~Table 12~~ provides an overview of the considered design options for both modules and inverters at utility scale.

6.1.3.3.1 Multi Si module and reference inverter and reference BOS (PO 1)

In this design option, a multi Si module has been combined with the reference inverter and a reference BOS.

6.1.3.3.2 O~~Multi Si o~~ptimis~~z~~ed PERC 2020 module and reference inverter and reference BOS (PO 2)

This design option combines the ~~multi Si o~~Optimized PERC 2020 module with the reference inverter and reference BOS.

6.1.3.3.3 BAT PERC 2019 module and reference inverter and reference BOS (PO 3)

This design option combines the BAT PERC 2019 module with the reference inverter and a reference BOS.

6.1.3.3.4 BAT PERC bifacial 2019 module and reference inverter and reference BOS (PO 4)

This design option combines the BAT PERC bifacial 2019 module with the reference inverter and reference BOS. The power gain due to the bifacial surface is set at 11~~5~~0%.

6.1.3.3.5 CdTe module and reference inverter and reference BOS (PO 5)
This design option combines a CdTe module with a reference inverter and reference BOS.

6.1.3.3.6 BAT PERC 2025 module with reference inverter and reference BOS (PO 6)

This design option combines the BAT PERC 2025 module with a reference inverter and reference BOS.

6.1.3.3.7 BNAT PERC bifacial 2025 + recycled wafer module with reference inverter and reference BOS (PO 7)

This design option combines the BNAT PERC bifacial 2025 + recycled wafer module with a reference inverter and reference BOS.

~~6.1.3.3.6~~6.1.3.3.8 Multi Si module and more efficient inverter and reference BOS (PO 8~~6~~)
This design option combines the reference multi Si module with a more efficient inverter. The Euro Efficiency of the inverter increases from 97% (reference inverter) to 98%.

~~6.1.3.3.7~~6.1.3.3.9 Multi Si module and more efficient string inverter and reference BOS (PO ~~7~~9)
This design option combines the reference multi Si module with a more efficient string inverter. The Euro Efficiency is 98% and the derate module mismatch is 98%.

~~6.1.3.3.8~~6.1.3.3.10 CdTe module, efficient string inverter and tracking (SO 1)
This design option combines a CdTe module with an efficient string inverter and tracking. Due to the use of tracking the radiation hours increase from 1331 hours to 1465 hours (from PVGIS simulation in Frankfurt~~Strasbourg~~).

Table 101011: Combination of design options for modules and inverters – residential scale systems

System		Base Case - PO 1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	PO 10	PO 11	PO 12	PO 13	SO 1	SO 2	SO 3
Parameters																	
Use phase parameters Task 3 + inverter efficiency of Task 4																	
PR = DRother x DR modelled	%	74,9%	74,9%	74,9%	74,9%	74,9%	74,9%	76,5%	74,9%	74,9%	77,2%	81,6%	74,9%	74,9%	77,2%	82,7%	84,0%
DR other	%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%	95,1%
Euro Efficiency ηconv[%]	%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	98,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	98,0%	98,0%	98,0%
DR Module mismatch	%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%
DR shading	%	90,0%	90,0%	90,0%	90,0%	90,0%	90,0%	90,0%	90,0%	90,0%	90,0%	98,0%	90,0%	90,0%	90,0%	96,0%	96,0%
DR temp effect	%	100,0%	100,0%	100,0%	100,0%	102,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
DR soiling	%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	98,0%	96,0%	96,0%	96,0%	96,0%	96,0%	98,0%
DR snow	%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%
DR cable losses	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,5%	99,0%
DR inv failure (downtime)	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,9%	99,0%	99,0%	99,0%	99,9%	99,9%	99,9%
DR modelled	%	78,78%	78,78%	78,78%	78,78%	78,78%	78,78%	80,42%	78,78%	78,78%	81,15%	85,78%	78,78%	78,78%	81,15%	87,00%	88,36%
reference irradiation	hours	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331,00
System yield - Yf (in year 1)		997	997	997	997	997	997	1018	997	997	1027	1086	997	997	1027	1101	1118
cleaning and maintenance cycle	#/y	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067
extra system loss storage(ESS) or grid(no ESS)	%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	**30,0%**	**10,0%**	5,0%	5,0%	5,0%
Technology parameters Task 4																	
power gain for bifacial or derating	Wp/m2	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
Rated power/m² or mod. Efficiency	Wp/m2	147	175	196	150	184	196	147	147	147	147	147	147	147	175	175	175
corrected rated power	Wp/m2	147	175	196	150	184	196	147	147	147	147	147	147	147	175	175	175
Performance degradation rate	%	0,70%	0,60%	0,50%	1,00%	1,00%	0,50%	0,70%	0,70%	0,70%	0,70%	0,70%	0,70%	0,70%	0,70%	0,70%	0,70%
Economic System Life (Task 1)	years	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
System yield average over life	hours	902	915	928	867	867	928	921	902	902	930	983	902	902	930	997	1012
Failure rate modules	%/year	0,05%	0,05%	0,05%	0,05%	0,05%	0,01%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%
Average module replacement	%/life	1,50%	1,50%	1,50%	1,50%	1,50%	0,15%	1,50%	1,50%	1,50%	1,50%	1,50%	1,50%	1,50%	1,50%	1,50%	1,50%
Failure rate inverters1/MTBF	%/year	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	3,86%	10,00%	10,00%	10,00%	10,00%	10,00%	3,86%	3,86%	3,86%
Average inverter replacements	%/life	300,0%	300,0%	300,0%	300,0%	300,0%	300,0%	300,0%	115,7%	300,0%	300,0%	300,0%	300,0%	300,0%	115,7%	115,7%	115,7%
Installed rated power modules	Wp	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
Rated Power inverter	VA	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500	2500
Overall output of electricity	kWh	81215	82330	83477	78062	78062	83477	82907	81215	81215	83661	88435	81215	81215	83661	89689	91098
total module area	m²	20,7	17,4	15,5	20,3	16,5	15,3	20,7	20,7	20,7	20,7	20,7	20,7	20,7	17,4	17,4	17,4
area of single modules	m²	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6	1,6
total modules	#	12,9	10,8	9,7	12,7	10,3	9,6	12,9	12,9	12,9	12,9	12,9	12,9	12,9	10,8	10,8	10,8
# m2 panel per kWh	**m²/kWh**	2,55E-04	2,11E-04	1,86E-04	2,60E-04	2,12E-04	1,84E-04	2,50E-04	2,55E-04	2,55E-04	2,48E-04	2,34E-04	2,55E-04	2,55E-04	2,07E-04	1,93E-04	1,90E-04
# 2.5 kVA inverter (incl repl)/kWh	**units (incl repl)/kWh**	1,23E-05	1,21E-05	1,20E-05	1,28E-05	1,28E-05	1,20E-05	1,21E-05	1,23E-05	1,23E-05	1,20E-05	1,13E-05	1,23E-05	1,23E-05	1,20E-05	1,11E-05	1,10E-05
Wafer Thickness	**micrometer**	2,00E+02	1,70E+02	1,80E+02	not relevant	1,50E+02	1,20E+02	2,00E+02	2,00E+02	2,00E+02	2,00E+02	2,00E+02	2,00E+02	2,00E+02	0,00E+00	0,00E+00	0,00E+00
Form factor losses silicon	**kg/m2 panel**	1,85E-01	1,51E-01	1,58E-01	not relevant	1,39E-01	1,05E-01	1,85E-01	1,85E-01	1,85E-01	1,85E-01	1,85E-01	1,85E-01	1,85E-01	0,00E+00	0,00E+00	0,00E+00
Kerf losses	**micrometer**	1,00E+02	7,50E+01	7,50E+01	not relevant	7,50E+01	5,00E+01	1,00E+02	1,00E+02	1,00E+02	1,00E+02	1,00E+02	1,00E+02	1,00E+02	0,00E+00	0,00E+00	0,00E+00
factory defect rate	**%**	1,5%	1,5%	1,5%	1,5%	1,5%	0,5%										

(PO 1): Multi Si module and reference inverter, (PO2): OMulti Si optimised PERC 202 module and reference inverter; (PO 3): BAT PERC 2019 module and reference inverter; (PO 4): CIGS module and reference inverter; (PO 5): Kerfless (old) module and reference inverter; (PO 65): Silicion heterojunction module and reference inverter; (PO 76): BNAT kerfless (new)PERC 2025 module and reference inverter; (PO 87): Multi Si module and more efficient inverter; (PO 89): Multi Si module and longer life inverter; (PO 109): Multi Si Module and inverter with repair; (PO 110): Multi Si module and inverter including monitoring; (PO 121): Multi Si module and multi-level inverter; (PO 123): Multi Si module and inverter including storage (worst case); (PO 143): Multi Si module and inverter including storage (best case).

(SO 1): OMulti Si optimised PERC 2020 + best inverter; (SO 2): OMulti Si optimised PERC 2020+ best inverter + better design; (SO 3): OMulti Si optimised PERC 2020+ best inverter + optimised O&M

Table 111112: Combination of design options for modules and inverters – commercial scale systems

System		Base Case - PO 1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
Parameters											
Use phase parameters Task 3 + inverter efficiency of Task 4											
PR = DRother x DR modelled	%	*82,5%*	*82,6%*	*82,6%*	*82,6%*	*82,6%*	*82,6%*	*82,6%*	*83,4%*	*82,6%*	*87,8%*
DR other	%	*98,2%*	*98,2%*	*98,2%*	*98,2%*	*98,2%*	*98,2%*	*98,2%*	*98,2%*	*98,2%*	*98,2%*
Euro Efficiency η_{conv}[%]	%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	98,0%	97,0%	98,0%
DR Module mismatch	%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	98,5%
DR shading	%	95,0%	95,0%	95,0%	95,0%	95,0%	95,0%	95,0%	95,0%	95,0%	98,0%
DR temp effect	%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
DR soiling	%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%	96,0%
DR snow	%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%
DR cable losses	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,5%
DR inv failure (downtime)	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%
DR modelled	%	*84,02%*	*84,10%*	*84,10%*	*84,10%*	*84,10%*	*84,10%*	*84,10%*	*84,97%*	*84,10%*	*89,46%*
reference irradiation	hours	1331	1331	1331	1331	1331	1331	1331	1331	1331	1331
System yield - Yf (in year 1)		*1098*	*1099*	*1099*	*1099*	*1099*	*1099*	*1099*	*1111*	*1099*	*1169*
cleaning and maintenance cycle	#/y	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067
extra system loss storage(ESS) or grid(no ESS)	%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%
Technology parameters Task 4											
power gain for bifacial or derating	Wp/m2	100,0%	100,0%	100,0%	115,0%	98,0%	100,0%	115,0%	100,0%	100,0%	115,0%
Rated power/m² or mod. Efficiency	Wp/m2	147	175	196	196	180	196	196	147	147	196
Rated power	Wp/m2	147	175	196	225	176	196	225	147	147	225
Performance degradation rate	%	0,70%	0,60%	0,50%	0,50%	0,50%	0,50%	0,50%	0,70%	0,70%	0,50%
Economic System Life time	years	30	30	30	30	30	30	30	30	30	30
System yield average over life	hours	*994*	*1008*	*1023*	*1023*	*1023*	*1023*	*1023*	*1005*	*995*	*1088*
Failure rate modules	%/year	0,05%	0,05%	0,05%	0,05%	0,05%	0,01%	0,05%	0,05%	0,05%	0,05%
Average module replacement	%/life	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*0,30%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*
Failure rate inverters =1/MTBF	%/year	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%
Average inverter replacements	%/life	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*
Capacity modules	Wp	24400	24400	24400	24400	24400	24400	24400	24400	24400	24400
Rated Power inverter	VA	20000	20000	20000	20000	20000	20000	20000	20000	20000	20000
Overall output of electricity	kWh	*727478*	*738197*	*748483*	*748483*	*748483*	*748483*	*748483*	*735714*	*728206*	*796143*
total module area	m²	*168,5*	*141,1*	*126,4*	*109,9*	*140,6*	*124,9*	*109,9*	*168,5*	*168,5*	*109,9*
area of single modules	m²	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*
total modules	#	*105,3*	*88,2*	*79,0*	*68,7*	*87,8*	*78,0*	*68,7*	*105,3*	*105,3*	*68,7*
# m2 panel per kWh	**m²/kWh**	*2,32E-04*	*1,91E-04*	*1,69E-04*	*1,47E-04*	*1,88E-04*	*1,67E-04*	*1,47E-04*	*2,29E-04*	*2,31E-04*	*1,38E-04*
# inverter (incl repl)/kWh	**units (incl repl)/kWh**	*1,37E-06*	*1,35E-06*	*1,34E-06*	*1,34E-06*	*1,34E-06*	*1,34E-06*	*1,34E-06*	*1,36E-06*	*1,37E-06*	*1,26E-06*
Wafer Thickness	**micrometer**	*2,00E+02*	*1,70E+02*	*1,80E+02*	*1,80E+02*	*not relevant*	*1,20E+02*	*1,80E+02*	*2,00E+02*	*2,00E+02*	*0,00E+00*
Form factor losses silicon	**kg/m2 panel**	*1,85E-01*	*1,51E-01*	*1,58E-01*	*1,58E-01*	*not relevant*	*1,05E-01*	*1,58E-01*	*1,85E-01*	*1,85E-01*	*0,00E+00*
Kerf losses	**micrometer**	*1,00E+02*	*7,50E+01*	*7,50E+01*	*7,50E+01*	*not relevant*	*5,00E+01*	*7,50E+01*	*1,00E+02*	*1,00E+02*	*0,00E+00*
factory defect rate	**%**	*1,5%*	*1,5%*	*1,5%*	*1,5%*	*1,5%*	*0,5%*	*1,5%*			

(SO 1): best combination and design; (PO 1): Multi Si module and reference inverter; (PO 2): OMulti Si optimised PERC 2020 module and reference inverter; (PO 3): BAT PERC 2019 module and reference inverter; (PO 4): BAT PERC bifacial 2019 module and reference inverter; (PO 5): CdTe module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter; (PO 68): Multi Si module and more efficient inverter; (PO 97): Multi Si module and inverter with repair

Table 121213: Combination of design options for modules and inverters – utility scale systems

System		Base Case - PO 1	PO 2	PO 3	PO4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
Parameters											
Use phase parameters Task 3 + inverter efficiency of Task 4											
PR = DRother x DR modelled	%	*82,5%*	*82,5%*	*82,5%*	*82,5%*	*82,5%*	*82,5%*	*82,5%*	*83,4%*	*84,3%*	*84,3%*
DR other	%	*93,2%*	*93,2%*	*93,2%*	*93,2%*	*93,2%*	*93,2%*	*93,2%*	*93,2%*	*93,2%*	*93,2%*
Euro Efficiency η_{conv}[%]	%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	98,0%	98,0%	98,0%
DR Module mismatch	%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	97,0%	98,0%	98,0%
DR shading	%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%
DR temp effect	%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
DR soiling	%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%	98,0%
DR snow	%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%	99,9%
DR cable losses	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%
DR inv failure (downtime)	%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%	99,0%
DR modelled	%	*88,48%*	*88,57%*	*88,57%*	*88,57%*	*88,57%*	*88,57%*	*88,57%*	*89,48%*	*90,40%*	*90,40%*
Reference irradiation	hours	1331	1331	1331	1331	1331	1331	1331	1331	1331	1465
System yield - Yf (in year 1)		*1098*	*1099*	*1099*	*1099*	*1099*	*1099*	*1099*	*1110*	*1121*	*1234*
cleaning and maintenance cycle	#/y	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067	0,067
extra system loss storage(ESS) or grid(no ESS)	%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%	5,0%
Technology parameters Task 4											
power gain for bifacial or derating	Wp/m2	100,0%	100,0%	100,0%	110,0%	98,0%	100,0%	110,0%	100,0%	100,0%	98,0%
Rated power/m² or mod. Efficiency	Wp/m2	147	175	196	196	180	196	196	147	147	180
Rated power	Wp/m2	147	175	196	216	176	196	216	147	147	176
Performance degradation rate	%	0,70%	0,60%	0,50%	0,50%	0,50%	0,50%	0,50%	0,70%	0,70%	0,50%
Economic System Life time	years	30	30	30	30	30	30	30	30	30	30,00
System yield average over life	hours	*993*	*1008*	*1022*	*1022*	*1022*	*1022*	*1022*	*1005*	*1015*	*1148*
Failure rate modules	%/year	0,05%	0,05%	0,05%	0,05%	0,05%	0,01%	0,05%	0,05%	0,05%	0,05%
Average module replacement	%/life	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*	*6,00%*	*1,50%*	*1,50%*	*1,50%*	*1,50%*
Failure rate inverters =1/MTBF	%/year	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%	10,00%
Average inverter replacements	%/life	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*	*300,0%*
Capacity modules	Wp	1875000	1875000	1875000	1875000	1875000	1875000	1875000	1875000	1875000	1875000
Rated Power inverter	VA	1500000	1500000	1500000	1500000	1500000	1500000	1500000	1500000	1500000	1500000
Overall output of electricity	kWh	*55871867*	*56695080*	*57485081*	*57485081*	*57485081*	*57485081*	*57485081*	*56504370*	*57086890*	*64589581*
total module area	m²	*12946,4*	*10844,6*	*9709,8*	*8827,1*	*10800,7*	*10140,3*	*8827,1*	*12946,4*	*12946,4*	*10800,7*
area of single modules	m²	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*	*1,6*
total modules	#	*8091,5*	*6777,9*	*6068,6*	*5516,9*	*6750,4*	*6337,7*	*5516,9*	*8091,5*	*8091,5*	*6750,4*
# m2 panel per kWh	**m²/kWh**	*2,32E-04*	*1,91E-04*	*1,69E-04*	*1,54E-04*	*1,88E-04*	*1,76E-04*	*1,54E-04*	*2,29E-04*	*2,27E-04*	*1,67E-04*
# inverter (incl repl)/kWh	**units (incl repl)/kWh**	*1,79E-08*	*1,76E-08*	*1,74E-08*	*1,74E-08*	*1,74E-08*	*1,74E-08*	*1,74E-08*	*1,77E-08*	*1,75E-08*	*1,55E-08*
Wafer Thickness	**micrometer**	*2,00E+02*	*1,70E+02*	*1,80E+02*	*1,80E+02*	*not relevant*	*1,20E+02*	*1,80E+02*	*2,00E+02*	*2,00E+02*	*not relevant*
Form factor losses silicon	**kg/m2 panel**	*1,85E-01*	*1,51E-01*	*1,58E-01*	*1,58E-01*	*not relevant*	*1,05E-01*	*1,58E-01*	*1,85E-01*	*1,85E-01*	*not relevant*
Kerf losses	**micrometer**	*1,00E+02*	*7,50E+01*	*7,50E+01*	*7,50E+01*	*not relevant*	*5,00E+01*	*7,50E+01*	*1,00E+02*	*1,00E+02*	*not relevant*
factory defect rate	**%**	*1,5%*	*1,5%*	*1,5%*	*1,5%*	*1,5%*	*0,5%*	*1,5%*			

(SO 1): best combination and design including single axis tracker; (PO 1): Multi Si module and reference inverter and reference BOS; (PO 2): OMulti Si optimised PERC 2020 module and reference inverter and reference BOS; (PO 3): BAT PERC 2019 module and reference inverter and reference BOS; (PO 4): BAT PERC bifacial 2019 module and reference inverter and reference BOS; (PO 5): CdTe module and reference inverter and reference BOS; (PO6): BAT PERC 2025 module and reference inverter and reference BOS; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter and reference BOS; (PO 68): Multi Si module and more efficient inverter and reference BOS; (PO 79): Multi Si module and more efficient string inverter and reference BOS

6.2 Environmental impacts (results from Ecoreport tool)

6.2.1 PV modules

Table 13Table 13Table 14 shows the relative environmental impacts of the single design options compared to base case PV modules under real life conditions.

Figure 1Figure 1 shows the results for the primary impact category 'Primary energy' per kWh for the different module types.

Table 14Table 14 shows the relative figures of the total environmental impactsprimary energy of the base case (=100%) and the single design options for selected environmental impact categories.

Table 131314: Life cycle impacts of PV modules design options with respect to the base case

Indicators (from Ecoreport)	Base case	Multi Si optimized Optimized PERC 2020	BAT PERC 2019	BAT PERCbi bifacial2019	CdTe	CIGS	SHJKerfless old	BAT PERC 2025SHJ	BNAT PERCbi 2025 + recycled waferkerfless new
Total Energy (GER)	100%100%	94%80%	84%87%	83%89%	28%30%	76%76%	87%106%	70%92%	60%69%
Water	100%100%	131%76%	118%121%	117%122%	10%11%	24%24%	65%103%	166%74%	95%99%
Waste, non-haz./ landfill	100%100%	115%81%	104%109%	104%114%	14%15%	27%27%	109%78%	82%118%	69%81%
Waste, hazardous/ incinerated	100%100%	38%84%	34%34%	33%34%	5%5%	8%8%	38%8%	33%36%	18%33%
Greenhouse Gases in GWP100	100%100%	96%81%	87%90%	86%93%	28%29%	76%76%	90%96%	72%95%	63%71%
Acidification, emissions	100%100%	95%81%	86%88%	85%94%	28%30%	64%64%	93%120%	76%96%	64%72%
Volatile Organic Compounds (VOC)	100%100%	83%84%	74%74%	74%75%	8%8%	13%13%	85%84%	70%81%	69%72%
Persistent Organic Pollutants (POP)	100%100%	94%82%	84%86%	84%89%	17%18%	45%45%	102%85%	67%103%	61%72%
Heavy Metals to air	100%100%	91%82%	81%83%	81%87%	19%20%	33%33%	112%94%	84%111%	56%72%
PAHs	100%100%	79%81%	71%72%	71%73%	5%6%	66%66%	79%90%	63%79%	57%63%
Particulate Matter (PM, dust)	100%100%	89%83%	79%80%	79%81%	60%63%	81%81%	87%98%	73%86%	70%73%
Heavy Metals to water	100%100%	83%84%	74%74%	74%75%	4%4%	26%26%	111%77%	58%105%	54%73%
Eutrophication	100%100%	102%82%	92%95%	92%99%	13%13%	45%45%	121%100%	66%124%	67%76%

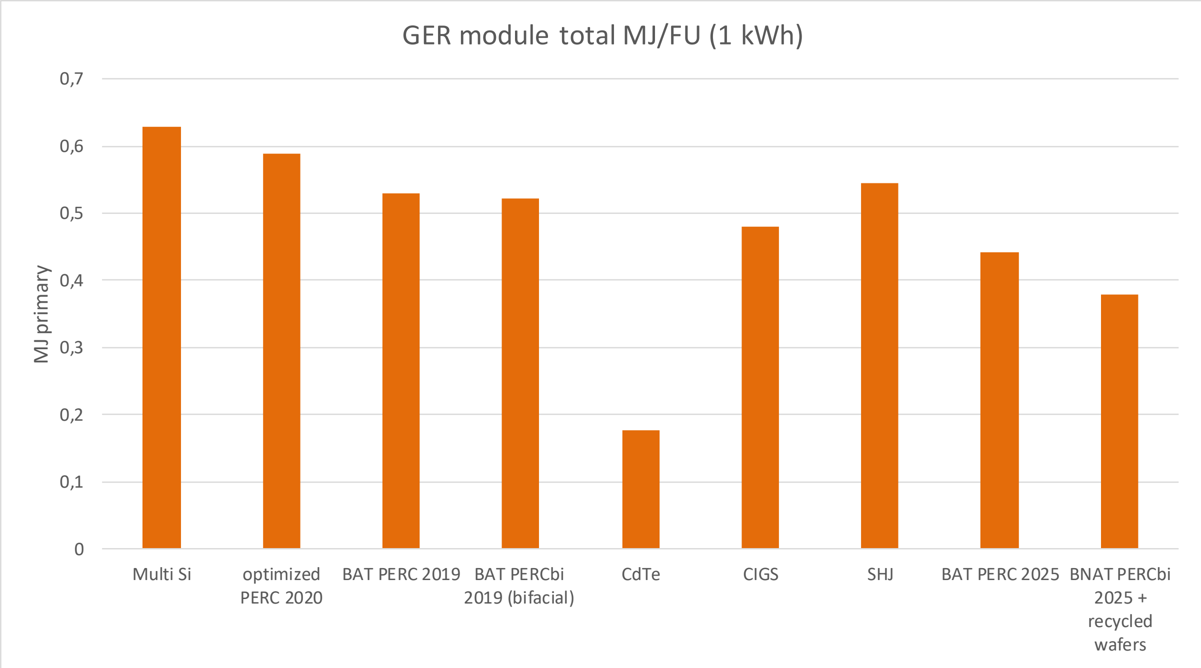

Figure 1: Primary energy results in MJ per kWh produced from modules

Table 14~~1415~~: Ranking of selected improvement options for PV Modules based on selected environmental indicators

Option	**Total Energy (primary energy)**
CdTe	28~~30~~%
BNAT PERCbi 2025 + recycled wafer~~kerfless new~~	60~~9~~%
BAT PERC 2025	70%
CIGS	76%
BAT PERCbi 2019~~Multi Si optimized~~	83~~0~~%
BAT PERC 2019	84~~7~~%
~~PERC bifacial~~	~~89%~~
SHJ	87~~92~~%
Optimized PERC 2020	94%
Multi Si Base Case	100%
~~Kerfless old~~	~~106%~~

6.2.1.1 Influence of the electricity mix on the results

The main impact of the multi-Si module comes from the electricity consumed by the production of the solar cell. Therefore, as well the amount of primary energy, the electricity mix or grid factor of the location of cell production can exert an influence on the results.

To evaluate this influence, the Base Case multi-Si cell has been used. To calculate the environmental impact of this cell, the global ecoinvent data record on the production of a multi Si cell with a global market electricity mix, represents the market for solar cell production.

To account for a variation in the production location, the electricity mixes along all processes of the production of the multi Si solar cell have been changed into the Swedish electricity mix, which is known as a clean electricity mix in Europe, and the EU average electricity mix. Electricity has only been changed in the following levels of the production chain of the solar cell, which were identified as being relevant:

- Cell assembly

- Wafer production
    - Silicon carbide production
    - Silicon solar grade production

All other records (e.g. metallization pastes) remained unchanged, but were also less relevant in the environmental profile of the multi Si cell. Burning of natural gas as an energy source remained unchanged as well.

Figure 2 compares the environmental impact of a multi Si cell produced using energy mixes representing the global market multi Si cell production and the adapted records using the Swedish and the EU average electricity mix.

Figure 3 shows the results at module level. The electricity mix has been changed for the cell only, as described above. The cell is then used in the multi-Si module.

The comparison is made in each case in percentage terms relative to the energy mix with the greatest impact in each category – which, with the exception of water, is the global market multi Si cell.

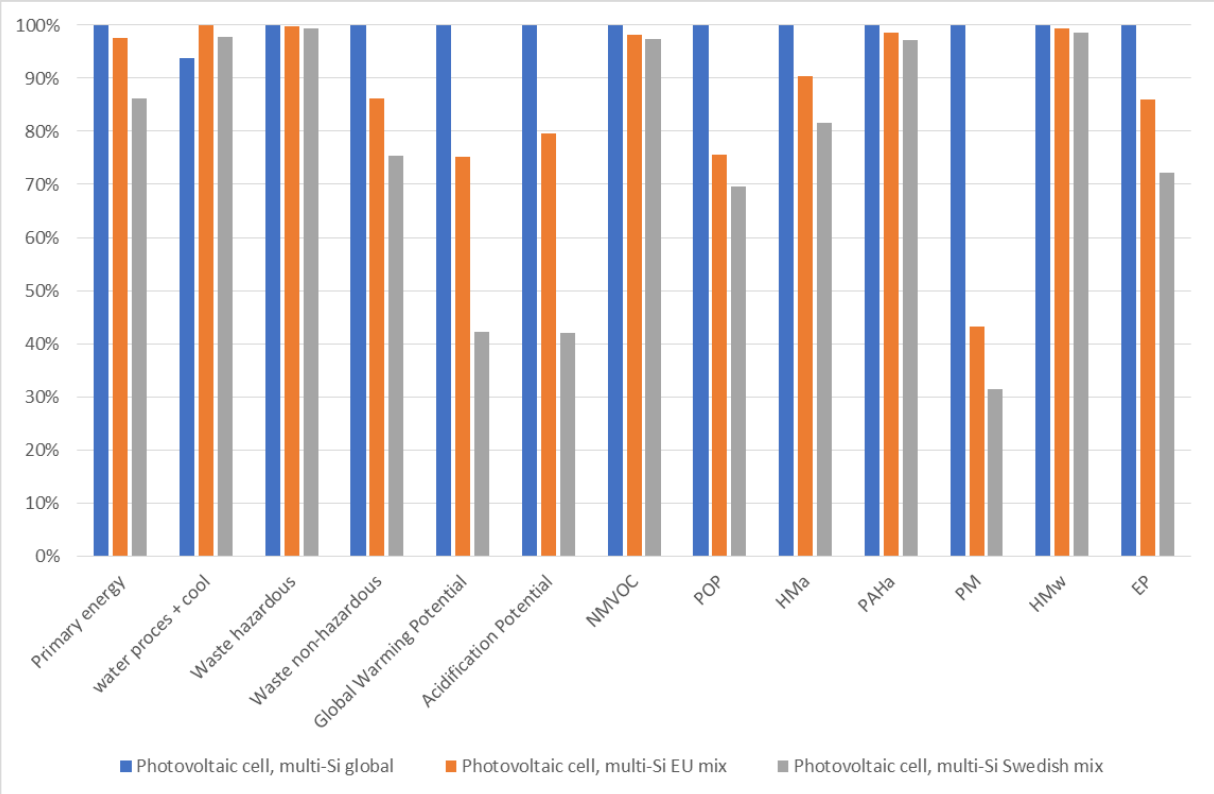

Figure 2: Comparison of environmental impact photovoltaic cell using global market mix (blue) the EU mix (orange) and using the Swedish mix (grey)

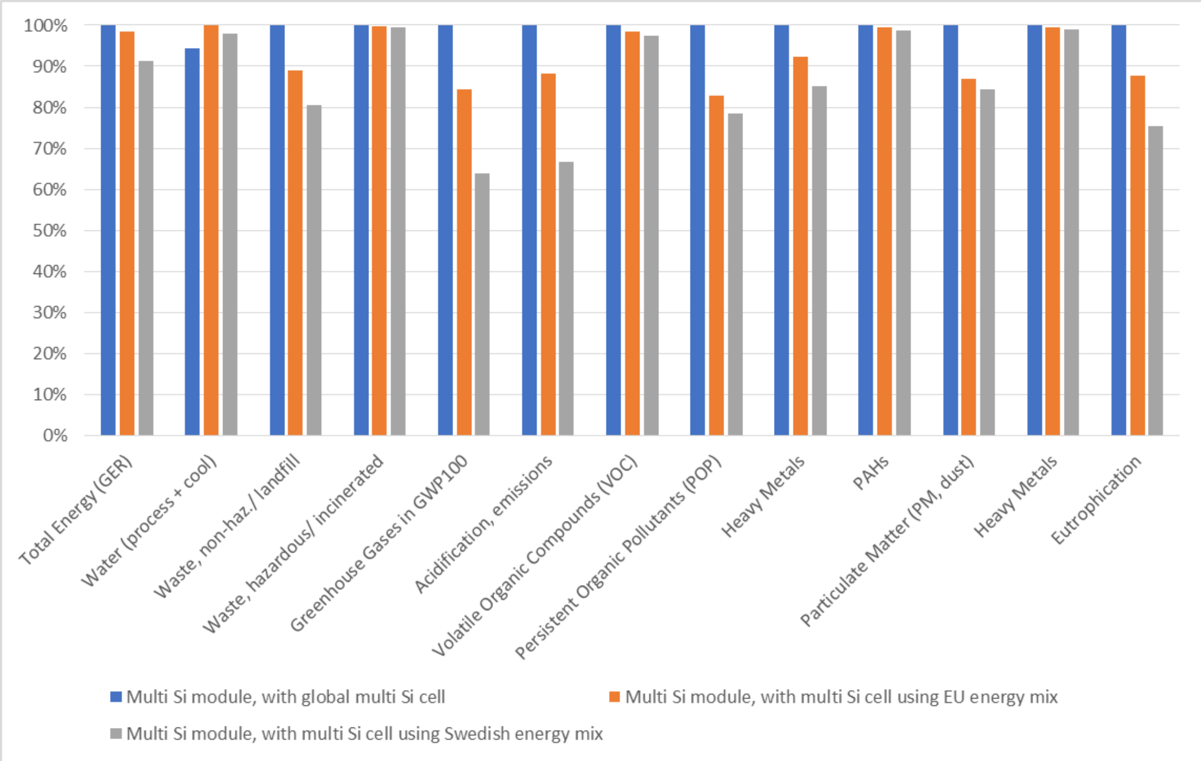

Figure 3: Comparison of the environmental impact of a multi Si module, using a cell produced according to the global market (blue) and a cell produced with the Swedish electricity mix (orange)

6.2.1.2 Influence of changes in metallis~~z~~ation and solder paste -to the results

The improved PERC module design (PERC 2025) is likely to contain lead free metallis~~z~~ation and solder paste.

The lead free alternative for metallis~~z~~ation paste contains Bismuth. It was not possible to model a lead free metallis~~z~~ation paste containing bismuth with ecoinvent datasets. Bismuth is not available in this database. The EF (Environmental Footprint) compliant datasets~~bases~~ contain~~s~~ a lead free metallis~~z~~ation paste with bismuth. The EF datasets are aggregated datasets and it is not possible to extract from these datasets the contribution of bismuth. One can also not directly compare results made with ecoinvent datasets versus results with EF datasets. Background data might differ substantially (e.g. energy/electricity mixes, assumptions for transport etc.). For this reason ~~we had to come up with~~ an alternative approach had to be devised.

Below ~~we will compare~~ the PERC 2020 module is compared with the PERC 2025 module. The PERC 2020 module includes lead containing metallis~~z~~ation paste and also lead in the solder. In this module ~~we've replaced~~ the ecoinvent dataset for metallization paste is replaced with the EF dataset for lead containing metallis~~z~~ation paste. This will allow ~~us to~~for a ~~make a~~ direct comparison to be made with the PERC 2025 module containing a lead free metallis~~z~~ation paste and lead free solder. The data source for the lead free metallization is the EF database.

~~The~~ In the tables below, the impact of the lead free metallis~~z~~ation paste is contained in the impact of the photovoltaic cell. The impact of the solder is shown separately in the categories 'interconnection – Tin', 'interconnection – lead' and 'interconnection – Copper'.

6.2.1.2.1 PERC 2020 – with ecoinvent lead containing metallis~~z~~ation paste and also lead in solder

Solder with lead, is directly modelled in ecoreport tool with ecoreport tool datasets.

Metallisation paste is as in ecoinvent (per m² cell):

Metallization paste, back side {GLO} market for | Cut-off, U	0,004931 kg	Changed into EF dataset in next step
Metallization paste, back side, aluminium {GLO}| market for | Cut-off, U	0,07191 kg	Does not contain lead, not changed to EF dataset
Metallization paste, front side {GLO}| market for | Cut-off, U	0,0073964 kg	Changed to EF dataset in next step

Table 15~~1514~~: Result for lead-free metalisation and solder paste (in absolute values per kWh)

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	9,21E-02	4,99E-01	1,06E+00	1,58E-02	3,53E+00	3,18E-02	1,43E-01	4,55E-02	1,05E-02	6,78E-02	2,86E-02	7,71E-02	6,45E-02	2,78E+01
interconnection - Tin	2,72E-03	8,71E-04	7,68E-04	8,59E-07	3,43E-03	5,82E-05	1,25E-03	5,34E-05	1,06E-05	6,97E-05	1,55E-05	6,71E-04	6,35E-06	2,56E-02
interconnection - Lead	1,53E-04	3,32E-06	3,15E-06	3,01E-09	8,19E-05	3,25E-07	7,42E-06	2,47E-07	7,25E-06	8,24E-06	1,30E-07	6,61E-07	4,88E-06	7,91E-04
interconnection - Copper	2,17E-02	2,53E-03	0,00E+00	5,25E-06	2,64E-04	1,35E-04	6,34E-03	2,09E-07	8,13E-05	1,20E-03	1,17E-04	6,17E-05	2,04E-03	3,35E-03
encapsulation - ethylvinylacetate	1,84E-01	1,72E-02	1,07E-02	6,37E-06	4,87E-02	5,25E-04	2,04E-03	4,60E-04	9,02E-05	1,32E-03	1,43E-04	6,43E-04	6,75E-05	6,17E-01
backsheet - PVF	2,36E-02	4,79E-03	3,43E-03	6,36E-06	2,21E-02	3,82E-04	1,50E-03	5,47E-05	9,61E-05	7,95E-04	6,95E-05	6,92E-04	5,42E-05	1,73E-01
backsheet - PET	7,29E-02	5,75E-03	5,32E-04	1,17E-04	6,72E-03	2,27E-04	2,51E-03	9,48E-05	0,00E+00	1,65E-04	1,06E-04	3,65E-04	1,46E-07	2,77E-02
pottant & sealing	2,57E-02	1,57E-03	3,04E-03	1,08E-06	7,17E-03	8,44E-05	3,88E-04	4,63E-05	1,98E-05	1,98E-04	2,57E-04	1,30E-04	3,27E-04	4,17E-02
alu frame	4,49E-01	8,65E-02	0,00E+00	0,00E+00	1,62E-01	4,65E-03	3,02E-02	2,97E-05	2,24E-03	1,63E-03	4,33E-02	7,59E-03	1,57E-02	2,22E-03
solar glass	1,69E+00	2,87E-02	1,41E-02	3,05E-05	2,31E-01	2,18E-03	1,79E-02	6,60E-04	5,60E-04	4,71E-03	5,92E-04	2,10E-03	9,66E-04	1,49E+00
junction box - diode	5,92E-04	4,75E-03	0,00E+00	1,40E-04	5,20E-03	2,99E-04	1,65E-03	4,08E-05	2,89E-05	2,64E-04	8,70E-06	4,31E-05	2,21E-03	1,27E-02
junction box - HDPE	5,02E-03	3,84E-04	1,71E-05	2,73E-05	1,92E-04	9,07E-06	3,06E-05	8,03E-07	0,00E+00	0,00E+00	1,73E-06	4,31E-06	0,00E+00	1,50E-04
junction box - glass fibre	6,22E-02	4,09E-03	3,38E-03	4,39E-04	1,93E-02	2,09E-04	1,81E-03	2,88E-07	0,00E+00	0,00E+00	4,03E-06	5,06E-04	2,94E-03	1,96E-01
Auxilaries	1,09E+00	1,18E-03	2,26E-03	1,35E-06	3,14E-02	6,01E-05	6,12E-04	2,21E-05	2,46E-05	3,67E-04	3,06E-05	1,15E-04	2,18E-05	5,98E-02
Total	**3,71E+00**	**6,57E-01**	**1,10E+00**	**1,66E-02**	**4,06E+00**	**4,06E-02**	**2,10E-01**	**4,69E-02**	**1,37E-02**	**7,85E-02**	**7,32E-02**	**9,00E-02**	**8,89E-02**	**3,04E+01**

Table 16~~1614~~: Relative result for lead-free metalisation and solder paste (in absolute values per kWh)

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	2%	76%	95%	95%	87%	78%	68%	97%	77%	86%	39%	86%	73%	91%
interconnection - Tin	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%
interconnection - Lead	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
interconnection - Copper	1%	0%	0%	0%	0%	0%	3%	0%	1%	2%	0%	0%	2%	0%
encapsulation - ethylvinylacetate	5%	3%	1%	0%	1%	1%	1%	1%	1%	2%	0%	1%	0%	2%
backsheet - PVF	1%	1%	0%	0%	1%	1%	1%	0%	1%	1%	0%	1%	0%	1%
backsheet - PET	2%	1%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%
pottant & sealing	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
alu frame	12%	13%	0%	0%	4%	11%	14%	0%	16%	2%	59%	8%	18%	0%
solar glass	45%	4%	1%	0%	6%	5%	9%	1%	4%	6%	1%	2%	1%	5%
junction box - diode	0%	1%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	2%	0%
junction box - HDPE	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
junction box - glass fibre	2%	1%	2%	3%	0%	1%	1%	0%	0%	0%	0%	1%	3%	1%
Auxilaries	29%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%

6.2.1.2.2 PERC 2020 – with EF lead containing metallization paste and also lead in solder

Solder with lead, directly modelled in ecoreport tool with ecoreport tool datasets -> not changed

Metallisation paste as in ecoinvent 3.4 or EF ~~database~~compliant datasets (per m² cell):

Metallization paste, front side| components mixing| production mix, at plant| 83% silver, 12% isopropanol, 5% lead {World} [LCI result]	0,004931 kg	EF dataset
Metallization paste, back side, aluminium {GLO}| market for | Cut-off, U	0,07191 kg	Remained from ecoinvent as it did not contain lead
Metallization paste, front side| components mixing| production mix, at plant| 83% silver, 12% isopropanol, 5% lead {World} [LCI result]	0,0073964 kg	EF dataset

Table 17171715: Result for lead-free metalisation and solder paste (in absolute values per kWh)

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	9,21E-02	5,00E-01	1,87E+00	1,58E-02	3,49E+00	3,19E-02	1,51E-01	4,49E-02	9,73E-03	8,51E-02	2,84E-02	7,53E-02	4,77E-02	2,41E+01
interconnection - Tin	2,72E-03	8,71E-04	7,68E-04	8,59E-07	3,43E-03	5,82E-05	1,25E-03	5,34E-05	1,06E-05	6,97E-05	1,55E-05	6,71E-04	6,35E-06	2,56E-02
interconnection - Lead	1,53E-04	3,32E-06	3,15E-06	3,01E-09	8,19E-05	3,25E-07	7,42E-06	2,47E-07	7,25E-06	8,24E-06	1,30E-07	6,61E-07	4,88E-06	7,91E-04
interconnection - Copper	2,17E-02	2,53E-03	0,00E+00	5,25E-06	2,64E-04	1,35E-04	6,34E-03	2,09E-07	8,13E-05	1,20E-03	1,17E-04	6,17E-05	2,04E-03	3,35E-03
encapsulation - ethylvinylacetate	1,84E-01	1,72E-02	1,07E-02	6,37E-06	4,87E-02	5,25E-04	2,04E-03	4,60E-04	9,02E-05	1,32E-03	1,43E-04	6,43E-04	6,75E-05	6,17E-01
backsheet - PVF	2,36E-02	4,79E-03	3,43E-03	6,36E-06	2,21E-02	3,82E-04	1,50E-03	5,47E-05	9,61E-05	7,95E-04	6,95E-05	6,92E-04	5,42E-05	1,73E-01
backsheet - PET	7,29E-02	5,75E-03	5,32E-04	1,17E-04	6,72E-03	2,27E-04	2,51E-03	9,48E-05	0,00E+00	1,65E-04	1,06E-04	3,65E-04	1,46E-07	2,77E-02
pottant & sealing	2,57E-02	1,57E-03	3,04E-03	1,08E-06	7,17E-03	8,44E-05	3,88E-04	4,63E-05	1,98E-05	1,98E-04	2,57E-04	1,30E-04	3,27E-04	4,17E-02
alu frame	4,49E-01	8,65E-02	0,00E+00	0,00E+00	1,62E-01	4,65E-03	3,02E-02	2,97E-05	2,24E-03	1,63E-03	4,33E-02	7,59E-03	1,57E-02	2,22E-03
solar glass	1,69E+00	2,87E-02	1,41E-02	3,05E-05	2,31E-01	2,18E-03	1,79E-02	6,60E-04	5,60E-04	4,71E-03	5,92E-04	2,10E-03	9,66E-04	1,49E+00
junction box - diode	5,92E-04	4,75E-03	0,00E+00	1,40E-04	5,20E-03	2,99E-04	1,65E-03	4,08E-05	2,89E-05	2,64E-04	8,70E-06	4,31E-05	2,21E-03	1,27E-02
junction box - HDPE	5,02E-03	3,84E-04	1,71E-05	2,73E-05	1,92E-04	9,07E-06	3,06E-05	8,03E-07	0,00E+00	0,00E+00	1,73E-06	4,31E-06	0,00E+00	1,50E-04
junction box - glass fibre	6,22E-02	4,09E-03	3,38E-03	4,39E-04	1,93E-02	2,09E-04	1,81E-03	2,88E-07	0,00E+00	0,00E+00	4,03E-06	5,06E-04	2,94E-03	1,96E-01
Auxilaries	1,09E+00	1,18E-03	2,26E-03	1,35E-06	3,14E-02	6,01E-05	6,12E-04	2,21E-05	2,46E-05	3,67E-04	3,06E-05	1,15E-04	2,18E-05	5,98E-02
Total	**3,71E+00**	**6,58E-01**	**1,91E+00**	**1,66E-02**	**4,02E+00**	**4,07E-02**	**2,17E-01**	**4,64E-02**	**1,29E-02**	**9,58E-02**	**7,31E-02**	**8,82E-02**	**7,21E-02**	**2,68E+01**

Table 181817: Relative results for lead-free metalisation and solder paste (in percentages)

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	2%	76%	97%	95%	87%	78%	69%	97%	75%	89%	39%	85%	66%	90%
interconnection - Tin	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%
interconnection - Lead	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
interconnection - Copper	1%	0%	0%	0%	0%	0%	3%	0%	1%	1%	0%	0%	3%	0%
encapsulation - ethylvinylacetate	5%	3%	1%	0%	1%	1%	1%	1%	1%	1%	0%	1%	0%	2%
backsheet - PVF	1%	1%	0%	0%	1%	1%	1%	0%	1%	1%	0%	1%	0%	1%
backsheet - PET	2%	1%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%
pottant & sealing	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
alu frame	12%	13%	0%	0%	4%	11%	14%	0%	17%	2%	59%	9%	22%	0%
solar glass	45%	4%	1%	0%	6%	5%	8%	1%	4%	5%	1%	2%	1%	6%
junction box - diode	0%	1%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	3%	0%
junction box - HDPE	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
junction box - glass fibre	2%	1%	1%	3%	0%	1%	1%	0%	0%	0%	0%	1%	4%	1%
Auxilaries	29%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%

6.2.1.2.3 BNAT 2025 – with EF lead free solder and lead free metallization

Lead in solder has been changed into copper in the ecoreport tool using ~~ecoreport tool~~the records provided.

Metallisation paste as in ecoinvent 3.4 or EF ~~database~~compliant datasets (per m² cell):

Metallization paste, back side| components mixing| production mix, at plant| 67% silver, 25% isopropanol, 8% bismuth {World} [LCI result] [18]	0,004931 kg	EF dataset
Metallization paste, back side, aluminium {GLO}| market for | Cut-off, U	0,07191 kg	Remained from ecoinvent as it did not contain lead
Metallization paste, back side| components mixing| production mix, at plant| 67% silver, 25% isopropanol, 8% bismuth {World} [LCI result] [19]	0,0073964 kg	EF dataset

Table 191917: Result for lead-free metalisation and solder paste (in absolute values per kWh)

~~Absolute values per kWh~~

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	6,09E-02	3,26E-01	1,35E+00	1,35E-02	2,29E+00	2,09E-02	9,97E-02	3,80E-02	6,84E-03	6,34E-02	1,89E-02	4,82E-02	4,07E-02	1,68E+01
interconnection - Tin	2,31E-02	7,40E-03	6,53E-03	7,30E-06	2,91E-02	4,95E-04	1,07E-02	4,54E-04	8,99E-05	5,93E-04	1,32E-04	5,70E-03	5,39E-05	2,18E-01
interconnection - Copper solder	7,15E-04	8,33E-05	0,00E+00	1,73E-07	8,70E-06	4,43E-06	2,09E-04	6,88E-09	2,68E-06	3,93E-05	3,84E-06	2,03E-06	6,72E-05	1,10E-04
interconnection - Copper	1,89E-02	2,20E-03	0,00E+00	4,58E-06	2,30E-04	1,17E-04	5,52E-03	1,82E-07	7,08E-05	1,04E-03	1,02E-04	5,37E-05	1,78E-03	2,92E-03
encapsulation - ethylvinylacetate	1,61E-01	1,50E-02	9,35E-03	5,55E-06	4,24E-02	4,58E-04	1,78E-03	4,00E-04	7,86E-05	1,15E-03	1,24E-04	5,60E-04	5,88E-05	5,38E-01
backsheet - HDPE	6,41E-02	4,91E-03	2,18E-04	3,49E-04	2,46E-03	1,16E-04	3,90E-04	1,03E-05	0,00E+00	0,00E+00	2,20E-05	5,51E-05	0,00E+00	1,91E-03
backsheet - PA	1,04E-02	1,24E-03	1,66E-04	1,97E-04	1,83E-03	8,88E-05	4,05E-04	9,34E-08	0,00E+00	0,00E+00	4,19E-06	5,60E-05	5,09E-04	1,94E-02
backsheet - TiO2	6,94E-03	5,81E-04	1,13E-03	7,41E-07	3,01E-02	3,82E-05	6,16E-04	9,20E-06	1,02E-05	1,21E-04	1,32E-05	3,76E-05	4,16E-04	3,10E-02
pottant & sealing	2,24E-02	1,37E-03	2,65E-03	9,44E-07	6,24E-03	7,35E-05	3,38E-04	4,03E-05	1,73E-05	1,73E-04	2,24E-04	1,13E-04	2,85E-04	3,64E-02
alu frame	3,91E-01	7,53E-02	0,00E+00	0,00E+00	1,41E-01	4,05E-03	2,63E-02	2,58E-05	1,95E-03	1,42E-03	3,78E-02	6,62E-03	1,37E-02	1,94E-03
solar glass	1,15E+00	1,95E-02	9,59E-03	2,07E-05	1,57E-01	1,48E-03	1,22E-02	4,49E-04	3,81E-04	3,20E-03	4,03E-04	1,43E-03	6,57E-04	1,02E+00
junction box - diode	5,16E-04	4,14E-03	0,00E+00	1,22E-04	4,53E-03	2,61E-04	1,44E-03	3,56E-05	2,52E-05	2,30E-04	7,58E-06	3,76E-05	1,93E-03	1,11E-02
junction box - HDPE	4,37E-03	3,35E-04	1,49E-05	2,38E-05	1,68E-04	7,90E-06	2,66E-05	6,99E-07	0,00E+00	0,00E+00	1,50E-06	3,76E-06	0,00E+00	1,30E-04
junction box - glass fibre	5,42E-02	3,57E-03	2,94E-03	3,82E-04	1,69E-02	1,82E-04	1,58E-03	2,51E-07	0,00E+00	0,00E+00	3,51E-06	4,41E-04	2,56E-03	1,71E-01
Auxilaries	9,48E-01	1,03E-03	1,97E-03	1,17E-06	2,73E-02	5,24E-05	5,33E-04	1,92E-05	2,14E-05	3,20E-04	2,66E-05	9,99E-05	1,90E-05	5,21E-02
Total	**2,91E+00**	**4,63E-01**	**1,38E+00**	**1,46E-02**	**2,75E+00**	**2,84E-02**	**1,62E-01**	**3,94E-02**	**9,49E-03**	**7,17E-02**	**5,77E-02**	**6,34E-02**	**6,28E-02**	**1,89E+01**

Table 202018: Relative results for lead-free metalisation and solder paste (in percentages)

~~Percentages~~

[18] *Thinkstep AG (2017): LCI datasets for EU Environmental Footprinting (EF) implementation 2017. Metallization paste, front side\| components mixing\| production mix, at plant\| 83% silver, 12% isopropanol, 5% lead, http://lcdn.thinkstep.com/Node, 2017, UUID: 8afeb660-6094-46bc-a9d9-21b49bc63ae3, http://lcdn.thinkstep.com. 2019.*

[19] *Thinkstep AG (2017): LCI datasets for EU Environmental Footprinting (EF) implementation 2017. Metallization paste, back side\| components mixing\| production mix, at plant\| 67% silver, 25% isopropanol, 8% bismuth {World}[LCI result], http://lcdn.thinkstep.com/Node, 2017, UUID: fc503796-57a7-412b-b44e-1143a5f3560b, http://lcdn.thinkstep.com. 2019.*

	weight	GER	water (proces + cool)	haz. Waste	non-haz. Waste	GWP	AD	VOC	POP	Hma	PAH	PM	HMw	EUP
photovoltaic cell	2%	70%	98%	92%	83%	74%	62%	96%	72%	88%	33%	76%	65%	89%
interconnection - Tin	1%	2%	0%	0%	1%	2%	7%	1%	1%	1%	0%	9%	0%	1%
interconnection - Copper solder	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
interconnection - Copper	1%	0%	0%	0%	0%	0%	3%	0%	1%	1%	0%	0%	3%	0%
encapsulation - ethylvinylacetate	6%	3%	1%	0%	2%	2%	1%	1%	1%	2%	0%	1%	0%	3%
backsheet - HDPE	2%	1%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
backsheet - PA	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%
backsheet - TiO2	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	1%	0%
pottant & sealing	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
alu frame	13%	16%	0%	0%	5%	14%	16%	0%	21%	2%	65%	10%	22%	0%
solar glass	39%	4%	1%	0%	6%	5%	8%	1%	4%	4%	1%	2%	1%	5%
junction box - diode	0%	1%	0%	1%	0%	1%	1%	0%	0%	0%	0%	0%	3%	0%
junction box - HDPE	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
junction box - glass fibre	2%	1%	0%	3%	1%	1%	1%	0%	0%	0%	0%	1%	4%	1%

6.2.2 PV inverters – residential scale

Table 21~~Table 21Table 16~~ shows the relative environmental impacts of the single design options compared to base case PV inverters under real life conditions.

Figure 4~~Figure 4~~ shows the results for the primary impact category 'Primary energy' per kWh for the defined inverters at residential scale.

Table 22~~Table 17~~ shows the relative figures of the total ~~environmental impacts~~primary energy of the base case (=100%) and the single design options.

Table 21~~21~~~~16~~: Life cycle impacts of inverter design options with respect to the base case (inverters, residential scale)

Indicators (from ecoreport)	**Base Case REF**	**Efficient**	**Longer life**	**Repair**	**Monitor.**	**MLI**	**Storage - worst**	**Storage - best**
Total Energy (GER)	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	46% ~~46%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Water	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	38% ~~38%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Waste, non-haz./ landfill	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	51% ~~51%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Waste, hazardous/ incinerated	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	47% ~~47%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Greenhouse Gases in GWP100	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	46% ~~46%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Acidification, emissions	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	46% ~~46%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Volatile Organic Compounds (VOC)	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	54% ~~54%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Persistent Organic Pollutants (POP)	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	38% ~~38%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Heavy Metals to air	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	54% ~~54%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
PAHs	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	45% ~~45%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Particulate Matter (PM, dust)	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	52% ~~52%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Heavy Metals to water	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	42% ~~42%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~
Eutrophication	100% ~~100%~~	98% ~~98%~~	39% ~~39%~~	50% ~~50%~~	97% ~~97%~~	92% ~~91%~~	120% ~~118%~~	120% ~~118%~~

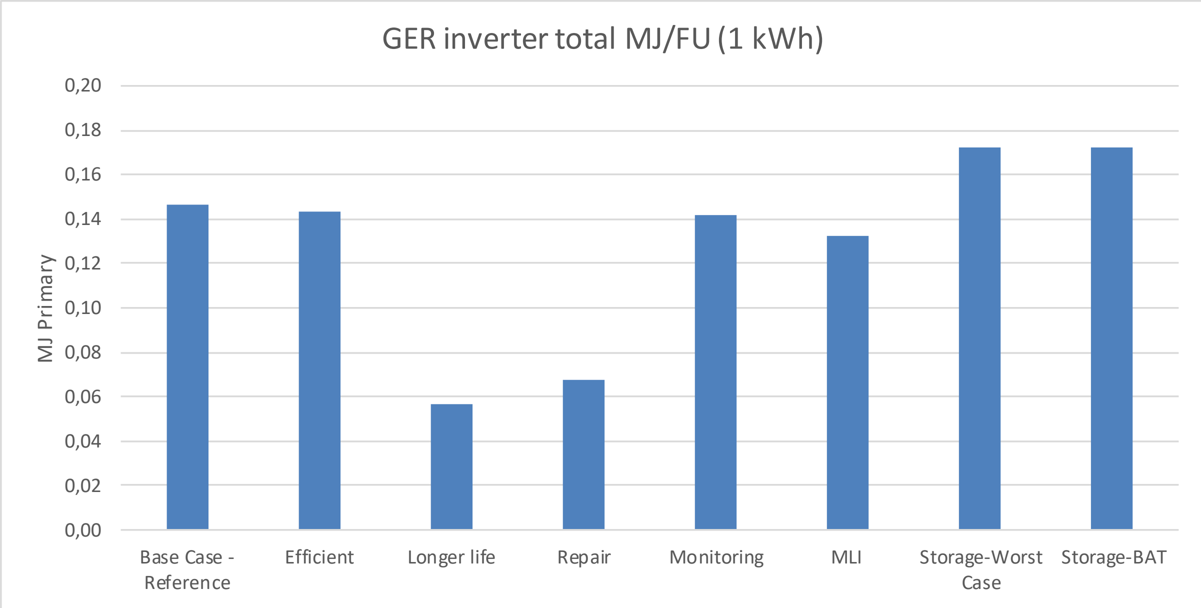

Figure 4: Primary energy results per kWh produced from inverters at residential scale

Table 22~~17~~: Ranking of selected improvement options for inverters based on selected environmental indicators (inverters, residential scale)

Option	Total Energy (primary energy)
Longer life	39%
Repair	46%
MLI (microinverter)	92~~1~~%
Monitoring	97%
Efficient	98%
Base Case - Reference	100%
Storage - BAT	120~~18~~%
Storage – worst case	120~~18~~%

6.2.3 PV inverters – commercial scale

Table 23 shows the relative environmental impacts of the single design options compared to base case PV inverters under real life conditions.

Figure 5~~Figure 5~~ shows the results for the primary impact category 'Primary energy' per kWh for the defined inverters at commercial scale.

Table 23~~18~~: Life cycle impacts of inverter design options with respect to the base case (inverters, commercial scale)

Indicator	Reference	Efficient	Repair
Total Energy (GER)	100%~~100%~~	99%~~99%~~	48%~~48%~~
Water	100%~~100%~~	99%~~99%~~	36%~~36%~~
Waste, non-haz./ landfill	100%~~100%~~	99%~~99%~~	50%~~50%~~
Waste, hazardous/ incinerated	100%~~100%~~	99%~~99%~~	47%~~47%~~
Greenhouse Gases in GWP100	100%~~100%~~	99%~~99%~~	48%~~48%~~
Acidification, emissions	100%~~100%~~	99%~~99%~~	46%~~46%~~
Volatile Organic Compounds (VOC)	100%~~100%~~	99%~~99%~~	55%~~55%~~
Persistent Organic Pollutants (POP)	100%~~100%~~	99%~~99%~~	38%~~38%~~
Heavy Metals to air	100%~~100%~~	99%~~99%~~	53%~~53%~~
PAHs	100%~~100%~~	99%~~99%~~	44%~~44%~~

Particulate Matter (PM, dust)	100%~~100%~~	99%~~99%~~	52%~~52%~~
Heavy Metals to water	100%~~100%~~	99%~~99%~~	43%~~43%~~
Eutrophication	100%~~100%~~	99%~~99%~~	53%~~53%~~

Table 24~~Table 24Table 19~~ shows the relative figures of the total ~~environmental impacts~~energy of the base case (=100%) and the single design options.

Table 24~~2419~~: Ranking of selected improvement options for inverters based on selected environmental indicators (inverters, commercial scale)

Option	**Total Energy (primary energy)**
Repair	48%
Efficient	99%
Base Case - Reference	100%

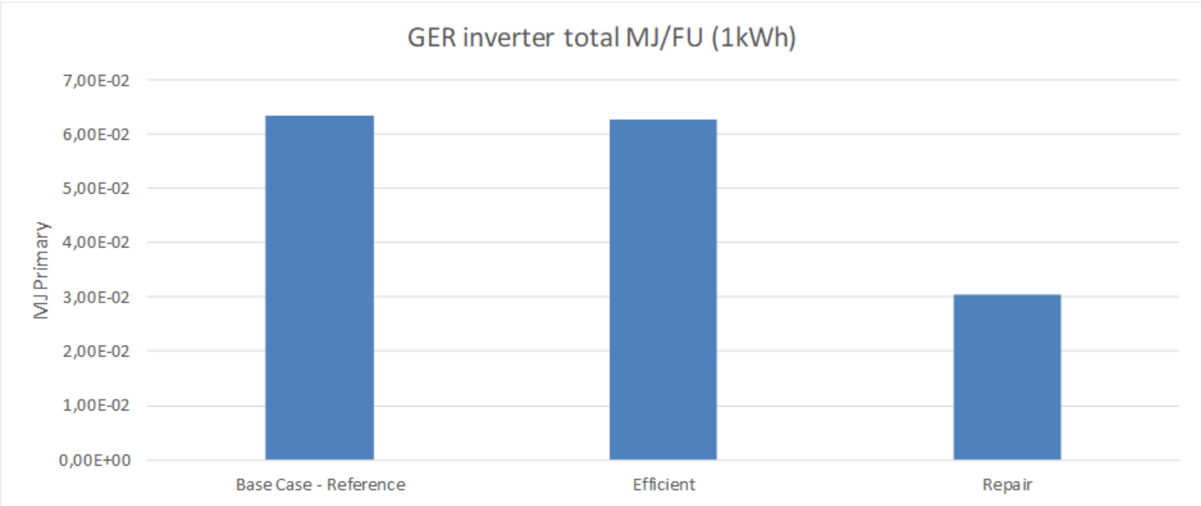

Figure 5: Primary energy results per kWh inverters commercial scale

6.2.4 PV inverters – Utility scale

Table 25~~Table 25Table 20~~ shows the relative environmental impacts of the single design options compared to base case PV inverters under real life conditions.

Figure 6~~Figure 6~~ shows the results for the primary impact category 'Primary energy' per kWh for the defined inverters at utility scale.

Table 26~~Table 26Table 21~~ shows the relative figures of the total ~~environmental impacts~~primary energy of the base case (=100%) and the single design options.

Table 25~~2520~~: Life cycle impacts of inverter design options with respect to the base case (inverters, utility scale)

Indicator	**Reference**	**Efficient**	**Efficient + string**
Total Energy (GER)	100%~~100%~~	99%~~99%~~	98%~~98%~~
Water	100%~~100%~~	99%~~99%~~	98%~~98%~~
Waste, non-haz./ landfill	100%~~100%~~	99%~~99%~~	98%~~98%~~
Waste, hazardous/ incinerated	100%~~100%~~	99%~~99%~~	98%~~98%~~
Greenhouse Gases in GWP100	100%~~100%~~	99%~~99%~~	98%~~98%~~
Acidification, emissions	100%~~100%~~	99%~~99%~~	98%~~98%~~
Volatile Organic Compounds (VOC)	100%~~100%~~	99%~~99%~~	98%~~98%~~
Persistent Organic Pollutants (POP)	100%~~100%~~	99%~~99%~~	98%~~98%~~
Heavy Metals to air	100%~~100%~~	99%~~99%~~	98%~~98%~~
PAHs	100%~~100%~~	99%~~99%~~	98%~~98%~~

Particulate Matter (PM, dust)	100%~~100%~~	99%~~99%~~	98%~~98%~~
Heavy Metals to water	100%~~100%~~	99%~~99%~~	98%~~98%~~
Eutrophication	100%~~100%~~	99%~~99%~~	98%~~98%~~

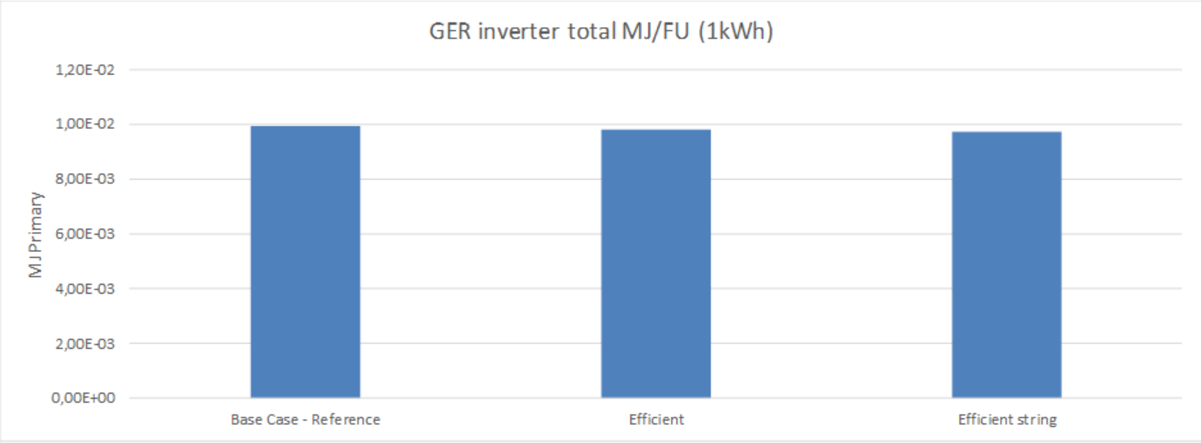

Figure 6: Primary energy results per kWh produced from inverters utility scale

Table 26~~2621~~: Ranking of selected improvement options for inverters based on selected environmental indicators (inverters, utility scale)

Option	**Total Energy (primary energy)**
Efficient +string	98%
Efficient	99%
Base Case - Reference	100%

6.2.5 PV Systems

~~6.2.5~~ In this section the results for systems composed of different module and inverter combinations, together with ~~Note: all system level results include~~ the Balance of System (BOS) are compiled. In each case the results are presented in both absolute and normalised forms.

6.2.5.1 BC 1 residential scale

To define the design options, a combination has been made of the reference inverter with the different module options and of the reference module with the different design options for the inverter (package options). In addition, optimised systems making use of the best module and best inverter have been considered as a system option. The best module available for use in a residential scale situation is either the CIGS option or the ~~optimised~~ BAT ~~multi-Si~~PERC 2025 module (a hypothetical case). The different options, called package options and system options are discussed in more detail in paragraph 6.1.3.1.

The best inverter combines the benefits of the inverter with a longer life span and the inverter with monitoring functions. In a final design option, the best module and inverter are combined with an optimised design.

Figure 7~~Figure 7~~ shows the results (primary energy) for the defined systems in absolute terms (the orange bars) and as normalised to the functional unit of 1 kWh electricity (the blue line). The optimised systems are the best performing systems, together with the system combining the BAT PERC 2025 module and reference inverter (PO 6).~~.~~

Table 27 shows from the Ecoreport LCA tool the relative environmental impacts of the design options for the residential scale compared to the base case at residential scale.

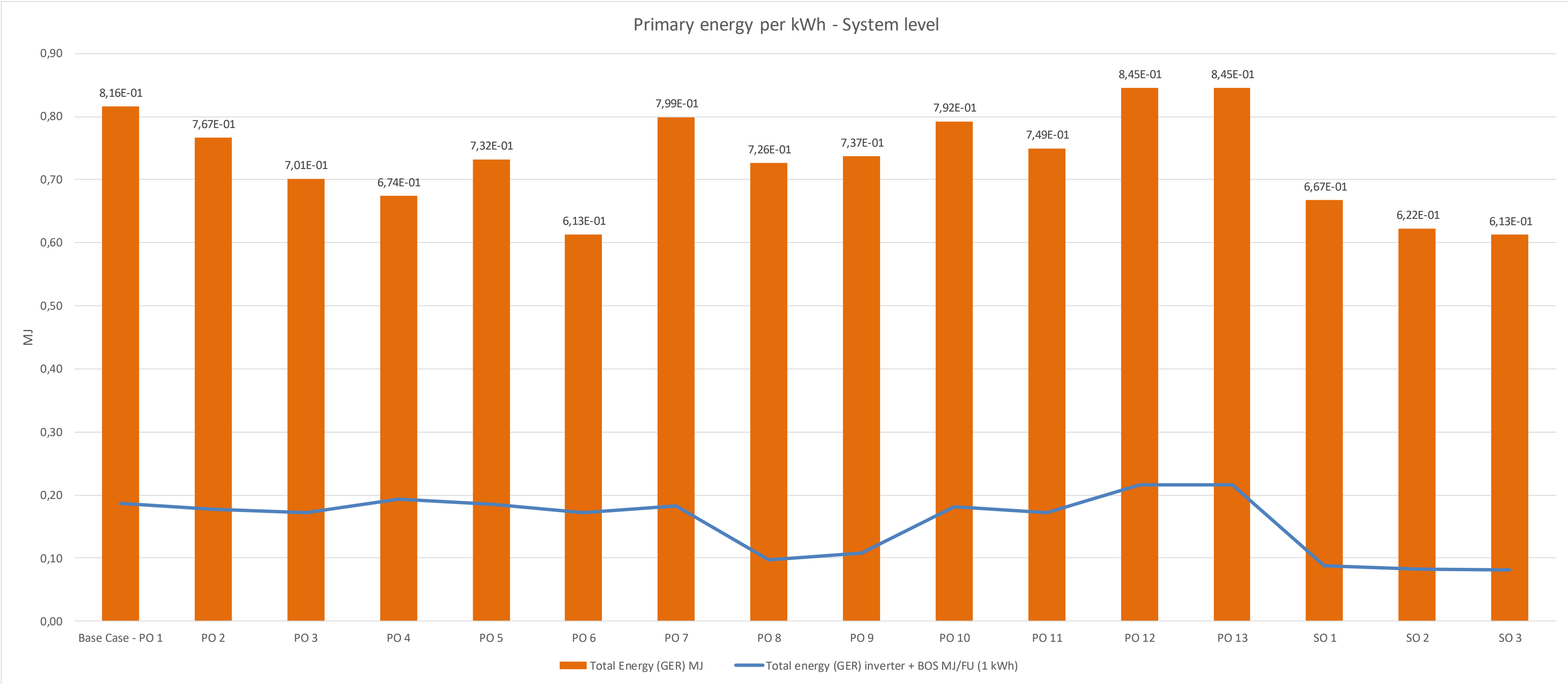

Figure 7: Primary energy at system level for different design options at residential scale

(PO 1): Multi Si module and reference inverter, (PO2): Optimised PERC 2020 module and reference inverter; (PO 3): BAT PERC 2019 module and reference inverter; (PO 4): CIGS module and reference inverter; (PO 5): Silicion heterojunction module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): Multi Si module and more efficient inverter; (PO 8): Multi Si module and longer life inverter; (PO 9): Multi Si Module and inverter with repair; (PO 10): Multi Si module and inverter including monitoring; (PO 11): Multi Si module and multi-level inverter; (PO 12): Multi Si module and inverter including storage (worst case); (PO 13): Multi Si module and inverter including storage (best case).

(SO 1): Optimised PERC 2020 + best inverter; (SO 2): Optimised PERC 2020+ best inverter + better design; (SO 3): Optimised PERC 2020+ best inverter + optimised O&M

Table 27: Life cycle impacts of residential package or system options with respect to the base case

Indicators (from Ecoreport)	Base case – PO1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	PO 10	PO 11	PO 12	PO 13	SO 1	SO 2	SO 3
Total Energy (GER)	100%	94%	86%	83%	90%	75%	98%	89%	90%	97%	92%	104%	104%	82%	76%	75%
Water	100%	117%	109%	58%	82%	137%	98%	74%	74%	97%	92%	108%	108%	90%	84%	83%
Waste, non-haz./ landfill	100%	112%	102%	41%	108%	85%	98%	90%	92%	97%	92%	103%	103%	100%	94%	92%
Waste, hazardous/ incinerated	100%	61%	57%	45%	63%	57%	98%	78%	81%	97%	92%	107%	107%	38%	36%	35%
Greenhouse Gases in GWP100	100%	96%	88%	82%	92%	77%	98%	89%	90%	97%	92%	104%	104%	84%	78%	77%
Acidification, emissions	100%	94%	86%	77%	94%	80%	98%	88%	90%	97%	92%	104%	104%	81%	76%	74%
Volatile Organic Compounds (VOC)	100%	84%	75%	19%	86%	71%	98%	96%	97%	97%	92%	101%	101%	79%	74%	73%
Persistent Organic Pollutants (POP)	100%	95%	88%	68%	102%	78%	98%	78%	78%	97%	92%	107%	107%	73%	68%	67%
Heavy Metals to air	100%	93%	87%	62%	108%	88%	98%	78%	83%	97%	92%	107%	107%	70%	65%	64%
PAHs	100%	81%	73%	69%	80%	65%	98%	96%	96%	97%	92%	101%	101%	75%	70%	69%
Particulate Matter (PM, dust)	100%	89%	80%	82%	88%	74%	98%	97%	98%	97%	92%	101%	101%	85%	80%	78%
Heavy Metals to water	100%	88%	81%	51%	109%	70%	98%	81%	82%	97%	92%	106%	106%	68%	63%	62%
Eutrophication	100%	102%	93%	53%	119%	70%	98%	93%	94%	97%	92%	102%	102%	93%	87%	85%

(PO 1): Multi Si module and reference inverter, (PO2): Optimised PERC 2020 module and reference inverter; (PO 3): BAT PERC 2019 module and reference inverter; (PO 4): CIGS module and reference inverter; (PO 5): Silicion heterojunction module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): Multi Si module and more efficient inverter; (PO 8): Multi Si module and longer life inverter; (PO 9): Multi Si Module and inverter with repair; (PO 10): Multi Si module and inverter including monitoring; (PO 11): Multi Si module and multi-level inverter; (PO 12): Multi Si module and inverter including storage (worst case); (PO 13): Multi Si module and inverter including storage (best case).

(SO 1): Optimised PERC 2020 + best inverter; (SO 2): Optimised PERC 2020+ best inverter + better design; (SO 3): Optimised PERC 2020+ best inverter + optimised O&M

6.2.5.2 BC 2 commercial scale

Again, the considered design options are a combination of the reference inverter with the different module options and of the reference module with the different design options for the inverter. In addition, an optimis~~z~~ed system has been defined which consist of a PERC bifacial module and the benefits of an inverter with improved repair and high efficiency. The derating factors in this system design are higher due to lower cable losses and a tailored design.

Figure 8~~Figure 8~~ shows the results (primary energy) for the different systems in absolute terms (the orange bars) and as normalised to the functional unit of 1 kWh electricity (the blue line). The system with the lowest contribution to primary energy is a system combining a CdTe module with a reference inverter (PO 5). The optimised system, using a bifacial PERC 2019 module and an optimised inverter has the third lowest contribution.

As an indication, ~~T~~the system combining the BNAT PERC bifacial 2025 + recycled wafers module with the reference inverter has the second lowest contribution. In the modelling of this system a first attempt has been made to take the potential for the recycling of wafers into account. Further investigation ~~in~~of the environmental impact of this system is however necessary before taking any further conclusions.

Table 28 shows from the Ecoreport LCA tool the relative environmental impacts of the design options for the commercial scale compared to the base case at residential scale.

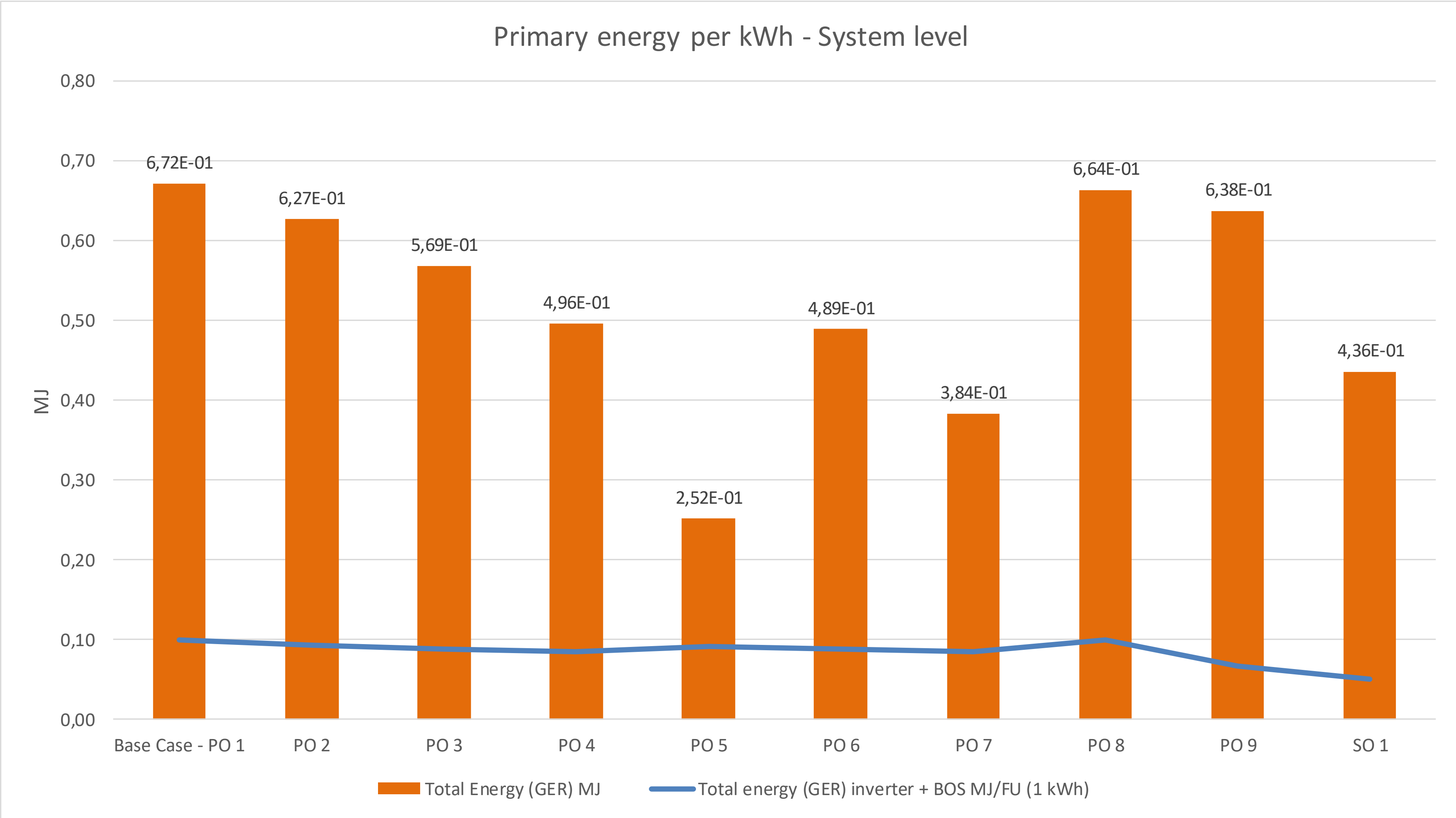

Figure 8: Primary energy at system level for different design options at commercial scale

(SO 1): best combination and design; (PO 1): Multi Si module and reference inverter; (PO 2): Optimised PERC 2020 module and reference inverter; (PO 3):BAT PERC 2019 module and reference inverter; (PO 4):BAT PERC bifacial 2019 module and reference inverter; (PO 5): CdTe module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter; (PO 8):Multi Si module and more efficient inverter; (PO 9): Multi Si module and inverter with repair

Table 28: Life cycle impacts of commercial package or system options with respect to the base case

Indicators (from Ecoreport)	Base case – PO1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
Total Energy (GER)	100%	93%	85%	74%	38%	73%	57%	99%	95%	65%
Water	100%	122%	112%	100%	34%	147%	86%	99%	83%	78%
Waste, non-haz./ landfill	100%	113%	103%	90%	23%	84%	63%	99%	95%	81%
Waste, hazardous/ incinerated	100%	53%	49%	45%	27%	49%	35%	99%	88%	32%
Greenhouse Gases in GWP100	100%	96%	87%	76%	37%	74%	59%	99%	95%	67%
Acidification, emissions	100%	93%	85%	75%	44%	78%	61%	99%	94%	65%
Volatile Organic Compounds (VOC)	100%	84%	75%	65%	10%	71%	61%	99%	98%	60%
Persistent Organic Pollutants (POP)	100%	94%	86%	78%	37%	74%	63%	99%	87%	61%
Heavy Metals to air	100%	92%	84%	76%	41%	86%	61%	99%	90%	62%
PAHs	100%	80%	72%	63%	9%	64%	51%	99%	98%	57%
Particulate Matter (PM, dust)	100%	89%	79%	69%	61%	74%	62%	99%	99%	64%
Heavy Metals to water	100%	86%	78%	70%	22%	65%	57%	99%	89%	56%
Eutrophication	100%	102%	92%	81%	18%	68%	61%	99%	97%	73%

SO 1): best combination and design; (PO 1): Multi Si module and reference inverter; (PO 2): Optimised PERC 2020 module and reference inverter; (PO 3):BAT PERC 2019 module and reference inverter; (PO 4):BAT PERC bifacial 2019 module and reference inverter; (PO 5): CdTe module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter; (PO 8):Multi Si module and more efficient inverter; (PO 9): Multi Si module and inverter with repair

6.2.5.3 BC 3 Utility scale

Also, at utility scale the considered design options are a combination of the reference (central) inverter with the different module options and of the reference module with the different design options for the inverter. In addition, an optimised system has been defined which consists of a CdTe module and an energy efficient inverter. The system makes use of single axis tracking.

Figure 9Figure 9 shows the results (primary energy) for the different systems in absolute terms (the orange bars) and as normalised to the functional unit of 1 kWh electricity (the blue line). The system with the lowest contribution to primary energy is the optimised a system combining a CdTe module with an efficient string inverter and tracking (SO 1)with a reference inverter. The option combining the CdTe module and reference inverter (PO 5) has the second lowest contribution to primary energy. compared to the system using a CdTe module in combination with a central inverter.

Table 29 shows from the Ecoreport LCA tool the relative environmental impacts of the design options for utility scale compared to the base case at residential scale.

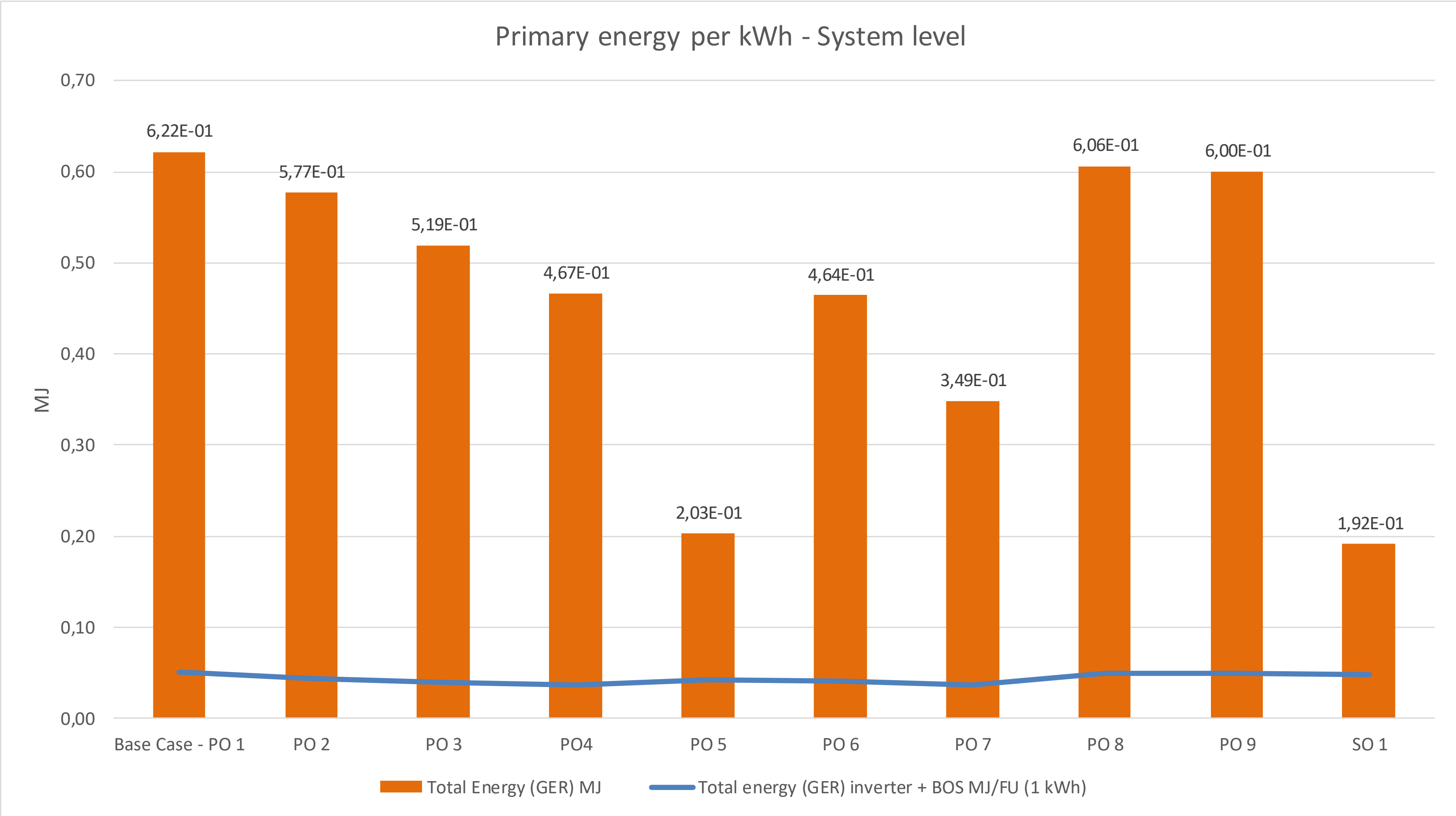

Figure 9: Primary energy at system level for different design options at utility scale

(SO 1): best combination and design including single axis tracker; (PO 1): Multi Si module and reference inverter and reference BOS; (PO 2): Optimised PERC 2020 module and reference inverter and reference BOS; (PO 3): BAT PERC 2019 module and reference inverter and reference BOS; (PO 4): BAT PERC bifacial 2019 module and reference inverter and reference BOS; (PO 5): CdTe module and reference inverter and reference BOS; (PO6): BAT PERC 2025 module and reference inverter and reference BOS; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter and reference BOS; (PO 8): Multi Si module and more efficient inverter and reference BOS; (PO 9): Multi Si module and more efficient string inverter and reference BOS

Table 29: Life cycle impacts of utility scale package or system options with respect to the base case

Indicators (from Ecoreport)	Base case – PO1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
Total Energy (GER)	100%	93%	84%	75%	33%	75%	56%	98%	97%	31%
Water	100%	122%	112%	104%	33%	155%	89%	98%	97%	31%
Waste, non-haz./ landfill	100%	114%	103%	94%	18%	87%	64%	97%	96%	22%
Waste, hazardous/ incinerated	100%	39%	34%	31%	6%	36%	18%	97%	96%	6%
Greenhouse Gases in GWP100	100%	96%	86%	78%	32%	76%	58%	98%	97%	30%
Acidification, emissions	100%	91%	82%	74%	45%	79%	61%	98%	97%	43%
Volatile Organic Compounds (VOC)	100%	84%	74%	68%	9%	74%	64%	97%	96%	9%
Persistent Organic Pollutants (POP)	100%	93%	85%	78%	32%	75%	62%	98%	97%	49%
Heavy Metals to air	100%	90%	80%	73%	33%	87%	56%	98%	97%	35%
PAHs	100%	79%	71%	64%	7%	67%	52%	97%	96%	8%
Particulate Matter (PM, dust)	100%	89%	79%	72%	61%	78%	64%	97%	96%	56%
Heavy Metals to water	100%	83%	74%	67%	6%	62%	50%	97%	96%	8%
Eutrophication	100%	102%	92%	84%	14%	70%	61%	97%	96%	13%

(SO 1): best combination and design including single axis tracker; (PO 1): Multi Si module and reference inverter and reference BOS; (PO 2): Optimised PERC 2020 module and reference inverter and reference BOS; (PO 3): BAT PERC 2019 module and reference inverter and reference BOS; (PO 4): BAT PERC bifacial 2019 module and reference inverter and reference BOS; (PO 5): CdTe module and reference inverter and reference BOS; (PO6): BAT PERC 2025 module and reference inverter and reference BOS; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter and reference BOS; (PO 8): Multi Si module and more efficient inverter and reference BOS; (PO 9): Multi Si module and more efficient string inverter and reference BOS

6.3 Analysis of BAT and LLCC

The design options identified in the technical, environmental and economic analysis in subtask 6.1 must be ranked regarding the Best Available Technology (BAT) and the Least (minimum) Life Cycle Costs. More specifically, ~~work in~~ this section ~~will~~ includes:

- Ranking of the identified design options by LCC (e.g. option 1, option 2, option 3), considering possible trade-offs between different environmental impacts;
- Estimating the cumulative improvement and cost effect of implementing the ranked options simultaneously (e.g. option 1, option 1+2, option 1+2+3, etc.), also taking into account 'rebound' side effects of the individual design measures;
- Ranking of the cumulative design options, drawing of a LCC-curve (Y-axis= LLCC, X-axis= options) and identifying the Least Life Cycle Cost (LLCC) point and the BAT point.

The improvement potential resulting from the ranking is discussed ~~will be discussed, such as~~and informs further discussion in the Task 7 report as to:

- the appropriateness to set minimum requirements at the LLCC point,
- to use the environmental performance of the BAT point or benchmarks set in other countries,
- if manufacturers will make use of this ranking to evaluate alternative design solutions and the achieved environmental performance of the products.

6.3.1 Lead environmental impact category and supplementary parameters

Based on the results of Tasks 4 and ~~/~~5 and the 14 impact categories that MEErP considers, GWP(CO_2eq) and the related Primary Energy(MJ) could be used as significant ~~(see Task 5)~~ parameters that can be optimis~~z~~ed.

Primary energy (referred to in Ecoreport as total primary energy) has been chosen as the lead indicator. It excludes the regionalised effects of process energy requirements as far as possible, such as the grid electricity generating mix, as analysed in 6.2.1.1 [20]. It instead ensures a focus on the improvement potential of production processes and material choices.

Other environmental parameters assessed in the MEErP Ecoreport tool are listed below,~~.~~ And can be seen to combine mid-point impact categories and inventory flow indicators: ~~They can be considered as secondary impact categories.~~

- Water
- Non hazardous waste
- Hazardous waste
- Acidification
- Volatile Organic Compounds
- Persistent Organic Pollutants
- Heavy Metals
- PAHs (Polycyclic Aromatic Hydrocarbons)
- Particulate Matter

[20] Regionalis~~z~~ed effects are assumed to be excluded in the materials which are available in the Ecoreport tool. A lot of materials had to be added to the Ecoreport tool to appropriately model the modules and inverters. The environmental impact for those materials was sourced from other databases and includes different types of energy sources and mixes.

Using a combination of the weightings according to societal costs in the Ecoreport tool and analysis of which impact categories contributions are not strongly linked to electricity generation, the following impact categories could be used as secondary indicators:

Modules:

- Polycyclic aromatic hydrocarbonsPAHs
- Volatile organic compounds
- Heavy metals

Inverters

- Photochemical ozone formation
- Polycyclic aromatic hydrocarbonsPAHs
- Heavy metals

6.3.2 LCC of the design options for PV modules

Figure 10Figure 10 provides the module costs in euro/Wp at residential scale. They represent average costs. To understand the LCOE for different modules the system design option results should be consulted (see 6.3.5). BNAT options have been omitted because of a lack of certainty on their costs.

These costs, particularly for mass market modules such as PERC 2019, can be expected to shift rapidly, with downward pressure from the demand side, for example from capacity auctions, and as further planned economies of scale are implemented from the supply side. For example, the Mono PERC spot price range is, as of later 2019 quoted within a range of 0.19 – 0.35 €/Wp. Some market commentators also segment costs into categories such as high efficiency, mainstream and low cost.

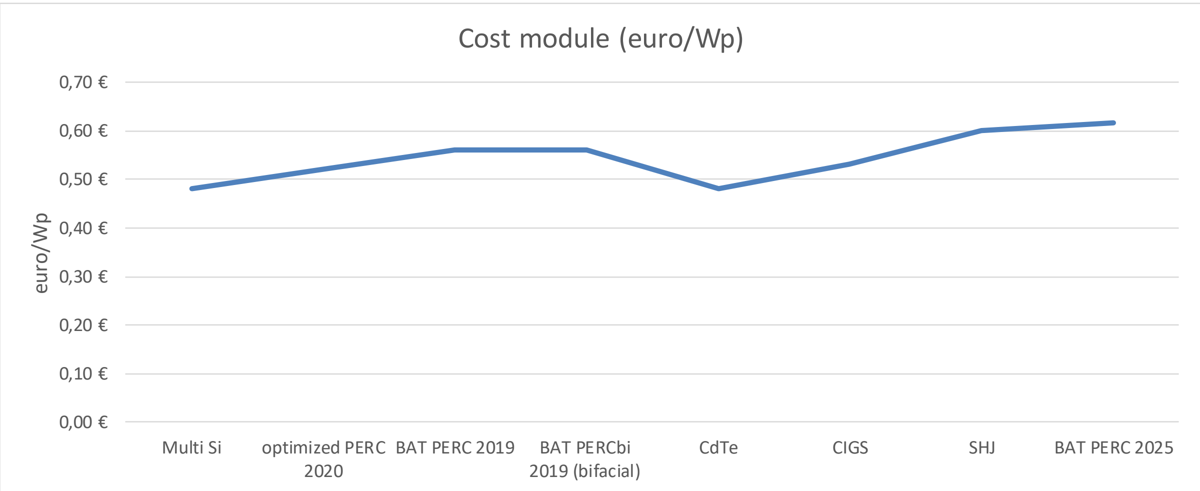

Figure 10: Module costs in euro per Wp

6.3.2.1 Residential scale (BC 1)

The CIGS module is the best (currently) available technology (BAT) from an environmental perspective (when looking at primary energy), taking into account that the 2025 option is a hypothetical case. Although the results may be within the margin of error. The multi Si base case has the lowest cost per Wp. and the Multi si optimized from a life cycle cost perspective. It is to be noted, however, that the CIGS technology has a very low penetration rate in the residential sector (see Task 2). Given that the Multi Si optimized is predicted to become obsolete from the market after 2020, it is suggested that after that

date, he CIGS becomes the best available technology from both environmental and cost perspectives.
Figure 11Figure 11 shows the results for the different modules on primary energy (per kWh) and costs (per Wp).

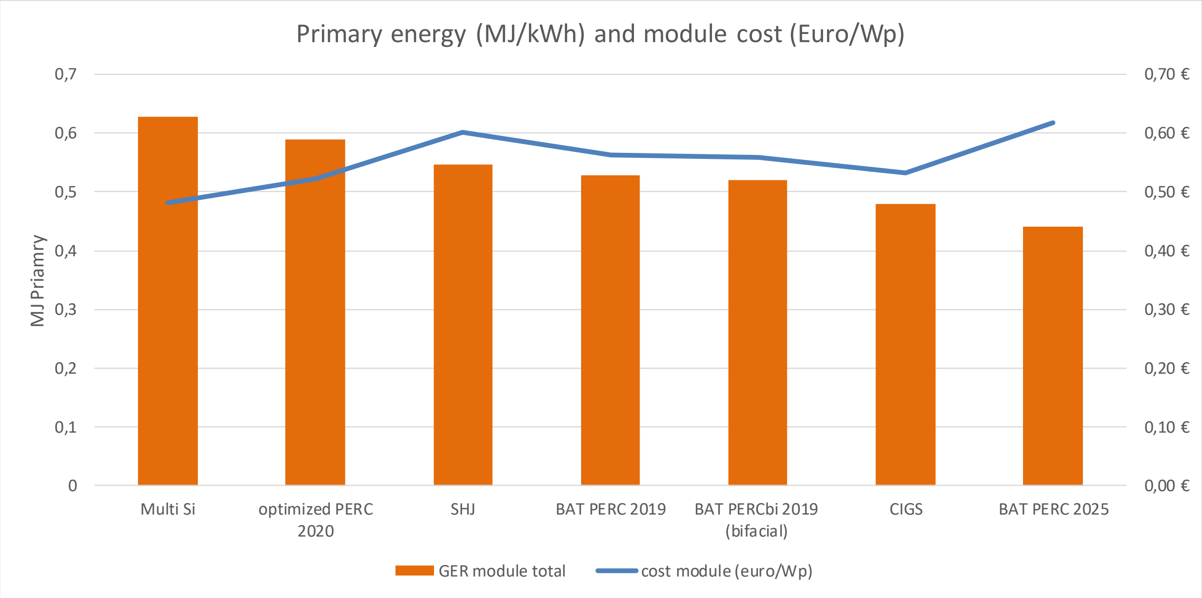

Figure 11: Modules Primary energy (MJ/kWh) and cost (per Wp) at residential scale

6.3.2.2 Commercial scale (BC 2)

The CdTe module is the best available technology (BAT) from an environmental (when looking at primary energy) and economic point of view (cost per Wp). The multi Si reference module has a comparable cost per Wp to the , the multi Si optimised module and the CdTe module all have comparable costs.

Figure 12Figure 12 shows the results for the different modules on primary energy (per kWh) and costs (per Wp). Information on costs of kerfless old modules, SHJ modules and BNAT kerfless new are missing.

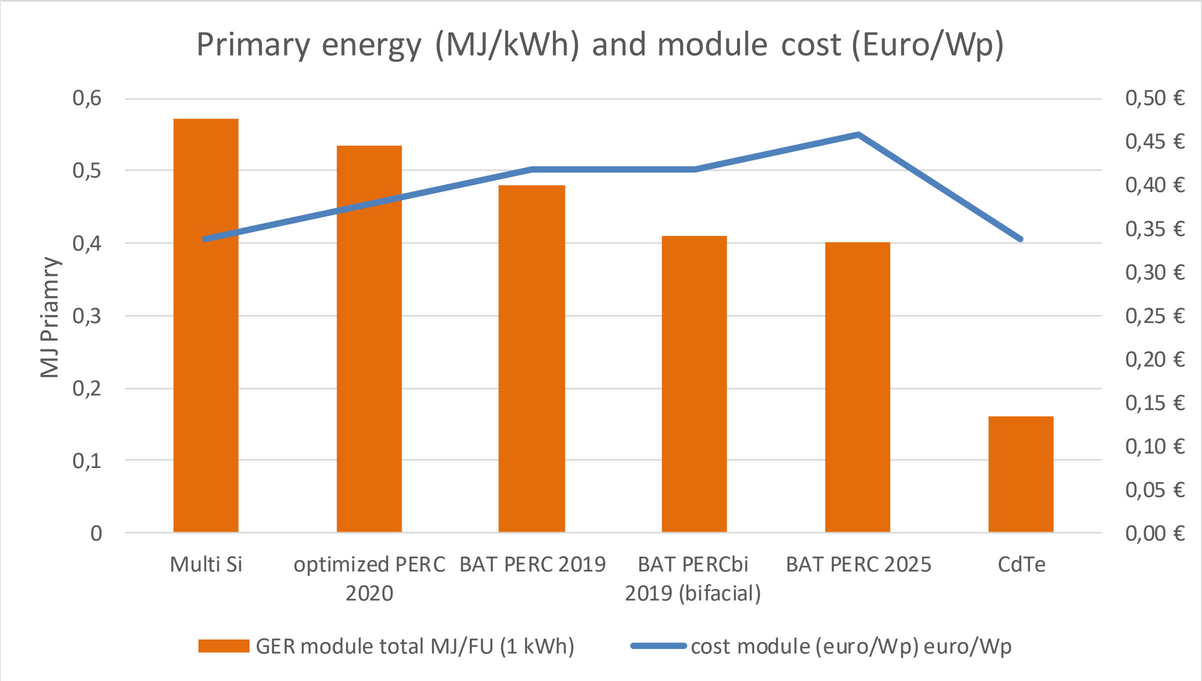

Figure 12: Modules Primary energy (MJ/kWh) and cost (per Wp) at commercial scale

6.3.2.3 Utility scale (BC 3)

The CdTe module is the best available technology (BAT) from an environmental (~~when looking at~~ primary energy) and economic point of view. The multi Si reference module has comparable costs to the ~~, the multi Si optimised module and the~~ CdTe module ~~all have comparable costs~~.

Figure 13~~Figure 13~~ shows the results for the different modules on primary energy (per kWh) and costs (per Wp). ~~Information on costs of kerfless old modules, SHJ modules and BNAT kerfless new are missing.~~

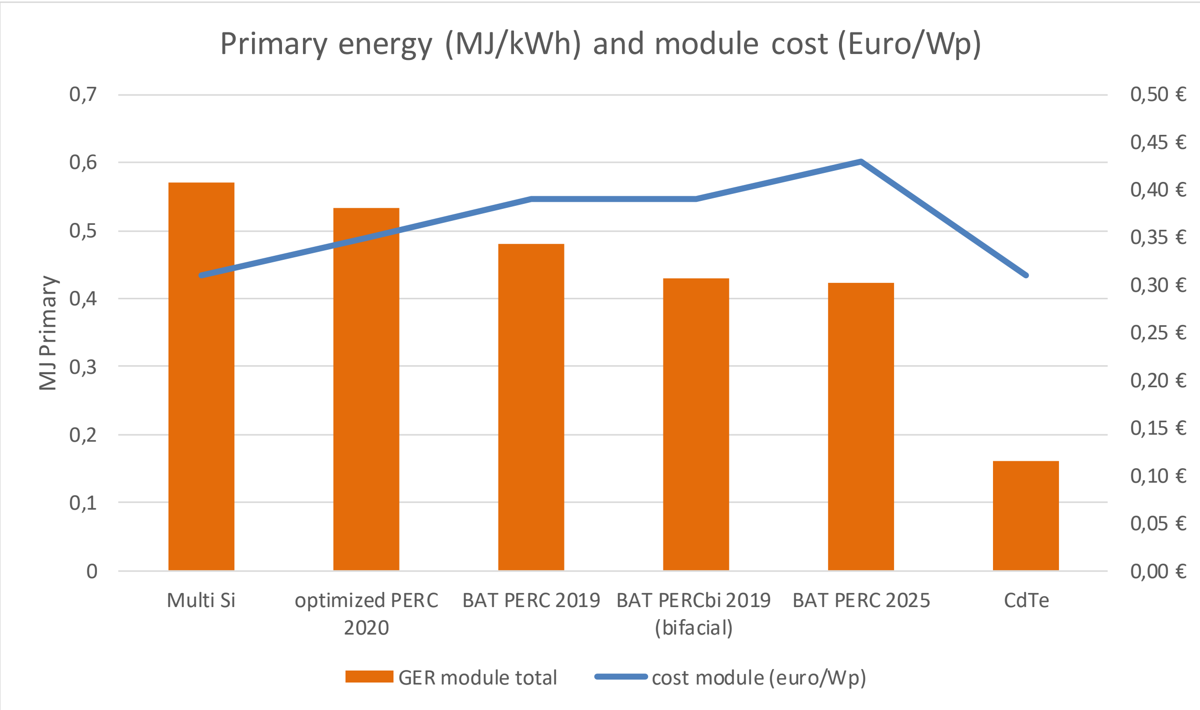

Figure 13: Modules Primary energy (MJ/kWh) and cost (per Wp) at utility scale

6.3.3 LCC of the design options for the inverters

6.3.3.1 Residential scale (BC 1)

Figure 14~~Figure 14~~ provides the inverter life cycle cost in euro per Watt.

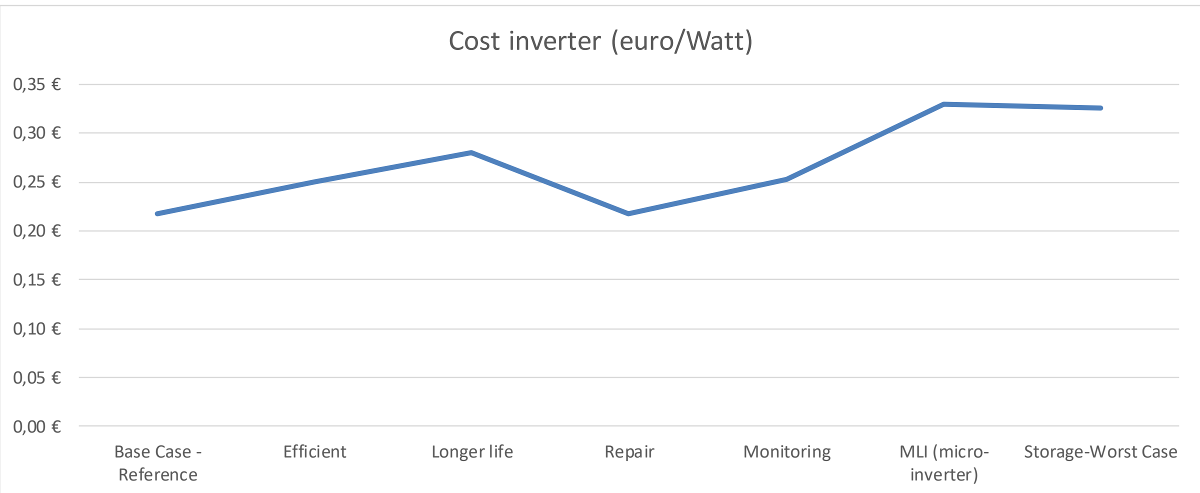

Figure 14: Inverter life cycle cost in Euro per Watt – residential scale

6.3.3.2 Commercial scale (BC 2)

Figure 15~~Figure 15~~ provides the inverter life cycle cost in euro per Watt.

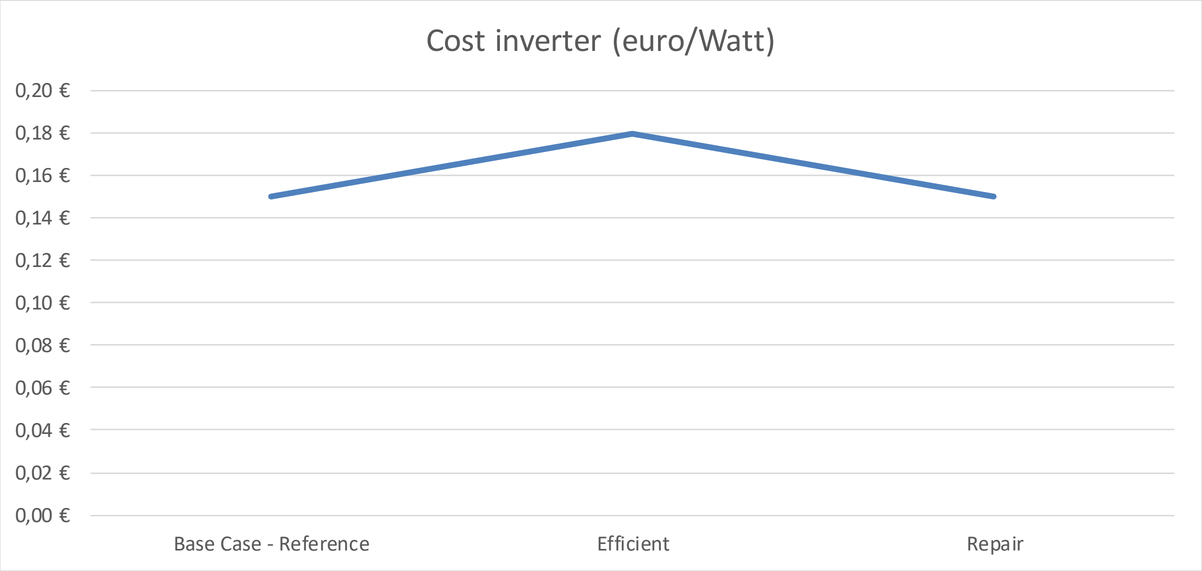

Figure 15: Inverter life cycle cost in Euro per Watt – commercial scale

6.3.3.3 Utility scale (BC 3)

Figure 16~~Figure 16~~ provides the inverter life cycle cost in euro per Watt.

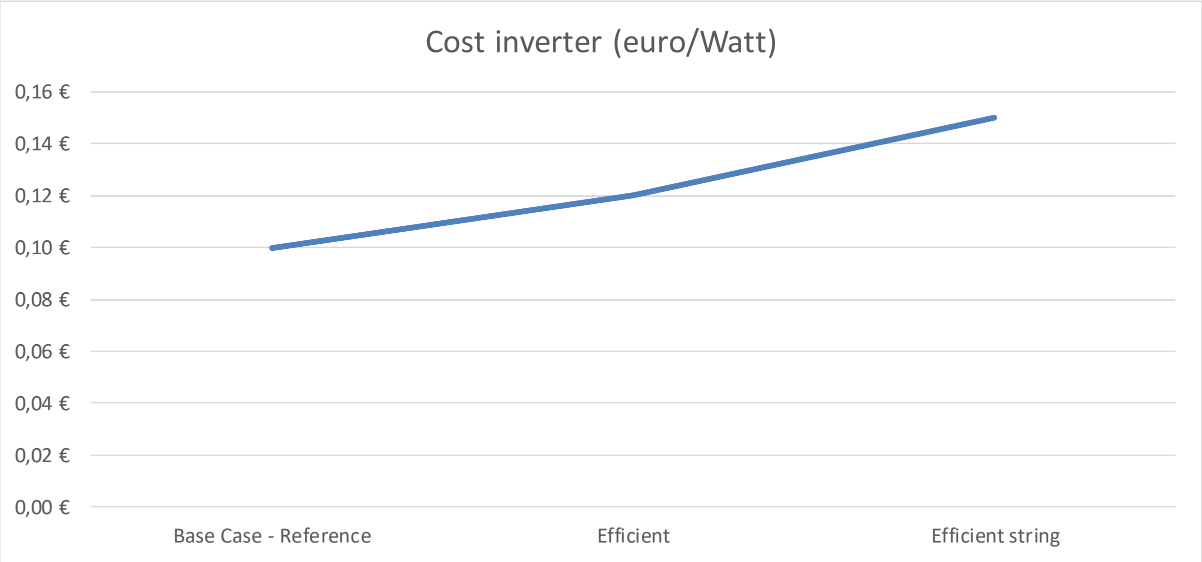

Figure 16: Inverter life cycle cost in Euro per Watt – utility scale

6.3.4 Best available and Least LCC options of inverters

6.3.4.1 Residential scale (BC 1)

The best available technology from an environmental point of view (primary energy only) is the inverter with a longer life span. ~~Form~~ From an economic point of view, the costs are lower for the reference inverter and repaired inverter. The benefits of the repair option could only be achieved if the ongoing servicing was provided to the household installing the inverter, which it is understood may not always be the case.

Figure 17Figure 17 shows the results for the different inverters on primary energy (per kWh) and costs (per Watt)

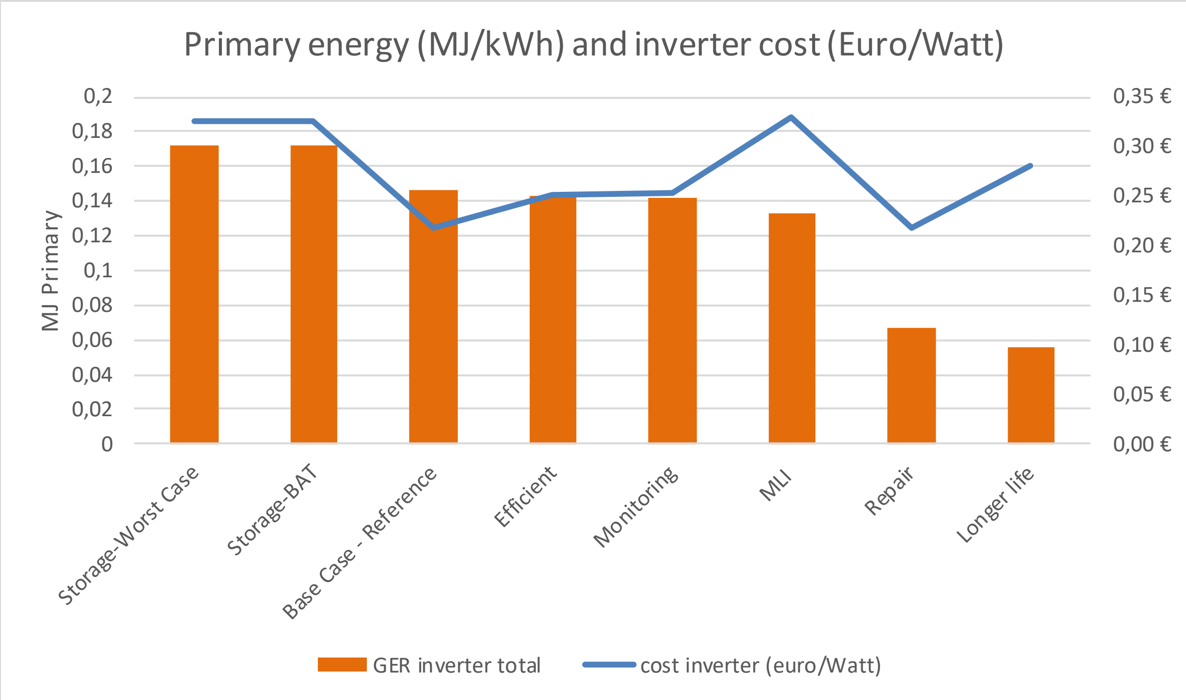

Figure 17: Inverters primary energy and cost – residential scale

6.3.4.2 Commercial scale (BC 2)

The best available technology from an environmental point of view (primary energy only) is the inverter with repair, also the costs are lowest for this design option.

Figure 18Figure 18 shows the results for the different inverters on primary energy (per kWh) and costs (per Watt)

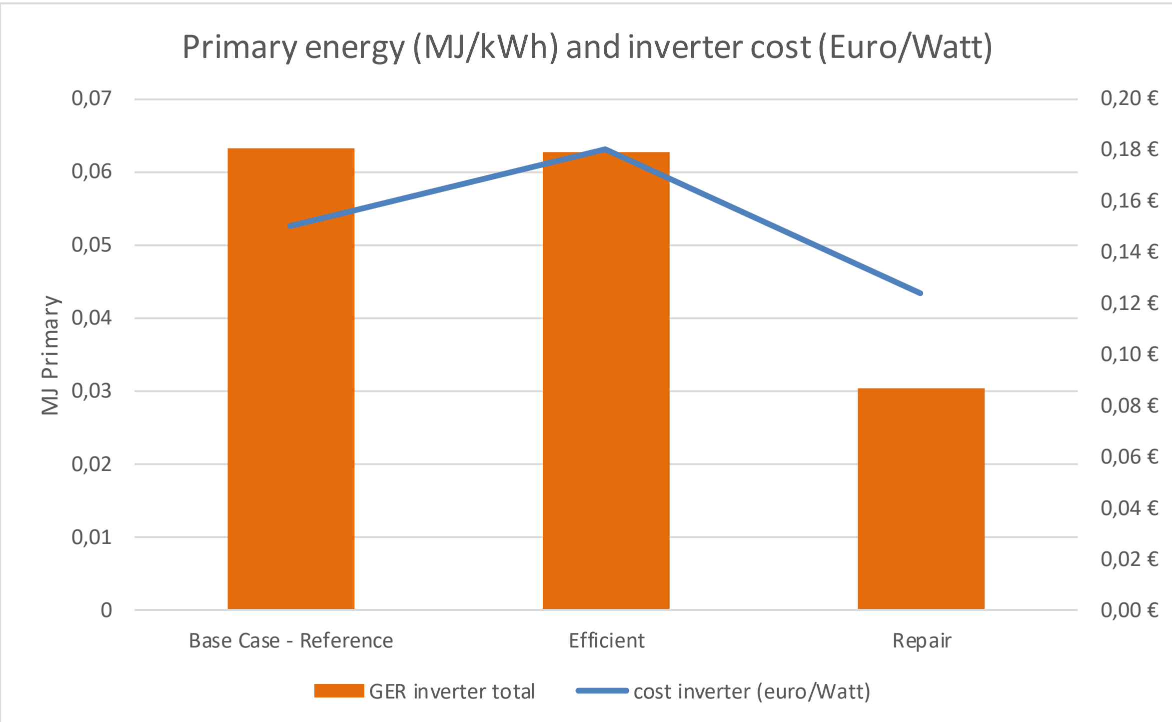

Figure 18: Inverters primary energy and cost – commercial scale

6.3.4.3 Utility scale (BC 3)

The best available technology from an environmental point of view (primary energy only) is the efficient string inverter. However, the difference in primary energy is marginal (note the scale) while the cost is relatively higher. The inverter with the lowest cost per Watt is the reference inverter.

Figure 19~~Figure 19~~ shows the results for the different inverters on primary energy (per kWh) and costs (per Wp)

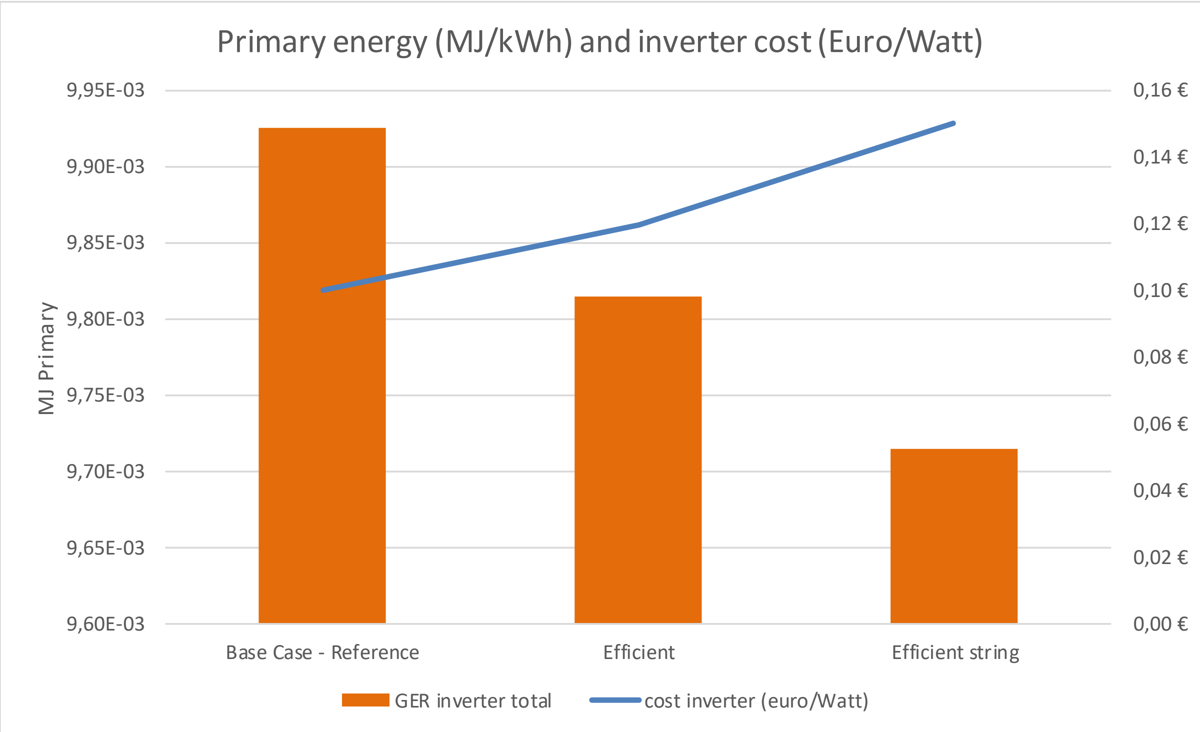

Figure 19: Inverters primary energy and cost – utility scale

6.3.5 Best available and Least LCC options of PV systems

~~6.3.5~~ To calculate the life cycle costs at system level the module cost, inverter cost, frame/mounting system cost, cost for cables and connectors, design and installation costs ~~and design costs~~, O&M costs and end-of-life costs (~~un~~dismantling~~installation~~, scra~~r~~p value, recycling costs) have been considered. Detailed information is published in Annex C.

6.3.5.1 Residential scale

The best available technology from an environmental point of view (primary energy) and life cycle cost point of view is the ~~Multi Si optimized~~Optimis~~z~~ed PERC 2020 + best ~~of best~~ inverter + ~~better design~~optimis~~z~~ed O&M (SO 3).

Figure 20~~Figure 20~~ shows the primary energy use and LCOE per kWh for the different design options ~~in~~ for base case 1, residential scale.

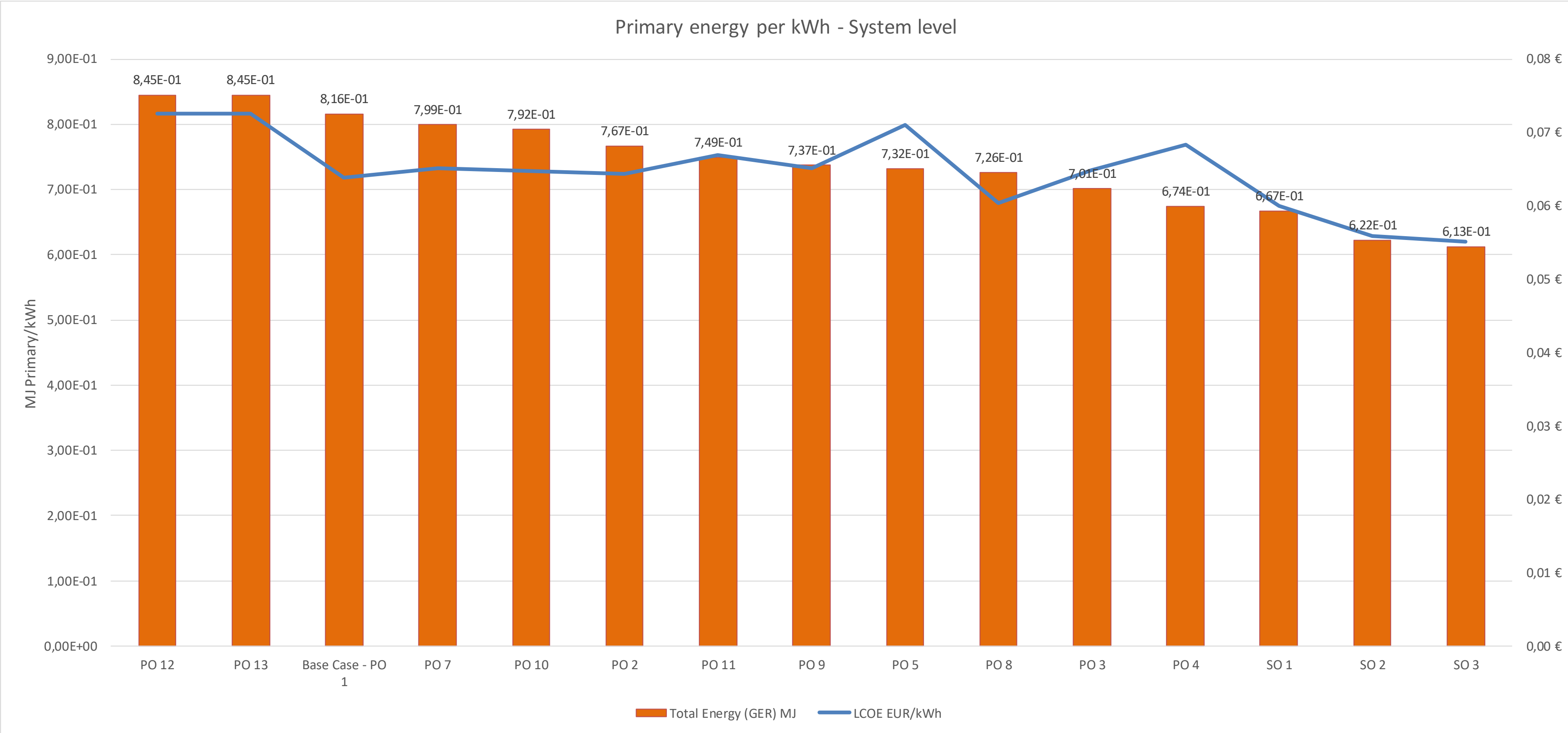

Figure 20: MJ primary energy and LCOE per kWh – residential scale

(PO 1): Multi Si module and reference inverter, (PO2): Optimised PERC 202 module and reference inverter; (PO 3): BAT PERC 2019 module and reference inverter; (PO 4): CIGS module and reference inverter; (PO 5): Silicion heterojunction module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 7): Multi Si module and more efficient inverter; (PO 8): Multi Si module and longer life inverter; (PO 9): Multi Si Module and inverter with repair; (PO 10): Multi Si module and inverter including monitoring; (PO 11): Multi Si module and multi-level inverter; (PO 12): Multi Si module and inverter including storage (worst case); (PO 13): Multi Si module and inverter including storage (best case).

(SO 1): Optimised PERC 2020 + best inverter; (SO 2): Optimised PERC 2020+ best inverter + better design; (SO 3): Optimised PERC 2020+ best inverter + optimised O&M

~~(PO 1): Multi Si module and reference inverter, (PO2): Multi Si optimised module and reference inverter; (PO 3): PERC module and reference inverter; (PO 4): CIGS module and reference inverter; (PO 5): Kerfless (old) module and reference inverter; (PO 6): Silicion heterojunction module and reference inverter; (PO 7): BNAT kerfless (new) module and reference inverter; (PO 8): Multi Si module and more efficient inverter; (PO 9): Multi Si module and longer life inverter; (PO 10): Multi Si Module and inverter with repair; (PO 11): Multi Si module and inverter including monitoring; (PO 12): Multi Si module and multi-level inverter; (PO 13): Multi Si module and inverter including storage (worst case); (PO 14): Multi Si module and inverter including storage (best case).~~

~~(SO 1): Multi Si optimised + best inverter; (SO 2): Multi Si optimised + best inverter + better design; (SO 3): Multi Si optimised + best inverter + optimised O&M~~

6.3.5.2 Commercial scale

The best available technology from an environmental ~~point of view~~ (primary energy) and life cycle cost point of view is the CdTe system. ~~From the life cycle cost point of view the optimised design using a PERC bifacial module and a tailored design is the best option, being also the second in the ranking in terms of primary energy.~~

Figure 21~~Figure 21~~ shows the primary energy use and LCOE per kWh for the different design options ~~in~~ for base case 2, commercial scale.

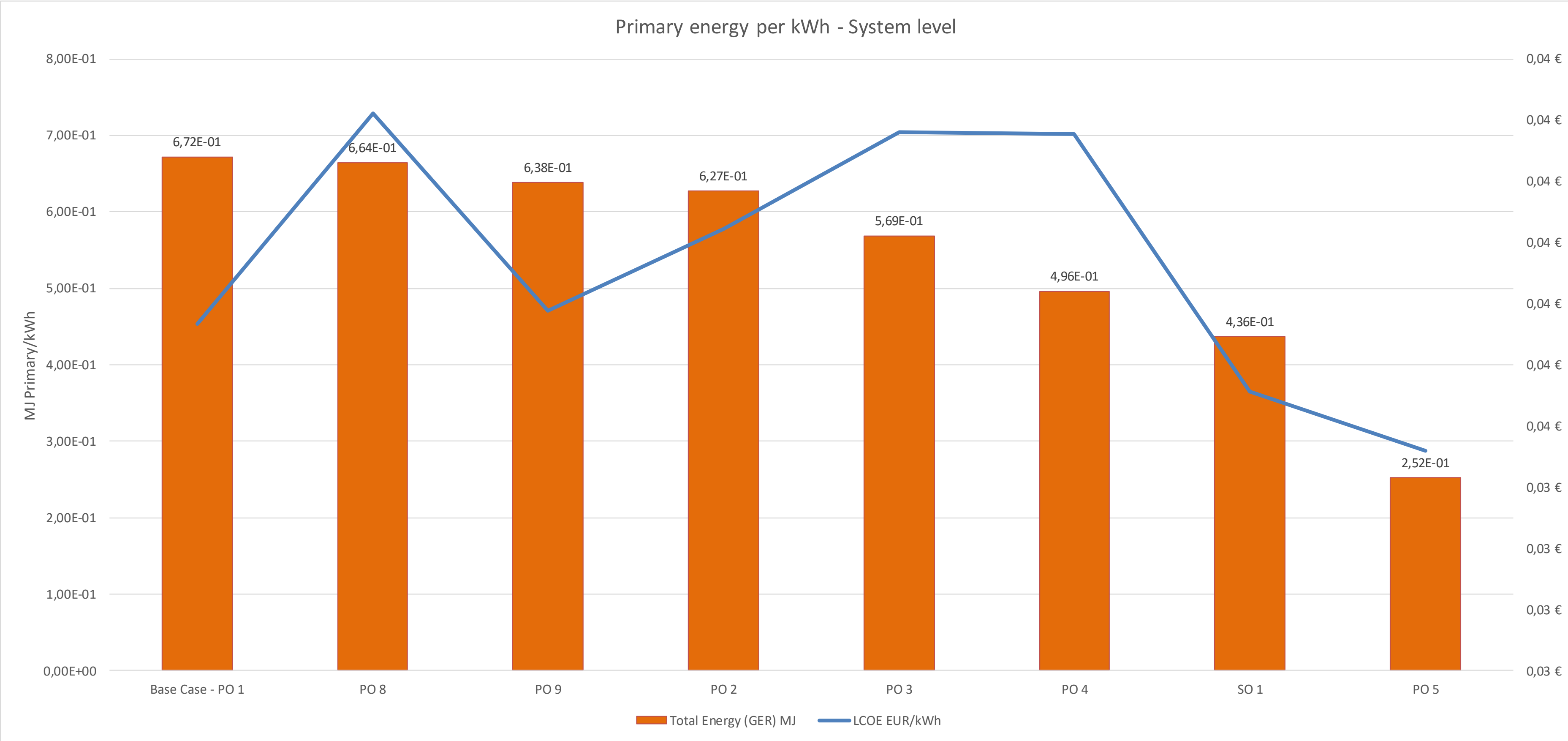

Figure 21: MJ primary energy and LCOE per kWh – commercial scale

(SO 1): best combination and design; (PO 1): Multi Si module and reference inverter; (PO 2): Optimised PERC 2020 module and reference inverter; (PO 3):BAT PERC 2019 module and reference inverter; (PO 4):BAT PERC bifacial 2019 module and reference inverter; (PO 5): CdTe module and reference inverter; (PO 6): BAT PERC 2025 module and reference inverter; (PO 8):Multi Si module and more efficient inverter; (PO 9): Multi Si module and inverter with repair~~(SO 1): best combination and design; (PO 1): Multi Si module and reference inverter; (PO 2): Multi Si optimised module and reference inverter; (PO 3):PERC module and reference inverter; (PO 4):PERC bifacial module and reference inverter; (PO 5): CdTe module and reference inverter; (PO 6):Multi Si module and more efficient inverter; (PO 7): Multi Si module and inverter with repair~~

6.3.5.3 Utility scale

The best available technology from an environmental point of view (primary energy) ~~is~~are the systems using CdTe modules. Note that the addition of a single axis tracker (SO 1) to the system does not appear to compensate the additional cost (SO 1 versus PO 5). The system '~~multi Si optimised~~CdTe + reference inverter + reference BOS' has the lowest LCOE ~~but close to the BAT, while it doubles the primary energy of the BAT~~. This illustrates the strong influence of the module selection on the primary energy.

Figure 22~~Figure 22~~ shows the primary energy use and LCOE per kWh for the different design options ~~in~~ for base case 3, utility scale.

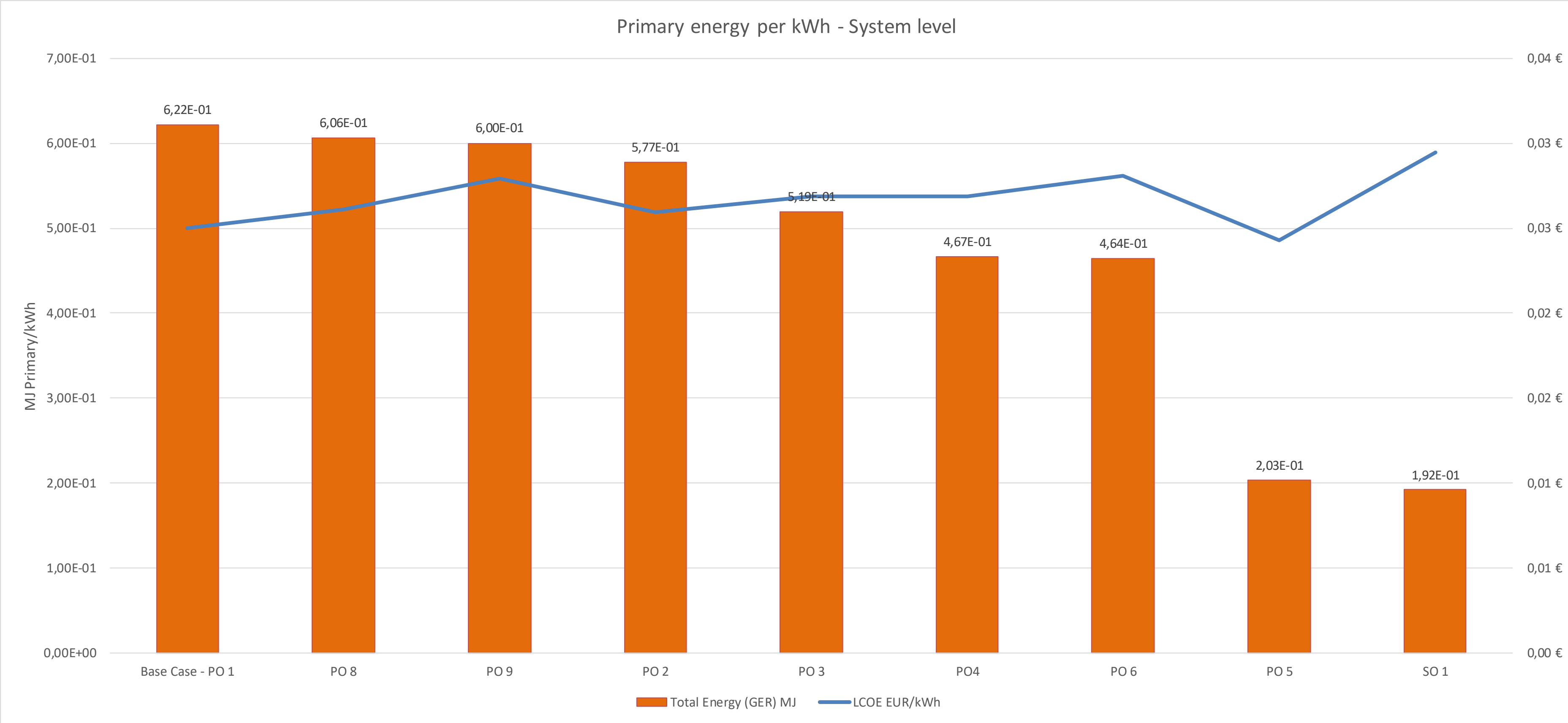

Figure 22: MJ primary energy and LCOE per kWh – utility scale

(SO 1): best combination and design including single axis tracker; (PO 1): Multi Si module and reference inverter and reference BOS; (PO 2): Optimised PERC 2020 module and reference inverter and reference BOS; (PO 3): BAT PERC 2019 module and reference inverter and reference BOS; (PO 4): BAT PERC bifacial 2019 module and reference inverter and reference BOS; (PO 5): CdTe module and reference inverter and reference BOS; (PO6): BAT PERC 2025 module and reference inverter and reference BOS; (PO 7): BNAT PERC bifacial 2025 + recycled wafer and reference inverter and reference BOS; (PO 8): Multi Si module and more efficient inverter and reference BOS; (PO 9): Multi Si module and more efficient string inverter and reference BOS(SO 1): best combination and design including single axis tracker; (PO 1): Multi Si module and reference inverter and reference BOS; (PO 2): Multi Si optimised module and reference inverter and reference BOS; (PO 3): PERC module and reference inverter and reference BOS; (PO 4): PERC bifacial module and reference inverter and reference BOS; (PO 5): CdTe module and reference inverter and reference BOS; (PO 6): Multi Si module and more efficient inverter and reference BOS; (PO 7): Multi Si module and more efficient string inverter and reference BOS.

6.4 Long term potential (BNAT) & systems analysis

This section deals with the long-term technical potential within the existing product system, including whether there is sufficient scope for product differentiation beyond the BAT and the LLCC options

6.4.1 BNAT analysis for modules

Based on the technology analysis made in Task 4, four 'lead' BNAT candidates can be identified and are presented here in notional descending order of proximity to market:

- TOPCon passivated contact cells: This technology is based on the application of an additional thin oxide passivation layer across the whole front of a silicon wafer. The technology is estimated to increase efficiencies by up to 23%. The first mass market application of this technology is projected to be n-type PERT multi crystalline cells, with over 1.5 GWp of production capacity anticipated to convert [21]. In China application to p-type crystalline cells, albeit more challenging, have already formed part of solutions entered into the Top Runner auction programme [22].
- Silicon wafer material and energy efficiency: The production of silicon wafers by alternative processes that are more efficient in their use of energy and silicon, such as epitaxial growth or 'lift-off' processes, are currently identified as BNAT, although in reality this will represent an optimisation of BAT designs that previously entered the market in the period 1999 – 2014 [23]. This type of wafer could potentially be introduced into multi-silicon module production lines, which in 2016 accounted for around 65% of the crystalline portion of the market, which at the present time is expanded from BSF cells to also now includes some PERx cell variants (PERC/PERL on p-type material). However, this portion is projected to decline to around 10% by 2030, when only multicrystaline PERC/PERL cells may remain, so the scope to bring process efficiency gains into the market may be constrained unless the associated modules are more competitively priced.
- Tandem perovskite cells: Perovskite technology is anticipated to first enter the market at a commercial scale in the form of tandem layered cells. The application of perovskite layers to monocrystalline wafers is currently being planned at commercial scale for 2020/21 by at least one company worldwide. The claimed benefit would be an increase in the overall efficiency of each cell from 20-22% to up to 30%. There is however a question mark over the raw materials required and potential lifetime of the perovskite layer, given the continuing challenges faced in seeking to achieve acceptable levels of stability. Pilot production modules incorporating tandem cells have already been certified to have passed IEC 61215 design approval.
- Back contact silicon heterojunction cells: The integration of the two technologies with some of the highest recorded commercial efficiencies and yields has been the subject of research under the Horizon 2020 programme [24]. The aim has been to achieve 26% cell efficiencies and 22% module efficiencies.

[21] PV Magazine, *TOPCon: The next big thing after PERC*, October 8th 2018, https://www.pv-magazine.com/2018/10/08/topcon-the-next-big-thing-after-perc/

[22] PV Magazine, *TOPCon boosts demand for EU equipment*, 15th December 2018, https://www.pv-magazine.com/2018/12/15/the-weekend-read-topcon-boosts-demand-for-eu-equipment/

[23] Manufacturers includes RWE-Schott, Astropower and Evergreen

[24] NextBase project: *The next generation baseline for solar modules*, https://nextbase-project.eu/

'Drop-in' ~~This~~ technology such as kerfless wafer production could be particularly important for the residential ~~scale~~market segment where the large scale deployment of the identified BAT (CIGS) is not yet demonstrated due to a small market penetration. This should therefore be taken into consideration in the design of any policy interventions.

A further option has been identified that has passed the prototyping stage and has entered small-scale production so can be considered intermediate to BNAT and BAT:

- Crystalline module redesign for recycling: Currently the majority of module designs present various difficulties at the moment of seeking to dismantle them to recovery materials for recycling. Once the junction box and aluminium frame (if present) have been removed the main difficulty is to separate the encapsulated components as well as the soldered connections and tabbing of the cells. This requires destructive thermal and mechanical processes to be used, which result in low grade, cross contaminated material recovery. Alternative module designs have been developed to pre-commercial stage that have eliminated the polymer encapsulants and laminates as well as the metal soldering that hinder dismantling [25]. Pilot production modules have already been certified to have passed IEC 61215 design approval.

As a conclusion considering all this, further improvements in GER and energy yield ~~reduction~~ can be expected beyond which ~~we were able~~it has been possible to model in this report.

6.4.2 BNAT analysis for inverters

The main candidates for the Best Not Yet Available Technology (BNAT) are inverter designs based on wider band gap semi-conductors (MOSFET). Whilst some products are ~~understood to have~~ entered the commercial scale market segment in 2018 – suggesting that they could eventually be candidates for BAT – their application field is, as yet limited.. Moreover, ~~I~~information is still lacking on ~~their~~ the potential benefits and trade-offs in relation to changes in the bill of materials and~~,~~ their performance under higher temperature conditions. Given the significance of thermally induced failures in inverters, this technology could be particularly important in warmer climates if the claimed benefits were to be confirmed.

[25] Einhaus et al, *Recycling and reuse potential of NICE PV-modules* (2016)

6.5 Conclusions

This task has sought to identify the design options of the photovoltaic product group with the Least Life Cycle Costs (LLCC) and the Best Available Technology (BAT). The results and conclusions are summarised for the three sub-products under study:

6.5.1 Solar photovoltaic module BAT and LLCC options

For solar PV modules 13 design options were carried forward from the Task 4 analysis, with 9 of them considered to represent technology that is available presently and to therefore be BAT candidates and 4 considered to represent BNAT technologies. The IBC and design for recycling options were not possible to model, either in part or fully, because of problems accessing confidential product data. The modules designs were summarised in Table 1.

Because of the rapid advances in module design, two of the solar PV module designs are composites. They consider changes:

- cell architectures (so as to represent advancement in the market 'base case');
- possible combinations of improvements in the Bill of Materials as well as;
- key performance parameters which are the outcome of changes to these two aspects, such as cell efficiency and degradation.

The composite designs were summarised in Table 5.

Based on the results obtained from the Ecoreport tool for the lead indicator of primary energy (GER), the Best Available Technology (BAT) is, for the residential market segment, the CIGS thin film design and for the commercial and utility segments, the CdTe thin film design.

It is notable that in the residential segment the composite designs based on PERx cell architectures are potentially within the margin of variance for the CIGS design for the GER results – suggesting that composite improvements to designs based on silicon wafers can approach BAT performance. This is particularly the case if BNAT options such as kerfless wafers and design for recycling were to be implemented.

For the secondary environmental indicators selected – namely PAHs, Volatile organic compounds and heavy metals to air and water – the two thin film technologies also achieve the best results for VOCs and heavy metals. However, the composite PERC 2025 and the BNAT options perform marginally better in respect of PAHs emissions and also have the potential to close the gap in the results for the other two impact categories to between 23-57%.

From a life cycle cost perspective, the thin film products also appear to deliver the least life cycle costs. However, in the case of CIGS in the residential market segment, the costs are closely matched and it is recommended to also consider them within the context of the whole PV system costs. Whilst silicon wafer-based design options can also deliver low life cycle costs, the results show that this can be at the expense of introducing less environmentally preferable products into the market, suggesting that requirements could be considered in order to ensure that the environmental performance is in parity.

Following comments from stakeholders, a sensitivity analysis of the influence of the electricity grid mix in difference global regions was made. This showed that whilst a variance of up to 10% in GER and up to 15% could be seen in the other three environmental impact categories, a greater variance could be seen if life cycle GWP were to be selected as the lead indicator. A variance of up to 38% can be seen in the results for life cycle GWP, suggesting that this could be considered as a further indicator to screen for the influence of electricity and fuel infrastructure.

6.5.2 Inverter BAT and LLCC options

For inverters 13 design options were carried forward from the Task 4 analysis, with 11 of them considered to represent technology that is available presently and to therefore be BAT candidates and 1 considered to represent a BNAT technology. The inverter designs were summarised in Table 2.

Based on the results obtained from the Ecoreport tool for the lead indicator of primary energy (GER), the Best Available Technology (BAT) options are, for the residential market segment, the longer life and repair options, with both achieving a significant margin of 54-61% improvement upon the base case. In the commercial segment repair comes out as the BAT, showing a 52% improvement. In the utility segment there is very limited margin to identify a BAT based on the design options modelled.

For the secondary environmental indicators selected – namely PAHs, Volatile organic compounds and heavy metals to air and water – the results and improvement potential are of a similar order of magnitude. However, for all impact categories the result for the two storage options modelled is higher than the base case, even without the modelling of the battery, so the benefits of promoting these options as part of a self-consumption strategy require careful consideration within the wider electricity system.

From a life cycle cost perspective, the repair design option appears to deliver the least life cycle costs in both the residential and commercial market segments. In the utility segment the string inverter improvement option incurs higher costs whilst offering very limited margin for environmental improvement.

6.5.3 PV system BAT and LLCC options

For PV systems 13 and 9 design options were carried forward from the Task 4 analysis for the residential and commercial/utility segments respectively. They largely consist of combinations (or 'packages') of the module and inverter technologies already referred to modelled within a system context. However, to these options have been added options that focus on improvements in system performance as a whole. The PV system designs were summarised in Table 3.

Based on the results obtained from the Ecoreport tool for the lead indicator of primary energy (GER), the Best Available Technology (BAT) options are, for the residential market segment:

- Package options which include a long life inverter or an inverter designed for repair, as well as;
- Options that have had the system performance ratio (PR) optimised – either from a design or an operation & maintenance perspective.

For the secondary environmental indicators selected – namely PAHs, Volatile organic compounds and heavy metals to air and water – the results and improvement potential are of a similar order of magnitude. The package option incorporating CIGS modules can also be seen to significant improvement for the VOC and heavy metal impact categories.

In the commercial market segment, the design option incorporating a CdTe module technology is the BAT. Whereas at the utility scale the design options incorporating a tracker and CdTe respectively are closely matched as the BAT.

From a life cycle cost perspective, the result in the residential and commercial market segment mirrors that for the environmental performance. In the residential segment, the results or the two system optimisation options are closely matched. In both the commercial and utility segments, the CdTe represents the least cost option. In the utility segment, the design option incorporating a single axis tracker appears to push up costs to the extent that they are above the other design options.

Annex A: Bill of Materials in EcoReport format for modules

Multi-Si: reference

Version 3.06 VHK for European Commission 2011,
modified by IZM for european commission 2014

Document subject to a legal notice (see below)

ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS Environmental Impact

Assessment of

Nr	multi Si panel 1 kWh	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	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell, multi-Si	1,26E-01	8-Extra	102-Photovoltaic cell, multi-Si wafer per kg	
4					
5	**interconnection**				
6	Tin	3,29E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,85E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	2,63E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	2,23E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Polyvinylfluoride film	2,86E-02	8-Extra	106-Polyvinylfluoride {GLO}| market for | Cut-off,	
15	Polyethylene terephthalate	8,82E-02	1-BlkPlastics	10 -PET	
16					
17	**pottant & sealing**				
18	Silicone product	3,11E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	5,43E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	2,25E+00	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	7,16E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	6,07E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	7,52E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	1,28E+00	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	Hydrogen fluoride	1,59E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	Potassium hydroxide	1,31E-02	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	4,06E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	3,75E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

BAT PERC 2020

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014					Document subject to a legal notice (see below)
ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS			EcoReport 2014: INPUTS Environmental Impact		Assessment of
Nr	PERC panel 1 kWh Products		Date	Author vito	
Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	9,21E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,72E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,53E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	2,17E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,84E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Polyvinylfluoride film	2,36E-02	8-Extra	106-Polyvinylfluoride {GLO}|	No
15	Polyethylene terephthalate	7,29E-02	1-BlkPlastics	10 -PET	No
16					
17	**pottant & sealing**				
18	Silicone product	2,57E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	4,49E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	1,69E+00	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,92E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	5,02E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	6,22E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	1,06E+00	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,32E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	1,08E-02	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	3,35E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	3,10E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

BAT PERC 2019

Version 3.06 VHK for European Commission 2011,
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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS | EcoReport 2014: INPUTS Environmental Impact | Assessment of

Nr	PERC panel 1 kWh Products	Date	Author vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	8,52E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,40E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,35E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	1,92E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,63E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Polyvinylfluoride film	2,08E-02	8-Extra	106-Polyvinylfluoride {GLO}| market for | Cut-off,	
15	Polyethylene terephthalate	6,44E-02	1-BlkPlastics	10 -PET	
16					
17	**pottant & sealing**				
18	Silicone product	2,27E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	3,96E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	1,64E+00	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,23E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	4,43E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	5,49E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	9,36E-01	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,16E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	9,57E-03	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	2,96E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	2,74E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
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40					

BAT PERCbi 2019 (bifacial)

Nr	PERC + bifacial panel 1 kWh		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	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	8,52E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,40E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,35E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	1,92E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,63E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Solar glass, low-iron & Tempering, flat glass	9,31E-01	8-Extra	108-solar glass and tempering - GLO	
15					
16					
17	**pottant & sealing**				
18	Silicone product	2,27E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	3,96E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	9,31E-01	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,23E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	4,43E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	5,49E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	9,36E-01	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,16E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	9,57E-03	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	2,96E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	2,74E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
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CdTe

Version 3.06 VHK for European Commission 2011,
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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS
Environmental Impact

Assessment of

Nr	CdTe panel 1 kWh	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	**materials**				
2	Solar glass and tempering	1,82E+00	8-Extra	102-solar glass and tempering - GLO	
3	Flat glass (uncoated)	1,69E+00	8-Extra	103-Flat glass, uncoated {GLO}| market for | Cut-	
4	Copper	2,38E-03	4-Non-ferro	30 -Cu wire	
5	Cadmium sulphide	7,29E-04	8-Extra	104-Cadmium sulfide, semiconductor-grade {GLO	
6	Cadmium telluride	4,92E-03	8-Extra	105-Cadmium telluride, semiconductor-grade {GL	
7	Ethylene vinyl acetate (EVA)	1,01E-01	8-Extra	106-Ethylvinylacetate, foil {GLO}| market for | Cu	
8	Glass fibre reinforced plastic	2,24E-02	2-TecPlastics	19 -E-glass fibre	
9	Silicone	6,36E-04	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
10	Silica sand	9,69E-03	8-Extra	108-Silica sand {GLO}| market for | Cut-off, U	
11	Tap water	4,12E+01	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
12	Nitrogen	1,52E-02	8-Extra	110-Nitrogen, liquid {RER}| market for | Cut-off, U	
13	Helium	7,54E-03	8-Extra	111-Helium {GLO}| market for | Cut-off, U	
14	Nitric acid	1,18E-02	8-Extra	112-Nitric acid, without water, in 50% solution st	
15	Sulphuric acid	8,14E-03	8-Extra	113-Sulfuric acid {GLO}| market for | Cut-off, U	
16	Hydrogen peroxide	3,46E-03	8-Extra	114-Hydrogen peroxide, without water, in 50% so	
17	Sodium hydroxide	1,02E-02	8-Extra	115-Sodium hydroxide, without water, in 50% sol	
18	Sodium chloride	9,38E-03	8-Extra	116-Sodium chloride, powder {GLO}| market for |	
19	Isopropanol	4,31E-04	8-Extra	117-Isopropanol {GLO}| market for | Cut-off, U	
20	Chemicals organic	2,02E-03	8-Extra		
21	Chemicals inorganic	7,78E-03	8-Extra		
22					
23					
24					
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CIGS

Version 3.06 VHK for European Commission 2011,
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Document subject to a legal notice (see below)

EcoReport 2014: INPUTS Assessment of Environmental Impact

ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

Nr	CIGS panel 1 kWh	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	**materials**				
2	**Laminate**				
3	Solar glass and tempering	2,00E+00	8-Extra	102-solar glass and tempering - GLO	
4	Flat glass (uncoated)	1,37E+00	8-Extra	103-Flat glass, uncoated {GLO}| market for | Cut-	
5	Aluminium	1,15E-02	4-Non-ferro	27 -Al sheet/extrusion	
6	Copper wire	2,54E-03	4-Non-ferro	30 -Cu wire	
7	Tin	3,20E-03	8-Extra	104-Tin {GLO}| market for | Cut-off, U	
8	Zinc oxide	2,36E-03	8-Extra	105-Zinc oxide {GLO}| market for | Cut-off, U	
9	Molybdenum	1,58E-03	8-Extra	106-Molybdenum {GLO}| market for | Cut-off, U	
10	Indium	7,33E-04	8-Extra	107-Indium {GLO}| market for | Cut-off, U	
11	Gallium	2,34E-04	8-Extra	108-Gallium, semiconductor-grade {GLO}| market	
12	Selenium	1,46E-03	8-Extra	109-Selenium {GLO}| market for | Cut-off, U	
13	Cadmium sulphide	7,00E-05	8-Extra	110-Cadmium sulfide, semiconductor-grade {GLO	
14	Diode	3,75E-04	6-Electronics	49 -SMD/ LED's avg.	
15	Flux	3,20E-03	8-Extra	111-Flux, for wave soldering {GLO}| market for |	
16	Ethylene vinyl acetate (EVA)	1,95E-01	8-Extra	112-Ethylvinylacetate, foil {GLO}| market for | Cu	
17	Polyvinyl butyral (PVB)	4,91E-02	8-Extra	113-Polyvinyl Butyral Granulate (PVB) | polymeri	
18	Polyethylene terephthalate (PET)	8,74E-02	1-BlkPlastics	10 -PET	
19	High-density polyethylene (HDPE)	1,26E-02	1-BlkPlastics	2 -HDPE	
20	Polyphenylene sulphide (PPS)	2,23E-02	1-BlkPlastics	5 -PS	
21	Silicone	1,05E-01	8-Extra	114-Silicone product {GLO}| market for | Cut-off,	
22	Nitrogen	4,08E+00	8-Extra	115-Nitrogen, liquid {RER}| market for | Cut-off, U	
23	Argon	4,94E-03	8-Extra	116-Argon, liquid {GLO}| market for | Cut-off, U	
24	Ammonia	2,42E-02	8-Extra	117-Ammonia, liquid {RER}| market for | Cut-off,	
25	Urea	2,99E-04	8-Extra	118-Urea, as N {GLO}| market for | Cut-off, U	
26	Hydrogen peroxide	6,01E-03	8-Extra	119-Hydrogen peroxide, without water, in 50% so	
27	Sodium hydroxide	8,69E-03	8-Extra	120-Sodium hydroxide, without water, in 50% sol	
28	Hydrochloric acid	2,58E-02	8-Extra	120-Hydrochloric acid, without water, in 30% sol	
29	Sulphuric acid	8,61E-03	8-Extra	120-Sulfuric acid {GLO}| market for | Cut-off, U	
30	Hydrogen sulphide	4,97E-02	8-Extra	120-Hydrogen sulfide {GLO}| market for | Cut-off,	
31	Butyl acrylate	2,63E-02	8-Extra	120-Butyl acetate {GLO}| market for | Cut-off, U	
32	Diborane	5,23E-05	8-Extra	120-Diborane {GLO}| market for | Cut-off, U	
33					
34	**Panel**				
35	Aluminium alloy	5,72E-01	4-Non-ferro	27 -Al sheet/extrusion	
36	Glass fibre reinforced plastic	1,04E-02	2-TecPlastics	19 -E-glass fibre	
37					
38					
39					
40					

SHJ

Version 3.06 VHK for European Commission 2011,
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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS
Environmental Impact

Assessment of

Nr	SHJ panel 1 kWh Products	Date	Author vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	7,93E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,73E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,54E-04	8-Extra	104-Lead {GLO}| primary lead production from cc	
8	Copper	2,18E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,85E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Polyvinylfluoride film	2,37E-02	8-Extra	106-Polyvinylfluoride {GLO}| market for | Cut-off,	
15	Polyethylene terephthalate	7,34E-02	1-BlkPlastics	10 -PET	
16					
17	**pottant & sealing**				
18	Silicone product	2,59E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	4,52E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	1,87E+00	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,95E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	5,05E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	6,25E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	1,07E+00	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,32E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	1,09E-02	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	3,37E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	3,12E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

BAT PERC 2025

Nr	PERC 2025 panel 1 kWh Products		Date	Author vito	
Pos nr	**MATERIALS Extraction & Production** Description of component	**Weight** in g	**Category** Click &select	**Material or Process** select Category first !	**Recyclable?**
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	6,09E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,31E-02	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Copper solder	7,15E-04	4-Non-ferro	30 -Cu wire	
8	Copper	1,89E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,61E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	HDPE	6,41E-02	1-BlkPlastics	2 -HDPE	
15	PA	1,04E-02	2-TecPlastics	12 -PA 6	
16	TiO2	6,94E-03	8-Extra	114-Titanium dioxide {RER}| market for | Cut-off,	
17	**pottant & sealing**				
18	Silicone product	2,24E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	3,91E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	1,15E+00	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,16E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	4,37E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	5,42E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	9,24E-01	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,15E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	9,44E-03	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	2,92E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	2,70E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

BNAT PERCbi 2025 + recycled wafer

Nr	PERCbifacial + rec wafer panel 1 kWh Products	Date	Author vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**materials**				
2	**photovoltaic cell**				
3	photovoltaic cell	8,52E-02	8-Extra	102-photovoltaic cell per kg	
4					
5	**interconnection**				
6	Tin	2,40E-03	8-Extra	103-Tin {GLO}| market for | Cut-off, U	
7	Lead	1,35E-04	8-Extra	104-Lead {GLO}| primary lead production from co	
8	Copper	1,92E-02	4-Non-ferro	30 -Cu wire	
9					
10	**encapsulation**				
11	Ethylvinylacetate, foil	1,63E-01	8-Extra	105-Ethylvinylacetate, foil {GLO}| market for | Cu	
12					
13	**backsheet**				
14	Solar glass, low-iron & Tempering, flat glass	9,31E-01	8-Extra	108-solar glass and tempering - GLO	
15					
16					
17	**pottant & sealing**				
18	Silicone product	2,27E-02	8-Extra	107-Silicone product {GLO}| market for | Cut-off,	
19					
20	**frame**				
21	Aluminium alloy, AlMg3	3,96E-01	4-Non-ferro	27 -Al sheet/extrusion	
22					
23	**glass**				
24	Solar glass, low-iron & Tempering, flat glass	9,31E-01	8-Extra	108-solar glass and tempering - GLO	
25					
26	**junction box**				
27	Diode, unspecified	5,23E-04	6-Electronics	47 -IC's avg., 5% Si, Au	
28	Polyethylene, HDPE	4,43E-03	1-BlkPlastics	2 -HDPE	
29	Glass fibre reinforced plastic, polyamide, injection moulding	5,49E-02	2-TecPlastics	19 -E-glass fibre	
30					
31	**Auxilaries**				
32	Tap water	9,36E-01	8-Extra	109-Tap water {GLO}| market group for | Cut-off,	
33	hydrogen fluoride	1,16E-02	8-Extra	110-Hydrogen fluoride {GLO}| market for | Cut-of	
34	potassium hydroxide	9,57E-03	8-Extra	111-Potassium hydroxide {GLO}| market for | Cut	
35	1-propanol	2,96E-03	8-Extra	112-1-propanol {GLO}| market for | Cut-off, U	
36	Isopropanol	2,74E-05	8-Extra	113-Isopropanol {GLO}| market for | Cut-off, U	
37					
38					
39					
40					

Annex B: Bill of Materials in EcoReport format for inverters.

BC1 – reference + efficient + monitoring + MLI

As the Bill of materials are expressed per kWh they differ slightly per design option as the generated kWh are different per design option and a consequence also the number of inverters necessary per kWh. The BOM below is for the reference inverter.

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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS — Assessment of Environmental Impact

Nr	1500 W inverter - 3 units	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	1,76E-01	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	7,82E-03	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	7,04E-02	4-Non-ferro	31-Cu tube/sheet	
5	steel, low-alloyed, at plant	3,34E-02	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	3,25E-02	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	7,45E-03	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	4,83E-03	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	3,21E-02	8-Extra	111-Inductor, ring core choke type, at plant/GL	
10	integrated circuit, IC, logic type, at plant	2,44E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	1,29E-03	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	1,10E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	4,83E-03	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	1,21E-02	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	3,54E-04	8-Extra	109-Tin {GLO}| market for | Cut-off, U	
17	connector, clamp connection, at plant	8,99E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
18	inductor, ring core choke type, at plant	4,83E-03	8-Extra	111-Inductor, ring core choke type, at plant/GL	
19	inductor, miniature RF chip type, MRFI, at plant	4,06E-05	8-Extra	104-Inductor, miniature radio frequency chip {(	
20	integrated circuit, IC, logic type, at plant	5,71E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	6,89E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	7,08E-04	6-Electronics	48 - IC's avg., 1% Si	
23	transistor, SMD type, surface mounting, at plant	1,54E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
24	diode, glass-, SMD type, surface mounting, at plant	7,41E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
25	light emitting diode, LED, at plant	5,31E-07	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	6,12E-03	8-Extra	105-Capacitor, film type, for through-hole mou	
27	capacitor, electrolyte type, > 2cm height, at plant	9,47E-03	8-Extra	106-Capacitor, electrolyte type, > 2cm height {	
28	capacitor, electrolyte type, < 2cm height, at plant	2,47E-04	8-Extra	107-Capacitor, electrolyte type, < 2cm height {	
29	capacitor, SMD type, surface-mounting, at plant	4,90E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
30	resistor, wirewound, through-hole mounting, at plant	4,13E-05	8-Extra	108-Resistor, wirewound, through-hole mount	
31	resistor, SMD type, surface mounting, at plant	1,68E-04	8-Extra	110-Resistor, SMD type, surface mounting, at p	
32	ferrite, at plant	9,40E-07	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	1,48E-03	8-Extra	111-Inductor, ring core choke type {GLO}| mark	
34	plugs, inlet and outlet, for network cable, at plant	1,03E-02	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	9,44E-04	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	8,85E-06	4-Non-ferro	30 - Cu wire	
37					
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BC 1 – longer life

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014			Document subject to a legal notice (see below)		
	ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS		EcoReport 2014: INPUTS Environmental Impact	Assessment of	
Nr	1500 W inverter - 1,156 units Products		Date	Author Vito	
Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	6,78E-02	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	3,01E-03	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	2,71E-02	4-Non-ferro	31-Cu tube/sheet	
5	steel, low-alloyed, at plant	1,29E-02	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	1,25E-02	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	2,87E-03	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	1,86E-03	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	1,24E-02	8-Extra	111-Inductor, ring core choke type, at plant/GL	
10	integrated circuit, IC, logic type, at plant	9,39E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	4,96E-04	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	4,25E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	1,86E-03	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	4,68E-03	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	1,36E-04	8-Extra	109-Tin {GLO}| market for | Cut-off, U	
17	connector, clamp connection, at plant	3,47E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
18	inductor, ring core choke type, at plant	1,86E-03	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
19	inductor, miniature RF chip type, MRFI, at plant	1,56E-05	8-Extra	104-Inductor, miniature radio frequency chip {(	
20	integrated circuit, IC, logic type, at plant	2,20E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	2,66E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	2,73E-04	6-Electronics	48 - IC's avg., 1% Si	
23	transistor, SMD type, surface mounting, at plant	5,92E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
24	diode, glass-, SMD type, surface mounting, at plant	2,86E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
25	light emitting diode, LED, at plant	2,05E-07	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	2,36E-03	8-Extra	105-Capacitor, film type, for through-hole mou	
27	capacitor, electrolyte type, > 2cm height, at plant	3,65E-03	8-Extra	106-Capacitor, electrolyte type, > 2cm height {	
28	capacitor, electrolyte type, < 2cm height, at plant	9,53E-05	8-Extra	107-Capacitor, electrolyte type, < 2cm height {	
29	capacitor, SMD type, surface-mounting, at plant	1,89E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
30	resistor, wirewound, through-hole mounting, at plant	1,59E-05	8-Extra	108-Resistor, wirewound, through-hole mount	
31	resistor, SMD type, surface mounting, at plant	6,49E-05	8-Extra	110-Resistor, SMD type, surface mounting, at p	
32	ferrite, at plant	3,62E-07	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	5,70E-04	8-Extra	111-Inductor, ring core choke type, at plant/GL	
34	plugs, inlet and outlet, for network cable, at plant	3,96E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	3,64E-04	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	3,41E-06	4-Non-ferro	30 - Cu wire	
37					
38					
39					
40					

BC 1 – increased repair

The table below combines failures into groups (see color coding).

Table 4 on inverter failure from task 4		
Inverter failure area	% of tickets	% of kWh lost
no-fault-found failures = software update	28,00%	15,00%
Card/board	13,00%	22,00%
AC Contactor	12,00%	13,00%
Fan(s)	6,00%	5,00%
Matrix/IGBT	6,00%	6,00%
Power supply	5,00%	5,00%
AC Fuses	4,00%	12,00%
DC Contactor	4,00%	1,00%
Surge Protection	3,00%	1,00%
GFI Components	3,00%	2,00%
Capacitors	3,00%	7,00%
Internal Fuses	3,00%	4,00%
Internal Relay/Swithces	3,00%	2,00%
DC Input Fuses	2,00%	1,00%
Other	5,00%	2,00%

The table below shows the number of tickets per group. A total of 61% of the tickets has been allocated to the different groups. Software failures have no implications on the BOM. Fans are not used anymore in new inverters. Also, the tickets under 'other' could not be allocated to a component of the bill of materials.

Translate task 4 data into input for task 6 report:	% tickets	rescale to 100%
Fuse/contactor	34%	56%
Card/board	13%	21%
Matrix/IGBT	6%	10%
Capacitors	3%	5%
Power supply	5%	8%
Total	61%	100%

In a next step a link has been made between the failure of the different components and the available bill of materials (see table below).

BOM Task 5 report - based on Treeze publication on LCA of inverters		infuence on BOM
individual components	**match with table task 4**	
aluminium, production mix, cast alloy, at plant		1
aluminium alloy, AlMg3, at plant		1
copper, at regional storage		1
steel, low-alloyed, at plant		1
polypropylene, granulate, at plant		1
polycarbonate, at plant		1
cable, connector for computer, without plugs, at plant		1
inductor, ring core choke type, at plant	Fuse/contactor	BOM*(1+(2*0,56))
integrated circuit, IC, logic type, at plant		1
ferrite, at plant		1
plugs, inlet and outlet, for network cable, at plant	Fuse/contactor	BOM*(1+(2*0,56))
glass fibre reinforced plastic, polyamide, injection moulding, at plant		1
printed board assembly		
printed wiring board, surface mount, lead-free surface, at plant	card/board	BOM*(1+(2*0,21))
tin, at regional storage		1
connector, clamp connection, at plant	card/board	BOM*(1+(2*0,21))
inductor, ring core choke type, at plant	card/board	BOM*(1+(2*0,21))
inductor, miniature RF chip type, MRFI, at plant	card/board	BOM*(1+(2*0,21))
integrated circuit, IC, logic type, at plant	card/board	BOM*(1+(2*0,21))
integrated circuit, IC, memory type, at plant	card/board	BOM*(1+(2*0,21))
transistor, unspecified, at plant	Matrix/IGBT	BOM*(1+(2*0,1))
transistor, SMD type, surface mounting, at plant	Matrix/IGBT	BOM*(1+(2*0,1))
diode, glass-, SMD type, surface mounting, at plant	card/board	BOM*(1+(2*0,21))
light emitting diode, LED, at plant	card/board	BOM*(1+(2*0,21))
capacitor, film, through-hole mounting, at plant	card/board	BOM*(1+(2*0,21))
capacitor, electrolyte type, > 2cm height, at plant	capacitors	BOM*(1+(2*0,05))
capacitor, electrolyte type, < 2cm height, at plant	capacitors	BOM*(1+(2*0,05))
capacitor, SMD type, surface-mounting, at plant	card/board	BOM*(1+(2*0,21))
resistor, wirewound, through-hole mounting, at plant	card/board	BOM*(1+(2*0,21))
resistor, SMD type, surface mounting, at plant	card/board	BOM*(1+(2*0,21))
ferrite, at plant	card/board	BOM*(1+(2*0,21))
transformer, low voltage use, at plant	power supply	BOM*(1+(2*0,08))
plugs, inlet and outlet, for network cable, at plant		1
glass fibre reinforced plastic, polyamide, injection moulding, at plant		1
cable, ribbon cable, 20-pin, with plugs, at plant		1

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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS	EcoReport 2014: INPUTS Environmental Impact		Assessment of

Nr	1500 W inverter - 1 unit incl repair	Date	Author
	Products		Vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	5,86E-02	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	2,61E-03	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	2,35E-02	4-Non-ferro	31-Cu tube/sheet	
5	steel, low-alloyed, at plant	1,11E-02	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	1,08E-02	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	2,48E-03	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	1,61E-03	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	2,27E-02	8-Extra	111-Inductor, ring core choke type, at plant/GL	
10	integrated circuit, IC, logic type, at plant	8,12E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	4,29E-04	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	7,80E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	1,61E-03	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	5,75E-03	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	1,18E-04	8-Extra	109-Tin {GLO}| market for | Cut-off, U	
17	connector, clamp connection, at plant	4,26E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
18	inductor, ring core choke type, at plant	2,29E-03	8-Extra	111-Inductor, ring core choke type, at plant/GL	
19	inductor, miniature RF chip type, MRFI, at plant	1,92E-05	8-Extra	104-Inductor, miniature radio frequency chip {G	
20	integrated circuit, IC, logic type, at plant	2,70E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	3,26E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	2,83E-04	6-Electronics	48 - IC's avg., 1% Si	
23	transistor, SMD type, surface mounting, at plant	6,15E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
24	diode, glass-, SMD type, surface mounting, at plant	3,51E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
25	light emitting diode, LED, at plant	2,51E-07	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	2,90E-03	8-Extra	105-Capacitor, film type, for through-hole mou	
27	capacitor, electrolyte type, > 2cm height, at plant	3,47E-03	8-Extra	106-Capacitor, electrolyte type, > 2cm height {	
28	capacitor, electrolyte type, < 2cm height, at plant	9,07E-05	8-Extra	107-Capacitor, electrolyte type, < 2cm height {	
29	capacitor, SMD type, surface-mounting, at plant	2,32E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
30	resistor, wirewound, through-hole mounting, at plant	1,95E-05	8-Extra	108-Resistor, wirewound, through-hole mount	
31	resistor, SMD type, surface mounting, at plant	7,97E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
32	ferrite, at plant	4,45E-07	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	5,72E-04	8-Extra	111-Inductor, ring core choke type, at plant/GL	
34	plugs, inlet and outlet, for network cable, at plant	3,43E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	3,15E-04	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	2,95E-06	4-Non-ferro	30 - Cu wire	
37					
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BC2 – reference + efficient

As the Bill of materials are expressed per kWh they differ slightly per design option as the generated kWh are different per design option and a consequence also the number of inverters necessary per kWh. The BOM below is for the reference inverter.

Version 3.06 VHK for European Commission 2011,
modified by IZM for european commission 2014

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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS Environmental Impact

Assessment of

Nr	20 kW inverter - 3 units	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	8,08E-02	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	3,59E-03	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	3,24E-02	4-Non-ferro	31-Cu tube/sheet	
5	steel, low-alloyed, at plant	1,54E-02	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	1,50E-02	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	3,43E-03	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	2,23E-03	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	1,48E-02	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
10	integrated circuit, IC, logic type, at plant	1,12E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	5,94E-04	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	5,07E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	2,21E-03	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	5,59E-03	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	1,62E-04	8-Extra	109-Tin {GLO}| market for | Cut-off, U	
17	connector, clamp connection, at plant	4,12E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
18	inductor, ring core choke type, at plant	2,21E-03	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
19	inductor, miniature RF chip type, MRFI, at plant	1,87E-05	8-Extra	104-Inductor, miniature radio frequency chip {(	
20	integrated circuit, IC, logic type, at plant	2,64E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	3,18E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	3,25E-04	6-Electronics	48 - IC's avg., 1% Si	
23	transistor, SMD type, surface mounting, at plant	7,09E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
24	diode, glass-, SMD type, surface mounting, at plant	3,40E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
25	light emitting diode, LED, at plant	2,44E-07	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	2,82E-03	8-Extra	105-Capacitor, film type, for through-hole mou	
27	capacitor, electrolyte type, > 2cm height, at plant	4,37E-03	8-Extra	106-Capacitor, electrolyte type, > 2cm height {	
28	capacitor, electrolyte type, < 2cm height, at plant	1,14E-04	8-Extra	107-Capacitor, electrolyte type, < 2cm height {	
29	capacitor, SMD type, surface-mounting, at plant	2,26E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
30	resistor, wirewound, through-hole mounting, at plant	1,90E-05	8-Extra	108-Resistor, wirewound, through-hole mount	
31	resistor, SMD type, surface mounting, at plant	7,75E-05	8-Extra	110-Resistor, SMD type, surface mounting, at p	
32	ferrite, at plant	4,33E-07	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	6,80E-04	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
34	plugs, inlet and outlet, for network cable, at plant	4,74E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	4,33E-04	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	4,07E-06	4-Non-ferro	30 - Cu wire	
37					
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39					
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BC2 – repair

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ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS

EcoReport 2014: INPUTS Assessment of Environmental Impact

Nr	20 kW inverter - 1 unit incl repair	Date	Author
	Products		Vito

Pos nr	MATERIALS Extraction & Production Description of component	Weight in g	Category Click &select	Material or Process select Category first !	Recyclable?
1	**individual components**				
2	aluminium, production mix, cast alloy, at plant	2,69E-02	4-Non-ferro	28 - Al diecast	
3	aluminium alloy, AlMg3, at plant	1,19E-03	4-Non-ferro	28 - Al diecast	
4	copper, at regional storage	1,08E-02	4-Non-ferro	31-Cu tube/sheet	
5	steel, low-alloyed, at plant	5,12E-03	3-Ferro	22 - St sheet galv.	
6	polypropylene, granulate, at plant	4,98E-03	1-BlkPlastics	4 - PP	
7	polycarbonate, at plant	1,14E-03	2-TecPlastics	13 - PC	
8	cable, connector for computer, without plugs, at plant	7,42E-04	4-Non-ferro	30 - Cu wire	
9	inductor, ring core choke type, at plant	1,04E-02	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
10	integrated circuit, IC, logic type, at plant	3,74E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
11	ferrite, at plant	1,98E-04	3-Ferro	25 - Ferrite	
12	plugs, inlet and outlet, for network cable, at plant	3,58E-04	1-BlkPlastics	8 - PVC	
13	glass fibre reinforced plastic, polyamide, injection moulding, at plant	7,37E-04	2-TecPlastics	12 - PA 6	
14	**printed board assembly**				
15	printed wiring board, surface mount, lead-free surface, at plant	2,64E-03	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
16	tin, at regional storage	5,41E-05	8-Extra	109-Tin {GLO}| market for | Cut-off, U	
17	connector, clamp connection, at plant	1,95E-04	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
18	inductor, ring core choke type, at plant	1,05E-03	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
19	inductor, miniature RF chip type, MRFI, at plant	8,83E-06	8-Extra	104-Inductor, miniature radio frequency chip {(	
20	integrated circuit, IC, logic type, at plant	1,25E-03	6-Electronics	47 - IC's avg., 5% Si, Au	
21	integrated circuit, IC, memory type, at plant	1,50E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
22	transistor, unspecified, at plant	1,30E-04	6-Electronics	48 - IC's avg., 1% Si	
23	transistor, SMD type, surface mounting, at plant	2,83E-04	6-Electronics	47 - IC's avg., 5% Si, Au	
24	diode, glass-, SMD type, surface mounting, at plant	1,61E-05	6-Electronics	47 - IC's avg., 5% Si, Au	
25	light emitting diode, LED, at plant	1,15E-07	6-Electronics	49 - SMD/ LED's avg.	
26	capacitor, film, through-hole mounting, at plant	1,33E-03	8-Extra	105-Capacitor, film type, for through-hole mou	
27	capacitor, electrolyte type, > 2cm height, at plant	1,60E-03	8-Extra	106-Capacitor, electrolyte type, > 2cm height {	
28	capacitor, electrolyte type, < 2cm height, at plant	4,17E-05	8-Extra	107-Capacitor, electrolyte type, < 2cm height {	
29	capacitor, SMD type, surface-mounting, at plant	1,07E-05	8-Extra	112-Capacitor, SMD type, surface-mounting, a	
30	resistor, wirewound, through-hole mounting, at plant	8,97E-06	8-Extra	108-Resistor, wirewound, through-hole mount	
31	resistor, SMD type, surface mounting, at plant	3,67E-05	8-Extra	110-Resistor, SMD type, surface mounting, at p	
32	ferrite, at plant	2,05E-07	3-Ferro	25 - Ferrite	
33	transformer, low voltage use, at plant	2,63E-04	8-Extra	102-Inductor, ring core choke type {GLO}| mar	
34	plugs, inlet and outlet, for network cable, at plant	1,58E-03	8-Extra	103-Plugs, inlet and outlet, for network cable, a	
35	glass fibre reinforced plastic, polyamide, injection moulding, at plant	1,44E-04	2-TecPlastics	12 - PA 6	
36	cable, ribbon cable, 20-pin, with plugs, at plant	1,35E-06	4-Non-ferro	30 - Cu wire	
37					
38					
39					
40					

BC3 – reference + efficient + efficient string

As the Bill of materials are expressed per kWh they differ slightly per design option as the generated kWh are different per design option and a consequence also the number of inverters necessary per kWh. The BOM below is for the reference inverter.

Version 3.06 VHK for European Commission 2011, modified by IZM for european commission 2014				Document subject to a legal notice (see below)	
ECO-DESIGN OF ENERGY RELATED/USING PRODUCTS		EcoReport 2014: INPUTS Environmental Impact		Assessment of	
Nr	1500 kW inverter - 1 unit incl repair	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	Alkyd paint, white, without solvent, in 60% solution state	1,18E-03	8-Extra	103-Alkyd paint, white, without solvent, in 60%	
3	Aluminium, cast alloy	7,03E-03	4-Non-ferro	28 -Al diecast	
4	Capacitor, electrolyte type, > 2cm height	4,12E-05	8-Extra	109-Capacitor, electrolyte type, > 2cm height {	
5	Capacitor, film type, for through-hole mounting	5,49E-05	8-Extra	108-Capacitor, film type, for through-hole mou	
6	Capacitor, tantalum-, for through-hole mounting	3,70E-06	8-Extra	104-Capacitor, tantalum-, for through-hole mo	
7	Copper	1,80E-02	4-Non-ferro	31-Cu tube/sheet	
8	Diode, glass-, for through-hole mounting	7,57E-06	6-Electronics	49 -SMD/ LED's avg.	
9	Electric connector, wire clamp	7,64E-03	8-Extra	106-Plugs, inlet and outlet, for network cable, a	
10	Fleece, polyethylene	1,61E-05	1-BlkPlastics	2 -HDPE	
11	Glass fibre reinforced plastic, polyamide, injection moulded	3,81E-03	2-TecPlastics	12 -PA 6	
12	Glass fibre reinforced plastic, polyester resin, hand lay-up	2,36E-03	1-BlkPlastics	10 -PET	
13	Inductor, ring core choke type	5,65E-05	8-Extra	114-Inductor, ring core choke type {GLO}| mark	
14	Integrated circuit, logic type	4,51E-06	6-Electronics	47 -IC's avg., 5% Si, Au	
15	Lubricating oil	4,73E-02	8-Extra	102-Lubricating oil {GLO}| market for | Cut-off,	
16	Polyethylene, high density, granulate	1,18E-03	1-BlkPlastics	2 -HDPE	
17	Polystyrene foam slab	8,59E-05	1-BlkPlastics	5 -PS	
18	Printed wiring board, for through-hole mounting, Pb containing surface	5,90E-05	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
19	Printed wiring board, for through-hole mounting, Pb free surface	0,00E+00	6-Electronics	51-PWB 6 lay 4.5 kg/m2	
20	Resistor, metal film type, through-hole mounting	8,05E-07	8-Extra	111-Resistor, wirewound, through-hole mounti	
21	Steel, low-alloyed, hot rolled	7,72E-02	3-Ferro	22 -St sheet galv.	
22	Transistor, wired, small size, through-hole mounting	6,12E-06	6-Electronics	48 -IC's avg., 1% Si	
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Annex C: Input data for LCC calculations at system level

Residential

System		Base Case - PO 1	PO 2	PO 3	PO 4	PO 5	PO 6	BC1-Reference	PO 7	PO 8	PO 9	PO 10	PO 11	PO 12	PO 13	SO 1	SO 2	SO 3
r (discount rate=interest - inflation)	%	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*		*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*
cost module (euro/Wp)	euro/Wp	0,48 €	0,52 €	0,56 €	0,53 €	0,60 €	0,62 €		0,48 €	0,48 €	0,48 €	0,48 €	0,48 €	0,48 €	0,48 €	0,52 €	0,52 €	0,52 €
cost inverter (euro/VA)	euro/VA	0,22 €	0,22 €	0,22 €	0,22 €	0,22 €	0,22 €		0,25 €	0,28 €	0,22 €	0,25 €	0,33 €	0,33 €	0,33 €	0,28 €	0,28 €	0,28 €
cost frames (euro/Wp)	euro/Wp	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €		0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €
cost cables+connectors (euro/Wp)	euro/Wp	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €		0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €
cost installation (euro/Wp)	euro/Wp	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €		0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €	0,50 €
cost design (euro/Wp)	euro/Wp	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €		0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €	0,07 €
CAPEX total installation	euro/installation	***3.826,86 €***	***3.946,86 €***	***4.066,86 €***	***3.976,86 €***	***4.186,86 €***	***4.235,50 €***		***3.908,46 €***	***3.982,86 €***	***3.826,86 €***	***3.916,19 €***	***4.107,86 €***	***4.098,86 €***	***4.098,86 €***	***4.102,86 €***	***4.102,86 €***	***4.102,86 €***
CAPEX scrap value at EOL	euro/Wp	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €		-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €
CAPEX uninstall labour	euro/Wp	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €		0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €	0,35 €
CAPEX recycle modules (€/module)	euro/module	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €		10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €	10,00 €
CAPEX total EOL	euro/installation	***1.029,46 €***	***1.008,45 €***	***997,10 €***	***1.026,88 €***	***1.003,43 €***	***995,81 €***		***1.029,46 €***	***1.029,46 €***	***1.029,46 €***	***1.029,46 €***	***1.029,46 €***	***1.029,46 €***	***1.029,46 €***	***1.008,45 €***	***1.008,45 €***	***1.008,45 €***
OPEX O&M	euro/service	150,00 €	150,00 €	150,00 €	150,00 €	150,00 €	151,00 €		150,00 €	150,00 €	250,00 €	150,00 €	150,00 €	150,00 €	150,00 €	150,00 €	150,00 €	150,00 €
OPEX total	euro/year/installation	***65,12 €***	***65,18 €***	***65,24 €***	***65,20 €***	***65,30 €***	***64,56 €***		***73,28 €***	***37,72 €***	***71,79 €***	***74,06 €***	***93,22 €***	***92,32 €***	***92,32 €***	***37,78 €***	***37,83 €***	***37,83 €***
PWF OPEX non elec		***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***		***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***
PWF CAPEX EOL		***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***		***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***
LCC	euro/installation	***5.186,01 €***	***5.300,49 €***	***5.417,95 €***	***5.336,41 €***	***5.540,86 €***	***5.575,25 €***		***5.398,14 €***	***4.903,67 €***	***5.292,65 €***	***5.418,24 €***	***5.916,51 €***	***5.893,11 €***	***5.893,11 €***	***5.018,15 €***	***5.018,95 €***	***5.018,95 €***
LCOE	EUR/kWh	***0,064 €***	***0,064 €***	***0,065 €***	***0,068 €***	***0,071 €***	***0,067 €***		***0,065 €***	***0,060 €***	***0,065 €***	***0,065 €***	***0,067 €***	***0,073 €***	***0,073 €***	***0,060 €***	***0,056 €***	***0,055 €***

Commercial

System		Base Case - PO 1	PO 2	PO 3	PO 4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
r (discount rate=interest - inflation)	%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%	4,0%
cost module (euro/Wp)	euro/Wp	0,34 €	0,38 €	0,42 €	0,42 €	0,34 €	0,46 €	0,46 €	0,34 €	0,34 €	0,42 €
cost inverter (euro/VA)	euro/VA	0,15 €	0,15 €	0,15 €	0,15 €	0,15 €	0,15 €	0,15 €	0,18 €	0,15 €	0,15 €
cost frames (euro/Wp)	euro/Wp	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €
cost cables+connectors (euro/Wp)	euro/Wp	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €
cost installation (euro/Wp)	euro/Wp	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €	0,25 €
cost design (euro/Wp)	euro/Wp	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €	0,05 €
CAPEX total installation	euro/installation	*19.531,00 €*	*20.507,00 €*	*21.483,00 €*	*21.483,00 €*	*19.531,00 €*	*22.501,70 €*	*22.501,70 €*	*20.131,00 €*	*19.531,00 €*	*21.483,00 €*
CAPEX scrap value at EOL	euro/Wp	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €
CAPEX uninstall labour	euro/Wp	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €	0,18 €
CAPEX recycle modules (€/module)	euro/module	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €
CAPEX total EOL	euro/installation	*3.698,49 €*	*3.613,01 €*	*3.566,87 €*	*3.515,36 €*	*3.611,23 €*	*3.562,20 €*	*3.515,36 €*	*3.698,49 €*	*3.698,49 €*	*3.515,36 €*
OPEX O&M	euro/service	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	500,00 €	600,00 €	600,00 €
OPEX total	euro/year/installation	*337,45 €*	*337,94 €*	*338,43 €*	*338,43 €*	*337,45 €*	*334,45 €*	*338,94 €*	*397,45 €*	*344,12 €*	*345,09 €*
PWF OPEX non elec		*16,00*	*16,00*	*16,00*	*16,00*	*16,00*	*16,00*	*16,00*	*16,00*	*16,00*	*16,00*
PWF CAPEX EOL		*0,308*	*0,308*	*0,308*	*0,308*	*0,308*	*0,308*	*0,308*	*0,308*	*0,308*	*0,308*
LCC	euro/installation	*26.069,36 €*	*27.026,81 €*	*27.996,39 €*	*27.980,51 €*	*26.042,46 €*	*28.950,10 €*	*29.007,36 €*	*27.629,15 €*	*26.176,00 €*	*28.087,15 €*
LCOE	EUR/kWh	*0,036 €*	*0,037 €*	*0,037 €*	*0,037 €*	*0,035 €*	*0,039 €*	*0,039 €*	*0,038 €*	*0,036 €*	*0,035 €*

Utility

System		Base Case - PO 1	PO 2	PO 3	PO4	PO 5	PO 6	PO 7	PO 8	PO 9	SO 1
r (discount rate=interest - inflation)	%	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*	*4,0%*
cost module (euro/Wp)	euro/Wp	0,31 €	0,35 €	0,39 €	0,39 €	0,31 €	0,43 €	0,47 €	0,31 €	0,31 €	0,31 €
cost inverter (euro/VA)	euro/VA	0,10 €	0,10 €	0,10 €	0,10 €	0,10 €	0,10 €	0,10 €	0,12 €	0,15 €	0,15 €
cost frames (euro/Wp)	euro/Wp	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,03 €	0,20 €
cost cables+connectors (euro/Wp)	euro/Wp	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €	0,01 €
cost installation (euro/Wp)	euro/Wp	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €	0,13 €
cost design (euro/Wp)	euro/Wp	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €	0,04 €
CAPEX total installation	euro/installation	***1.115.625,00 €***	***1.190.625,00 €***	***1.265.625,00 €***	***1.265.625,00 €***	***1.115.625,00 €***	***1.338.750,00 €***	***1.419.187,50 €***	***1.145.625,00 €***	***1.190.625,00 €***	***1.503.125,00 €***
CAPEX scrap value at EOL	euro/Wp	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €	-0,05 €
CAPEX uninstall labour	euro/Wp	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €	0,09 €
CAPEX recycle modules (€/module)	euro/module	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €	5,00 €
CAPEX total EOL	euro/installation	***115.457,59 €***	***108.889,44 €***	***105.343,19 €***	***102.584,72 €***	***108.752,16 €***	***106.688,46 €***	***102.584,72 €***	***115.457,59 €***	***115.457,59 €***	***108.752,16 €***
OPEX O&M	euro/service	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	2.500,00 €	3.125,00 €
OPEX total	euro/year/installation	***15.457,29 €***	***15.494,79 €***	***15.532,29 €***	***15.532,29 €***	***15.457,29 €***	***15.247,10 €***	***15.609,07 €***	***18.457,29 €***	***22.957,29 €***	***22.998,96 €***
PWF OPEX non elec		***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***	***16,00***
PWF CAPEX EOL		***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***	***0,308***
LCC	euro/installation	***1.398.485,93 €***	***1.472.060,71 €***	***1.546.567,21 €***	***1.545.716,72 €***	***1.396.418,52 €***	***1.615.544,97 €***	***1.700.507,45 €***	***1.476.475,55 €***	***1.593.459,98 €***	***1.904.559,09 €***
LCOE	EUR/kWh	***0,025 €***	***0,026 €***	***0,027 €***	***0,027 €***	***0,024 €***	***0,028 €***	***0,030 €***	***0,026 €***	***0,028 €***	***0,029 €***