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Solar photovoltaic modules, inverters and systems: options and feasibility of EU Ecolabel and Green Public Procurement criteria

Preliminary report

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Contents

1. Introduction

1.1. Background to the Preliminary Assessment

This document is intended to provide the background information for a preliminary assessment of the feasibility of establishing EU Ecolabel and/or Green Public Procurement (GPP) criteria for solar photovoltaic modules, inverters and systems. This preliminary assessment forms part of a wider Preparatory Study to examine the feasibility of a four policy instruments – Ecodesign, Energy Labelling, the Ecolabel and GPP.

The study is being carried out for the European Commission's Directorate General for Internal Market, Industry, Entrepreneurship and SMEs (GROW) by the Joint Research Centre with technical support from VITO and Imec.

The main purpose of this document is to provide a summary of the technical background, options for possible criteria areas and a preliminary evaluation of their potential and feasibility. This document and the findings presented herein have been the subject of a webinar meeting held in April 2019.

This document is complemented and supported by the wider Preparatory Study Task Reports, which comprise:

1. Product scope
2. Market data and trends
3. User behaviour and system aspects
4. Technical analysis including end of life
5. Environmental and economic assessment of base cases

Furthermore, during the course of the revision process a general questionnaire on the scope and improvement potential was sent out to selected stakeholders. The target groups were industry, Member States, NGOs and research institutions. The specific information, views and suggestions arising from questions about the scope, and improvement potential are summarised in this report and are taken into consideration as far as possible in the preliminary assessment.

The supporting Preparatory Study Task Reports have been developed and revised based on a stakeholder engagement process, as well as follow-up research and analysis. Stakeholder working group meetings were held on the 29th June and 19th December 2018, and 10th and 11th July 2019, with each being complemented by an eight-week period of written consultation.

1.2. Framework for the assessment

The wider Preparatory Study is designed to assess the feasibility of adopting each of four possible policy instruments, two of which would be mandatory – Ecodesign and Energy Labelling – and two of which would be voluntary – the Ecolabel and GPP.

The Ecolabel and GPP are designed to support the market for the products with the best environmental performance - exerting a 'pull' effect. It is therefore necessary to evaluate whether possible configurations of these two policy interventions could have the intended effect In order to do this a set of evaluation criteria have been established. These criteria are based on existing criteria that are used by DG Environment and the JRC to evaluated new product groups, together with consideration in more detail of:

- the findings from analysis of LCA literature,
- the EU policy context, and
- the potential application of GPP criteria to PV installation projects.

1.2.1. Evaluation as a potential new EU Ecolabel product group

The preliminary assessment will be made based on an adaptation of criteria used for the evaluation of new product groups for the EU Ecolabel. The existing criteria of DG Environment have been adapted further by the Joint Research Centre and are listed in the box below.

In order to assess the potential of the product group(s) to contribute positively to these criteria two supporting technical analysis have been made:

1. Life cycle hot spot analysis: The mapping of hot spots to have emerged from the LCA literature review onto tangible 'front runner' product improvements that:
   - exist in the market today,
   - for which differentiation can be made in product performance and
   - which could be verifiable
2. Policy contribution analysis: The identification of EU policy expectations for the product group in the short to medium term and, linked to this, the extent to which 'front runner' products can contribute to furthering these policy goals.

EU Ecolabel evaluation criteria for the Solar Photovoltaic product group

Adaptation of existing DG ENV/JRC screening criteria

- Feasibility of definition and scope: Is it possible to clearly define and classify the product/sub-products as the basis for a criteria scope?
- Existence of other ecolabels and schemes: Is there an existing basis in the EU or internationally for product group criteria?
- Market significance: Could the Ecolabel criteria be effectively targeted at mainstream products that can be clearly identified from market data?
- Visibility: Would the product group provide a high level of consumer visibility for the ecolabel?
- Potential uptake: What existing indications are there of the potential uptake?
- Alignment with legislation and standards: Could the Ecolabel make a positive contribution to specific EU environmental policy objectives?
- Environmental impacts analysis; Can practical, verifiable criteria be identified that are based upon and could address LCA hot spots and non-LCA issues that are of significance?

1.2.2. Evaluation as a potential new GPP product group

The preliminary assessment will be made based on an adaptation of criteria used as the basis for evaluations of new product groups for the EU GPP Advisory Group. The 'decision model' has been adapted further by the Joint Research Centre and the steps are described in the box 1 below.

Steps 1 and 2 are covered in part by the EU Ecolabel evaluation whereas Steps 3 and 4 are proposed to be addressed for a solar PV system installations by making a technical analysis of the options for beneficial criteria at different project stages– from design through to decommissioning.

BOX 1. *GPP evaluation criteria for the Solar Photovoltaic product group*

Proposed decision model for the selection of product groups for EU GPP

Step 1: Contribution to objectives

- Reduction of the environmental impact (CO_2 reduction, energy/resource efficiency, air pollution, etc.) of products, services or works
- Stimulation of innovation
- Cost reduction

Step 2: Determine the added value of GPP to existing policy instruments

The next step is to determine the added value of GPP criteria for the proposed product group to existing policy instruments like:

- Covenants[1]
- GPP
- Ecolabel
- Ecodesign
- Directives
- Subsidies
- Fiscal instruments
- Communication

Step 3: Determine if GPP is the most effective instrument to achieve the objectives

The next step is to decide if GPP is among the most effective instruments to reach the objectives (go/no go moment). For this decision there are the following questions:

1. If by means of procurement public authorities have considerable direct or indirect influence on the sustainable objectives of the product group concerned.
2. If the influence of public authorities is small, you can further ask if there are other policy objectives (such as acting as role model) to include the product group in GPP.
3. Does it seem possible to translate the objective(s) into legally admissible and technically achievable procurement instrument/criteria.

Step 4: Determine the best form of GPP implementation

If you decide, that GPP is an effective instrument, choose the best way to implement it. Elements can include:

- Product criteria (mainly for products*)
- Functional criteria (mainly for works*)
- Process criteria (mainly for services*)
- Support systems for procurers
- Guidelines
- Training

(* = in general, but there are many exceptions)

[1] E.g. Covenant of Majors run by DG Energy

2. Scope, definition and review of existing initiatives

The aim of this chapter is to analyse the product scope and definition, together with relevant legislation, existing ecolabels and initiatives. The starting point for the preliminary assessment is the product scope of the wider Preparatory Study – namely photovoltaic modules, inverters for photovoltaic applications and photovoltaic systems.

Standards that apply to the product group are reviewed in a separate report of the JRC which will inform possible transitional methods that may be required to support any mandatory regulations [2].

2.1. Product Scope and Definition

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

2.1.1. Basic introduction to photovoltaic technology

The solar photovoltaic effect was discovered in 1839 as an off shoot from photochemical experiments. The first silicon photovoltaic cell was created in the 1950's and this technology has been constantly refined since then.

The photovoltaic effect takes place when a semiconductor material absorbs light and positive and negative electrons are released. These are then extracted from the semiconductor as electric current.

There are different types of solar cells and these are formed into different types of solar panels. The first type is a *crystalline* silicon solar cell; the other type is *amorphous*. *Crystalline* cells are cut from a solid ingot of silicon whereas *amorphous* (also known as *thin film*) is made by depositing a silicon compound on to a glass. One of the main activities in the PV industry is to increase the level of efficiency of cells, in relation to their cost.

Crystalline PV cells are more efficient in their conversion of light to electricity because of their contiguous crystalline structure but usually this comes at a higher cost. There are two types of crystalline cell: the monocrystalline and the polycrystalline. Monocrystalline can be generally more efficient, but has been traditionally more expensive because it requires ingots that are grown using special processes and made of silicon with a higher purity (see Figure 1).

Figure 1 Early example of monocrystalline cells in a module Source: Green Building Advisor (2018)

[2] Dunlop E.D., Gracia Amillo A., Salis E., Sample T., Taylor N., Standards for the assessment of the environmental performance of photovoltaic modules, power conditioning components and photovoltaic systems, EUR 29247 EN, Publications Office of the European Union, Luxembourg, 2018

Thin films do not have the same level of performance as crystalline PV cells and despite being substantially less expensive, have not had the same market penetration either. The development of thin film has been detrimentally affected by the constant reduction in the cost of crystalline panels.

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

Solar power systems

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

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

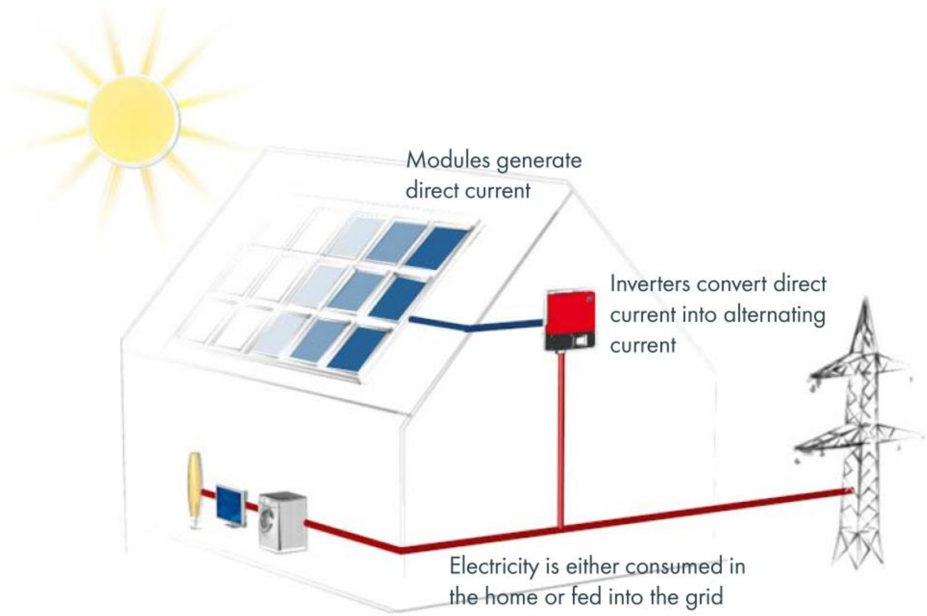

Figure 2. Basic installation of a domestic solar photovoltaic system. Source: SMA (2018)

The sun's energy

The impact of the sun's rays on earth is called irradiance. Levels of irradiance differ depending on the location. Attention therefore has to be paid to the level of irradiance available for a solar project as this will influence the electricity yield. Figure 3 reproduces the map of EU levels of irradiance. This shows that the Southern latitude (e.g. Spain and Italy) are the best places for solar power, where the average irradiance is 2000-2200 kWh/m^{2}yr. This level makes the energy payback times (EPBT) – the amount of time it takes to generate more energy than it took to make the system - are shorter. However, the greatest interest in installing solar PV has, to date, been in central EU. Germany, France and Italy have been the pioneers in the deployment of solar energy.

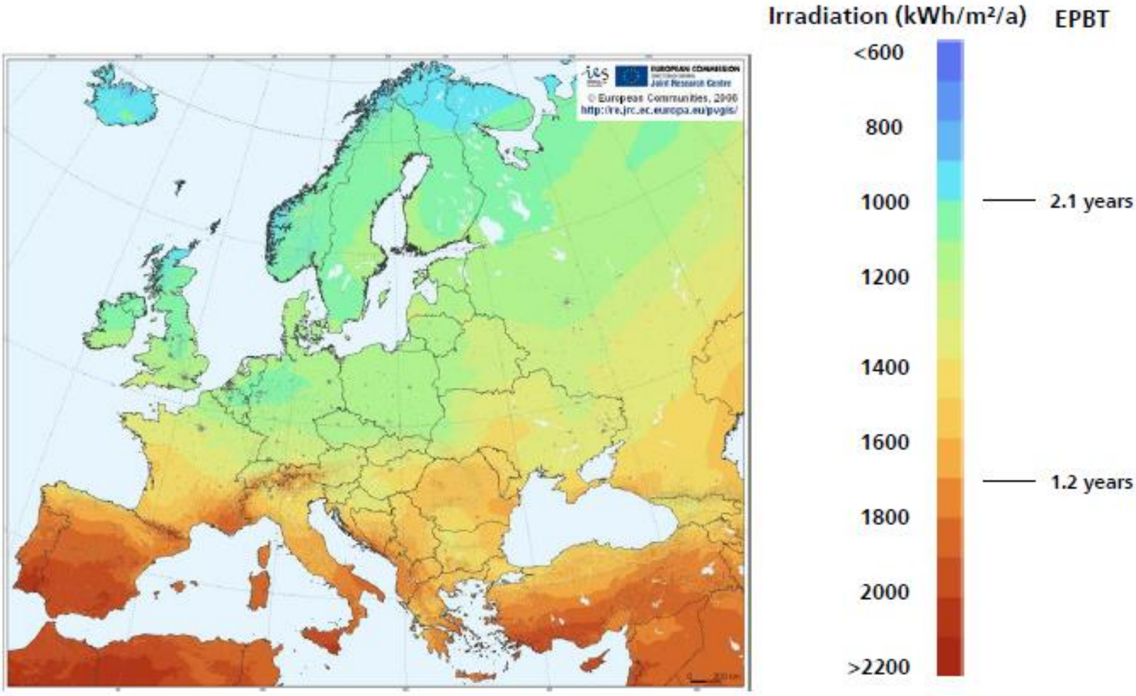

Figure 3. EU irradiation and solar electricity potential

2.1.2. Product scope and definition

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

- PRODCOM codes and activities;
- Definitions and categorisations according to EN, IEC and ISO standards;
- Other product specific definitions and categories e.g. labels, Product Category Rules;

The product scope and definition is analysed in turn for each of the three sub-products that are a focus for the wider Preparatory Study. A first proposal of the scope and definition for modules, inverters and systems as it could apply to the Ecolabel and Green Public Procurement is presented in the following section.

2.1.2.1. Module products

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

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

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

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

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

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

Proposed solar photovoltaic module definition and scope

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

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

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

Specifically excluded from this scope are:

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

2.1.2.2. Inverter products

Product definitions developed by the IEC and the US EPA addressing both inverters and more broadly power conditioning equipment were consulted in order to develop a definition for the Preparatory Study. Stakeholders were consulted on an example definition and possible scope delimitations from December 2017 to January 2018. The headline results were as follows, and are partly reflected in the first formal proposal to stakeholders:

- The majority of respondents considered that:
  - All types of inverters should be included in the scope
  - Power output and intended configuration should be addressed in the scope and definition
- Power Conversion Equipment categories in the draft IEC 62093 standard should form a component of the scope and definition
- It shall be made clear that DC optimisers shall not quality as inverters

The comments have largely been addressed by redrafting the proposal to incorporate the thresholds and categories of draft IEC 62093 standard. However, upon further consideration of the possible grid and module configurations that may need to be modelled, the following new proposals are presented for discussion:

- That the scope shall encompass those that are able to function in a utility interactive mode. The rationale is that the majority of inverters will be connected to distribution grids and this configuration is specifically covered in testing standards.

- That 'central solution' inverters combining a transformer connected to a distribution network are proposed as being excluded. The rationale is to ensure comparability and to avoid an overlap with existing Ecodesign Regulations.

- That inverters falling within draft IEC 62093 Category 1[3] should be excluded from this scope, but shall be within the scope of photovoltaic systems. The rationale is the potential difficulty in making a meaningful comparison between standalone and module-integrated functions. Moreover, this approach would reflect that adopted by Germany's Blue Angel ecolabel inverter criteria.

The first proposal for the product definition and scope of inverters for photovoltaic applications is presented below.

> *Proposed definition and scope of inverters for photovoltaic applications*
>
> An inverter is as an electric energy converter that changes the direct electric current (DC) output from a solar photovoltaic array to single-phase or polyphase alternating current (AC). The scope shall correspond to:
>
> - Utility interactive inverters that are designed to operate grid connected in stand-alone and parallel modes.
> - Inverters with a maximum circuit voltage of 1500 V DC and connections to systems not exceeding 1000 V AC. Hybrid inverters and micro-inverters sold separately are falling within this category.
> - String inverters falling within category 2 as defined in draft IEC 62093 ('String-level power electronics') and designed to interface multiple series or parallel connected modules and specified for wall, roof, ceiling or rack mounting.
> - Central inverters falling within Category 3 as defined in IEC 62093 ('Large-scale power electronics') and designed to interface multiple series or parallel connected modules, but due to its complexity, size and weight are housed in a free-standing electrical enclosure.
>
> Specifically excluded from this scope are:
>
> - Central inverters that are packaged with transformers (sometimes referred to as central solutions) as defined in Commission Regulation (EU) No 548/2014 on Ecodesign requirements for small, medium and large power transformers.

2.1.2.3. System products

As for modules and inverter products, system definitions developed by IEC and IEA, were consulted with the aim to develop a suitable system definition. They all establish several concepts used to make the categorisation. Systems can be categorised according to the following distinguishing features/properties:

- Spatial arrangement: Based on the spatial relationship between the different component arrays (e.g. centralised, distributed).

- Electricity end-use: Based on the primary end use that the electricity generated is earmarked for (e.g. domestic, non-domestic).

[3] Category 1: Module-level power electronics (MLPE) – specified to operate at a PV module base level interfacing up to four modules.

- Grid configuration: Based on the type of physical interface with the electricity distribution grid (e.g. grid connected, off-grid, hybrid).
- Electrical configuration: Based on the systems modes of operation (e.g. isolated, utility interactive).

In the same way as for modules and inverter products, stakeholders were consulted in the same questionnaire on an example and possible scope delimitations for photovoltaic systems. The feedback received can be summarized as it follows:

- Market segmentation, i.e. residential, commercial, utility, and system size, should be included in the definition and scope
- The main scope exclusion selected by respondents is 'specific end-uses' of the electricity such as street lighting and urban furniture or consumer electronic products and other gadgets.
- Grid configuration, module array, power conditioning, tracking systems, spatial configuration, roof or ground mounted, and were considered to be of relevance for the definition and scope of PV systems.

In addition, the majority of respondents considered that all systems should be included within the scope. However, to reflect the main scope exclusion proposed by some respondents, and given that most systems are connected to the grid, the scope of the Preparatory study does not include street lighting, urban furniture, consumer electronic products nor standalone systems. These systems are too complex and often tailor made. The savings of introducing a regulation are minimal in comparison with the grid connected systems (including solar home systems). Moreover, public authorities or consumers are buying these products with solar PV integrated or not, whereas our focus is on the purchase of a solar PV system.

Substations and transformers for power conditioning directly connected to the distribution network, that may be present in utility scale PV plants are neither considered within the scope. Transformers are already in the scope of the Commission Regulation (EU) No 548/2014 on Ecodesign requirements for small, medium and large power transformers.

The first proposal for the product definition and scope of photovoltaic systems is presented below.

Proposed solar photovoltaic system definition and scope

A photovoltaic system is an assembly of components that produce and supply electricity based on photovoltaic conversion of solar energy. It comprises the following sub-systems: module array, switches, controls, meters, power conditioning equipment, PV array support structure, and electricity storage components. It also comprises cabling connecting these components.

Included in the scope of systems are therefore DC optimisers and module integrated inverters falling within category 1 as defined in IEC 62093 ('Module-level power electronics') and specified to operate at a PV module base level interfacing up to four modules.

The provision of energy generated by solar PV systems as a service shall be included within the scope for the purpose of public procurement.

Excluded from the scope are products which are only designed for the following specific applications:

- For use only in street lighting, urban furniture, electric vehicles
- PV integrated consumer and electronic products, i.e. power banks, watches, calculators, etc.
- Systems in which there are modules with DC output power of less than 50 Watts under Standard Tests Conditions (STC)
- Substations and transformers for power conditioning

2.2. Measurement and standards

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

A definition of technical lifetime and operational service life is still not laid down in standards and this is subject of ongoing discussions and analysis within the frame of private sector initiatives such as PVQAT[4];

However, following the future IEC TS 62994, the IEC/TR 62635 and the guidelines in the ISO 15686 series an agreed method is considered to be achievable. The issues of recyclability, repairability and durability will be covered by the general framework of standards being developed under the Mandate M/543 but PV-specific standards deriving from the horizontal ones will be necessary.

Dedicated standards have been developed for PV inverter performance, such as EN 50530. This however is officially marked as withdrawn, although the procedure for determining the "European Efficiency" could still be considered technically valid and is used by industry as a performance metric. This would allow a transitional method for calculating a functional parameter in terms of AC power output for a nominal PV array. Regarding the definition of technical lifetime and operational service life the situation is similar to that for PV modules and again a transitional method may be required, also taking into account field data.

The situation for PV systems reflects a combination of the situation for PV modules and inverters, as well as the system location and design. Aspects of PV system design are the subject of new draft norms, including the full construction cycle and the local environmental conditions, that can have a significant effect on the final energy yield (and therefore also on the material balance).

On-site power measurement and verification standards exist. However, there is no single standard for the calculation of expected energy yield of a PV system. A transitional method would be required here, based either on existing monitoring standards or on the module energy rating standards and integrating a model to include the effects of local environment relative to the specific geophysical position and other derate factors.

2.3. Existing legislation

2.3.1. Legislation and agreements at European Union level

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

- Energy Union and reshaping of the EU electricity market: With reference to the Energy Union Strategy (2015) and proposed new rules for the common electricity market amending the Electricity Directive (2009/72/EC)
- Driving the market for renewable electricity generation: With reference to the Renewable Energy Directive 2009/28/EC recast and proposals for a revised Directive.
- Driving the market for building renovation and near zero energy buildings: With reference to the recast Energy Performance of Buildings Directive 2010/31/EU (EPBD) and revised Directive (2018/844/EU).

[4] International PV Quality Assurance Task Force, https://www.pvqat.org/

- Improving information on construction product performance: With reference to The Construction Products Regulation (EU) No 305/2011.
- Improving material efficiency and creating a Circular Economy: With reference to the Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU and the EU action plan for the Circular Economy (2015)
- Restricting the presence of hazardous substances in products, with reference to Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast), RoHS
- Product policy and consumer information: With reference to the Ecodesign Directive 2009/125/EC and Energy Labelling Directive 2010/30/EU

Table 1 summarises the findings of the review with the identification of the potential short to medium term influences on the EU solar photovoltaic market.

Table 1 Potential influence of EU policy instruments on the EU solar PV market

Thematic policy area	**Possible influence on the EU solar PV market**
Energy Union and reshaping of the EU electricity market	• The proposed new common rules for the electricity market will impose more favourable market conditions for self-consumption and local energy communities • Provisions for non-discriminatory handling of grid connections, including associated charges and procedures, will support 'active consumers'
Driving the market for renewable electricity generation	• The proposed recast Directive will support self-consumption and storage by simplifying permitting and removing restrictions. • A new calculation methodology for the minimum contribution of renewable sources in new buildings and major renovations will further support rooftop solar PV
Driving the market for building renovation and near zero energy buildings	• Targets for all new buildings and major renovations to achieve Nearly Zero Energy performance by 2020 will further drive BAPV and BIPV, which are already favoured options. [5] • A renewed focus on the large scale renovation and decarbonisation of the existing building stock could further drive BAPV deployment. • Buildings will increasing need to demonstrate their 'smart readiness' and this will include energy systems • The EN ISO 52000 series calculation method for BAPV/BIPV performance will be widely used
Improving information on construction product performance	• The EN 15804 and EN 15978 LCA standards, together with the Commission's Level(s) framework will drive an increased focus on the life cycle performance of building components. • Circular thinking will increasingly need to form part of building design and operation.
Improving material efficiency and creating a Circular Economy	• The Critical Raw Materials indium, gallium and silicon metal will be the focus of actions to foster material efficient solutions • Member State reporting on rising solar PV waste streams will increase the focus on end of life routes
Product policy and consumer information	• Products will need to be smart ready, with the potential to interact with home management systems and appliances.

[5] Building attached photovoltaics (BAPV) and Building Integrated photovoltaics (BIPV)

2.3.2. Market leaders at Member State level

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

In this section a summary is presented of the review made in the Task 1 Report of the Ecodesign Preparatory study. This focussed on the legislation and agreements for thirteen selected Member States. They have been selected based on the significance of their solar photovoltaic markets, in terms of a combination of historical, present and projected market penetration. The most important policy instruments have been briefly analysed together with selected examples of electricity price subsidy qualification requirements for equipment, systems and installers. The Member States that have been selected are identified in Table 2

Table 2 Clustering of the Member States analysed based on their market evolution and penetration

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

The review has enabled the identification and characterisation of a number of different types of policy interventions that are influencing the deployment, quality and performance of solar photovoltaic systems. They are briefly summarised in Table 3.

.

Table 3 Effect of Member State policies and requirements on solar PV deployment

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

2.4. Existing voluntary labelling schemes

In this section initial review is made of existing voluntary labelling schemes at EU and international level. For each existing scheme an analysis is made of the product scope and definition used, together with the criteria areas of focus.. Initial feedback gathered from the relevant questions in the stakeholder questionnaire is also analysed.

2.4.1. Existing Ecolabel criteria sets at EU and international level

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

- TÜV Rheinland: The private body is considering the establishment of criteria for photovoltaic modules under its Green Product Mark ecolabel[6]. These are likely to be adopted from EPEAT, the ecolabel scheme of the US Green Electronics Council (GEC).
- Japan Environment Association (JEA): Criteria have only been developed for consumer products incorporating photovoltaic cells[7].
- Korea Environmental Industry & Technology Institute: Criteria have only been developed for consumer products incorporating photovoltaic cells [8].
- Singapore Environment Council: Criteria have only been developed for consumer products incorporating photovoltaic cells [9].

It can be seen that the majority have focussed on photovoltaic cells incorporated into consumer products, which are excluded from the wider Preparatory Study scope.

In addition to those initiatives listed by the GEN there are three further ecolabelling initiatives that are of more direct relevance because they focus on modules and inverters that may be used as components of grid connected photovoltaic systems:

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

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

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

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

Photovoltaic inverters product group (RAL-UZ 163)

The 2012 Blue Angel criteria for inverters apply to string and multi-string inverters with up to an output power of 13.8 kVA that are designed for use in grid-connected PV power systems. They identify maximising inverter efficiency as part of a photovoltaic system and engaging in network management to support grid stability as key challenges that the criteria seek to

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

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

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

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

address. The eight technical criteria areas are listed in . Excluded from the product group are inverters integrated into a module (micro-inverters) and inverters designed for use in stand-alone systems. The criteria are all pass or fail. There are currently no licenses awarded.

Table 4. Blue Angel photovoltaic inverters criteria overview (Germany). Source: RAL (2012)

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

Criteria development for modules and systems

The Blue Angel has made previous attempts to develop criteria sets for systems (2002 and 2008) and modules (2013) [10]. Neither of these criteria sets were adopted, in both cases due to problems reaching agreement on the assessment of energy yield and the restriction of hazardous substances.

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

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

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

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

The US organisation NSF International, with the support of the Green Electronics Council (GEC), has been leading since 2015 a process to develop environmental criteria for photovoltaic modules. The starting point for the criteria set has been the US Silicon Valley Toxics Coalition's (SVTC) 'Solar Scorecard' and the aim has been to develop a criteria set that addresses the full life cycle of a module. The final criteria set will become ANSI standard 457 and will be qualified to become an EPEAT standard as part of the global ecolabelling scheme for IT products [11]. Given the global success of the EPEAT standards for ICT equipment, this new standard therefore has potentially wider significance than just within the USA.

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

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

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

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

Moreover, the product definition then establishes the following exclusions:

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

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

- mobile photovoltaic cell where the inverter is so integrated with the photovoltaic cell that the solar cell requires disassembly before recovery

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

Table 5. NSF/ANSI 457 Sustainability Leadership Standard for Photovoltaic Modules required criteria overview Source: NSF International (2017)

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

	social responsibility (corporate)	operations and their suppliers
	Public disclosure of use of conflict minerals in products (corporate)	– Declaration of whether products contain conflict minerals

2.4.1.3. Cradle to Cradle certification (USA)

The Cradle to Cradle programme is a third party verified labelling scheme that aims to determine the extent to which the design and material composition of a product are able to facilitate future recycling. Two major solar PV module manufacturers are currently listed as having products certified according to the US Cradle to Cradle scheme – Sunpower and Jinko Solar [12]. The programme's criteria are grouped according to the following attributes [13]:

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

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

Table 6. Cradle to Cradle certification 'basic' level criteria overview (USA). Source: Cradle to Cradle Institute (2016)

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

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

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

2.4.2. Summary of the results from the first stakeholder questionnaire

2.4.2.1. Modules

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

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

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

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

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

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

2.4.2.2. Inverters

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

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

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

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

2.4.2.3. Systems

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

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

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

- the French photovoltaic national call for tenders (4 respondents),

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

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

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

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

2.5. Existing Green Public Procurement (GPP) criteria and initiatives

In this section an initial review is made of GPP initiatives at EU level. Where possible an attempt has been made to identify the products addressed and the type of GPP criteria that have been specified.. Initial feedback gathered from the relevant questions in the December 2017 stakeholder questionnaire is also analysed.

2.5.1. Existing GPP criteria sets used in the EU.

There is not currently an EU GPP criteria set for the solar photovoltaic product group. An EU criteria set for green electricity was published in 2012 by DG Environment [14]. The criteria document states part of EU GPP approach shall be to *'increase the share of electricity from renewable energy sources*'. No specific criteria or references to solar photovoltaic technology could be found in the current criteria document. A review of European Commission surveys of Member State GPP criteria [15] and collaborative EU projects such as PRIMES and GPP 2020 did not reveal any national criteria sets to be currently in use [16].

2.5.2. Summary of the GPP results from the first stakeholder questionnaire

2.5.2.1. Modules

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

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

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

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

- the French photovoltaic system national call for tenders, which contain *'a carbon criterion for modules and some additional environmental criteria'* (6 respondents),

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

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

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

- NSF/ANSI 457 Sustainability Leadership standard (1 respondent),
- The German renewable energy law (EEG) which sets a requirement for the type of land to be used for PV projects (1 respondents)
- US EPA GPP webinar entitled 'Improving Solar PV Results through Collaborative Procurement' which covered the Renewable Energy Procurement (REP) Project in California (1 respondent)

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

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

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

2.5.2.2. Inverters

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

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

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

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

2.5.2.3. Systems

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

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

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

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

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

3. Market analysis

In this section an overview of the market for PV modules, inverters and systems is presented. The market and stock data have been compiled primarily from market research conducted by GTM Research (inverters) and the Becquerel Institute (modules and systems). The module and system data is in part based on research carried out in support of annual reporting for the IEA PVPS programme [17] and the PV Market Alliance[18].

A brief overview of key technology trends in the market is also presented, drawing upon the Task 2 report of the Ecodesign Preparatory Study and authoritative sources such as the International Technology Roadmap for Photovoltaic (ITRPV) roadmap.

3.1. Market and stock data

3.1.1. PV Modules

The global market share for PV modules is dominated by crystalline silicon cell types for the reference year 2016 and projected to 2027. The six categories of PV modules with a market share greater than 1% are: multi-crystalline, mono-crystalline, amorphous silicon thin films, cadmium telluride films, and CIGS films. Until 2015 mono crystalline was dominant at utility-scale but since then prices for mono-crystalline have declined as production has expanded.

Although Cadmium telluride is the technology which has experienced the largest growth in the decade 2007-2016, in 2016 Mono silicon represented almost 70% of the market, Multi around 23%, CdTe ca. 4%, closely followed by high efficiency almost 3%, and CIGS (around 500% each). Concentration and Ribbon PV modules figures were found to be negligible. Figure 4 illustrates global module shipments to 2016.

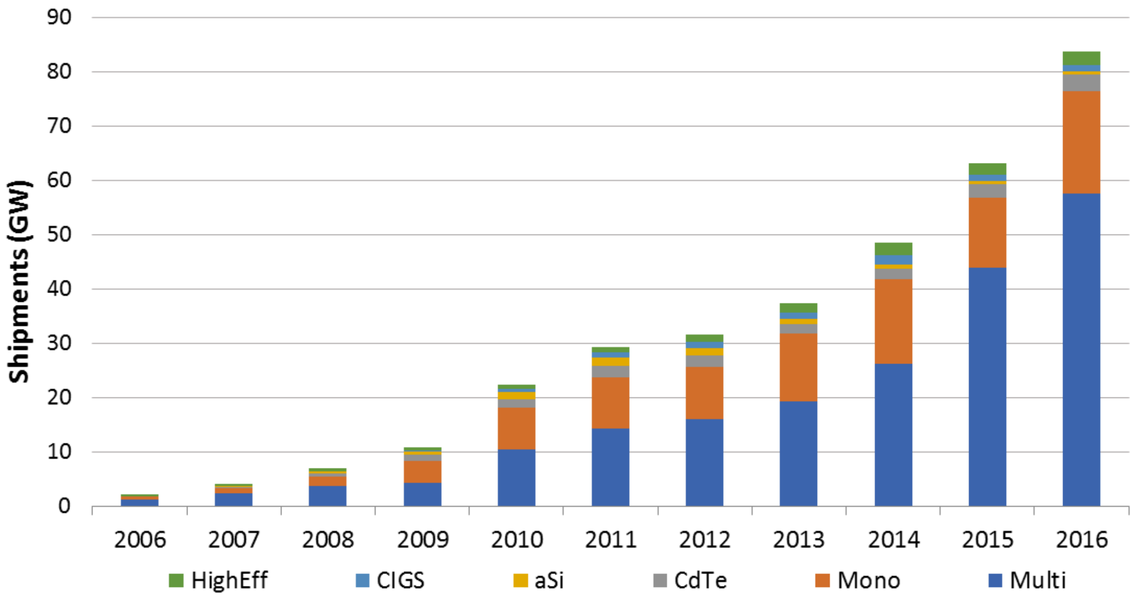

Figure 4. Cumulative global shipments of PV modules to the EU per technology. CPV and Ribbon PV data are negligible.

Source: Becquerel Institute, 2018

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[17] IEA Photovoltaic Power Systems Programme (PVPS) http://www.iea-pvps.org/

[18] The PV Market Alliance, http://www.pvmarketalliance.com/about-us/the-pv-market-alliance/

A new technology that has quickly entered the market and already achieved a significant market share, is the PERC family of cell structures (Passivation emitter rear cell). These cell structures in general are based on additional passivation of the semiconductor in order to capture more light.. They are projected to account for the largest market share by 2021. Bifacial cell types which are a further variance of the PERC cell structure are projected to grow steadily, reaching approximately 20% market share by 2021, driven largely by large rooftop and utility scale system installations. The ITRPV projects that once PERC cell structures have become mainstream then bifacial modules will quickly follow in a 12-18 month period.

The total cumulative power of PV modules imported into Europe was approximately 87 GW up until the reference year, 2016. Adding the local production (23.92 GW) and subtracting the exports (9.43 GW), the installed base that constitutes the stock is estimated at 101.86 GW for year 2016. This figure represents one third of the cumulative global shipments up until the reference year (340 GW).

The photovoltaic modules market is highly competitive, which means that there are limited margins, which in turn restricts the number of intermediaries. Manufacturers' channels to market for conventional modules are generally limited to:

- Direct sales to developers or large installers,
- Sales via local subsidiaries,
- Sales via distributors then to installers
- Products then sold under the brand name of another company.

The market share of distributors in the large-commercial and industrial segment is rather small, due to the small margins, and larger installations do not normally use distributors for cost reasons.

3.1.2. Inverters for photovoltaic applications

The European inverter market is dominated by single and three phase string inverter technology (73%). The remaining portion of the market is accounted for by centralised inverters (26%), delivered either as a standalone unit or packaged with other power conditioning equipment such as transformers, and micro-inverters (1%).

Inverter capacity is generally expressed in watts of AC rated output (WAC). In total 6,854 MW_{AC} of inverter capacity was shipped to the EU market in 2016. Figure 5 illustrates inverter shipments to the EU, with estimates through to 2022. There is understood to be a mismatch between shipment data and sales because stock destined for Africa is shipped first to the EU.

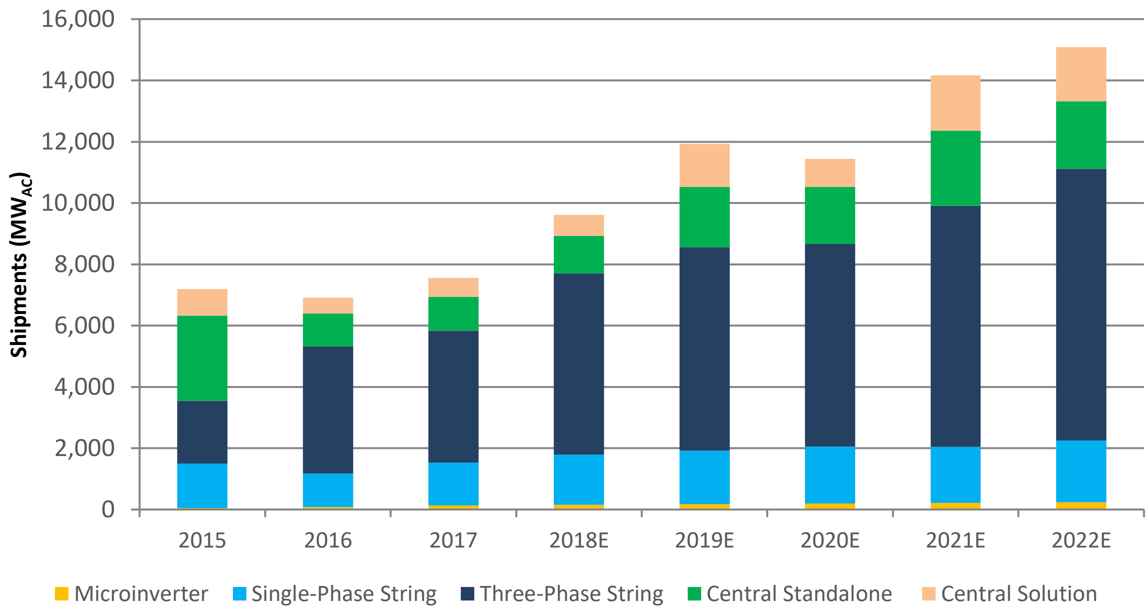

Figure 5 EU inverter shipments by technology (MWac) E=Estimate

Source: GTM Research (2017)

With an adjustment for the undersizing of inverter AC capacity in proportion to module DC capacity on larger systems, the installed new stock in 2016 is estimated to be in the range of 5,678 and 6,151 MW_{AC}. Using similar assumptions the total installed stock until the end of 2016 is estimated to be in the range of 94,400 and 96,913 MW_{AC}.

In terms of channels to market, for systems of a size greater than 100 kW, the system developer will in general tend to go directly to the inverter manufacturer. The regional or country representatives of manufacturers are in general subsidiaries of the manufacturers. Distributers tend to be well established companies (e.g. Krannich solar in Germany) that sell mostly to the residential and commercial segments.

3.1.3. PV systems

The early demand for systems came from a relatively small group of so-called pioneers who were committed to PV's environmental, energy security, and self-generation benefits. The PV industry has now evolved to so-called 1st Generation PV business models where the product is more attractive to a broader market, moving into the so-called early adopter customer category. 2nd Generation business models have yet to emerge, but will emphasise greater integration of the PV systems into the grid because emerging technologies and regulatory initiatives are likely to make such integration more viable and valuable.

In terms of the installed stock for systems, the ground mounted installations (which can be mainly considered as utility scale) experienced the largest growth in the years 2001-2016, followed by the industrial and commercial sectors where there were years especially between 2008 and 2011 when the growth doubled (over 100% each year).

The total installed system stock in 2016 was 101,788 MW_{DC}. The majority of this stock was accounted for by commercial (32%) and ground mounted (31%) systems. Residential and industrial systems accounted for 19% and 18% respectively. Figure 6 illustrates the cumulative capacity installed up to 2016.

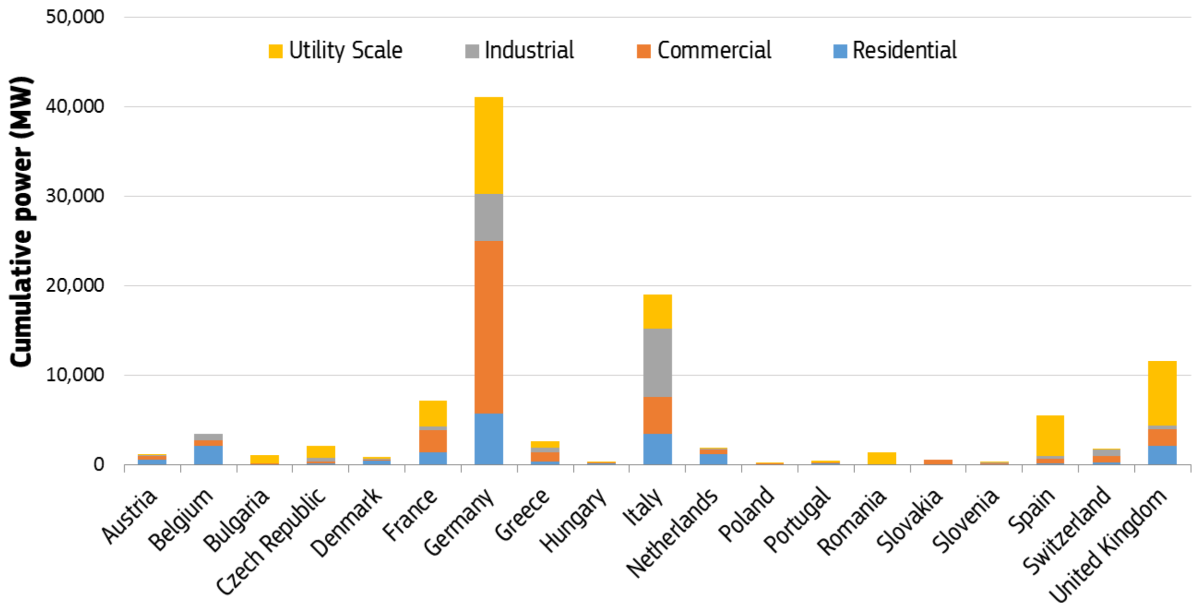

Figure 6.Cumulative Capacity installed in most European countries up to 2016 in MW_{DC}.

Source: Solar Power Europe, 2017.

As seen for PV modules and inverters, when dealing with systems, the channels to market can be quite diverse depending also on the scale of the system, whether it is large scale or small residential installer market. Project developers and engineering procurement and construction (EPC) companies are normally present in large installations, while system installers normally act at all scales.

The main PV developers in Europe are found in Germany (with an accumulated value of 2,040 MWp), France (811), Austria (469), the UK (358) and the Netherlands (307). In the case of EPC contractors, the Member States whose firms have the highest accumulated capacity are Germany (3,569 in MW_{AC}), Spain (631), the UK (585), Austria (466), France (369) and Portugal (318).

3.2. Market trends in technology

3.2.1. PV modules

The principal trends apparent to purchasers of modules relate to the cell structure and efficiency. In particular a number of new cell types, dimensions and bus bar arrangements have rapidly gained global market share. These improvements have in turn been reflected in higher stabilised efficiency values for the cells used to manufacture module and, for modules products as a whole, improved Cell to Module (CTM) power ratios. For some products such as CIGS and CdTe there has been a progressive evolution of the technology platform, such that efficiencies are comparable with some of the crystalline products in the market.

It can be seen in

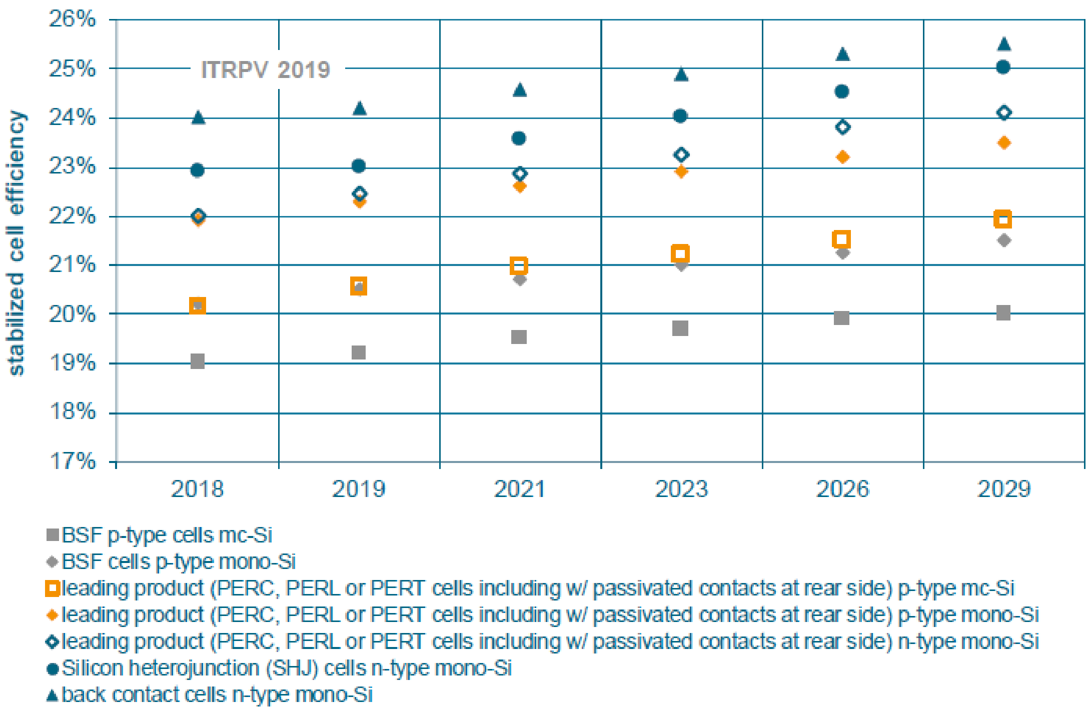

Figure 7 that p-type polycrystalline cell types achieved an upper limit to efficiency levels of approximately 21% in 2016, projected to rise to 23% by 2027 (represented by PERC/PERT cell types) whereas n-type monocrystalline cell types supported efficiency levels in the range of 21% to 23% in 2016, projected to rise to 24 -26% by 2027 (represented by heterojunction and back contact cell types).

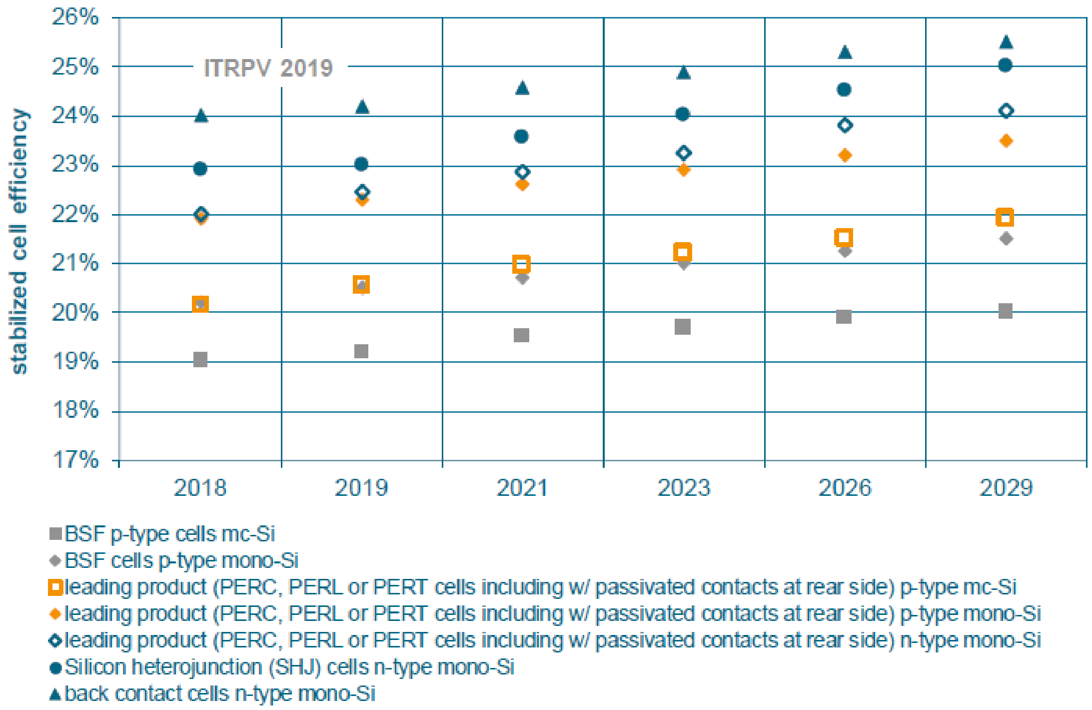

Figure 7. Average stabilised efficiency level for C-Si solar cells (156 x 156mm^2)

Source: ITRPV (2019)

In terms of cell technology trends, other than those that related to the PERC family, the following can be identified:

- *Back contact cell types* without visible front busbars have also been available for some time in the market as a niche product that provides both improved efficiency and distinct aesthetics. The market share for this cell type is projected to continue to grow steadily after 2017.
- *Silicon heterojunction cell types* have been available for some time in the market, as pioneered by Sanyo, but they are not projected to achieve a market share greater than 10% until 2021 - 2024.
- *Silicon-based tandem cells* can theoretically achieve higher efficiencies by layering an additional cell with a different spectral band gap on top of a silicon cell, but for the purposes of this study are still considered to be classified as a Best Not (yet) Available Technology (BNAT) They are currently projected to enter the market in some form from 2019 onwards, although the status of research into perovskite type cells, which are commonly identified as a potential tandem cell component, suggests that this is an optimistic.
- *Bifacial cell types* allow for both faces of a cell to generate electricity. Field tests suggest increases in yield of between 5 and 20%. This cell type is considered to be particularly relevant to modules that will be installed on raised or ground mountings, usually in systems on commercial roofs or at a utility scale. It is anticipated that the predominant bifacial cell structure will be PERT with n-type silicon [19]. This module type will come at a higher cost due to the 5-10% premium for the n-type wafer, so commentators have also suggested that new cell structures that allow for use of cheaper p-type wafer substrates will gain market share – for example, mcPERT and pPERT.

[19] Kopecek,R, *Who's who at the leading edge of bifacial PV technology*, PV-Tech special report, September 2017.

Whilst the *number of cells* in a module is anticipated to increase, with the market standard number increasing from 60 to 72 by 2021, *the size of cells* is anticipated to now decrease in order to minimise *cell interconnection losses*. Half cells are projected to grow steadily, achieving a market share of 20% by 2024.

A number of *module level design innovations* are available in the market and are claimed to offer a range of life cycle and operational benefits. They include:

- Alternative framing materials: Steel instead of aluminium is claimed to give a reduction in life cycle embodied CO_2 emissions, as well as simplified manufacturing processes[20]. However, frame material changes are not projected to gain market significance in the medium term.
- Frameless modules: With associated reductions in framing materials and the advantage of greater protection of the cells from damage [21] whilst allowing for bifacial performance gains. Their market share is projected to rise to over 20% by 2028.
- Simplified fixing systems: With associated reductions in the bill of materials, the time of site required for installation and the spacing between modules.
- Anti-soiling coatings: The application of repellent coatings to the module glass which can reduce the accumulation of dust and dirt on the surface of each module[22].

Within a module, the number of cells is anticipated to increase, and despite the efforts to decrease the cost of encapsulants and back sheet materials these will be both main contributors in module manufacturing; new materials are being developed (EVA still having the major share). With the quality and durability of modules being a major focus, in line process control and automated optical inspections and testing/sorting are rising techniques in modules and cells manufacturing.

For thin film technologies information on trends is rather limited. Improvements for the mainstream products mainly refer to cost reduction and improving material efficiency, i.e. solar cells with less material but with higher efficiency. Moreover, because the encapsulation techniques used thin-film technologies fulfil most of the architects' and constructors' requirements for the building skin, hence the BIPV market is expected to gain importance for these technologies.

3.2.2. Inverters for photovoltaic applications

With the exception of micro-inverters, which still appear to have potential for efficiency improvements, inverter efficiency has increased to the point where the majority of system-level inverters have a declared efficiency in the region of 98%.

In the field of string inverters with a power rating of up to 100 kW, transformerless circuit topologies with high switching frequencies and Maximum Power Point Tracking devices represent the state of the art. Although still limited, the application of three phase string inverters to larger utility scale systems is an important application trend. Reducing the bill of materials through the introduction of silicon carbide (SiC) and gallium nitride (GaN) switching components (transistors) is a main trend in inverters. As was identified in the analysis of module trends, there are indications that the integration of power electronics at module level will continue to increase. This will see the further development of modules with integrated micro-inverters and DC power optimisers.

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[20] Bessing, N, *Q Cells – Steel frame and other module level innovations*, Presentation made by Q Cells at PV Module Technology & Applications Forum 2018, 29th January 2018.

[21] Verlinden,P. *Advance module concepts*, Chapter 10.4, p-502 in Reinders et al (2017) *Photovoltaic solar energy – from fundamentals to applications*, Wiley.

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

3.2.3. PV systems

New market demands are being created by customers e.g. new technologies, contracting services, and maintenance services. In the EU, there are two major applications for grid-tied PV: residential and utilities with 22% and 38% of the total EU capacity, respectively. Residential prosumers are anticipated to increase although the remuneration conditions are not uniform across EU. For large installations, the major investments portfolios are principally located in three countries, UK, Germany and France.

The trends in systems can be seen at two main project stages: *design* and *operation*:

At the *design stage* it is expected that dynamic energy simulation grows, especially for large installations where it is already common its use, but also in small installations. Also in the design stage, 1 axis trackers are foreseen to increase a 50% by 2020, coupled together with bifacial modules, and eventually becoming the dominant design. The expected increase in the self-consumption will stimulate further storage options to be developed. There are already some manufacturers offering inverter products combined with batteries, or their integration at module level. Also at module level, there is a trend to include power electronic solutions. To then connect the modules, the trend expected to continue is the use of combiner boxes.

At *operational stage*, monitoring and data analytics are increasingly forming part of operation and maintenance contracts. These services are growing in complexity and range from vegetation trimming to modules cleaning.

3.3. Consumer aspects

In this section the role of public and private consumers as prospective purchasers of PV systems is analysed. Whilst the level of consumer interaction with a PV system is more limited than most products that carry the EU Ecolabel, it is nonetheless important to understand the drivers and motivations for those purchasing systems, as well their expectations of quality and performance. The analysis includes the perspective of public authorities procuring systems.

3.3.1. The drivers to become 'prosumers'

The installation of a PV system offers the potential for a consumer to produce and consume energy behind the electricity meter - also referred to as 'prosumers'. Examples of prosumers could include:

- residential prosumers producing electricity at home mainly through the use of PV panels installed on their rooftop;
- citizen-led energy cooperatives or community organisations;
- housing associations;
- commercial and industrial prosumers whose main business activity is not electricity production;
- public institutions.

Moreover, evolving electricity market legislation has introduced the concept of communities of prosumers – collective self-consumption. In this way each prosumer may have a different geographical location, but they may agree to share the self-produced electricity.

3.3.1.1. Defining what is a prosumer

According to the International Energy Agency (IEA) and cited by (GfK Belgium Consortium, 2017), prosumer installations below 10kW are defined as belonging to the residential sector. Typical residential PV systems do not exceed 20 kW and are usually roof mounted according to (IRENA, 2012). However, according to (GfK Belgium Consortium, 2017), this number is lower: "residential prosumer installations across Europe are generally lower than 10kW".

The legal definition of residential prosumers is not clear or harmonised among different countries. Also the definition of self-consumption or auto-consumption may differ and include different attributes. Some countries also refer to active consumers and self-producers[23]. In some countries, residential prosumers are defined according to the size or the capacity of the installation.

More recently there are also collective prosumers that perform collective self-consumption. In France for example in 2016 a law has been introduced to allow for this[24]. Article L 315-2 of the French energy code defines that self-consumption is collective when the electricity exchange is made between one or more electricity producers and one or more final consumers, linked together by a legal entity, and from which the injection and exit points are on the same low-voltage loop of the public distribution grid. The key benefit of such an approach is that it enables electricity users who have no suitable or a collective roof (e.g. apartment) to become photovoltaic prosumers.

3.3.1.2. Market testing of prosumer attitudes

In the context of the EU funded CLEAR project (Consumers Learn Engage Adopt Renewable Energy Technologies) a market enquiry was launched in Spain, Portugal, Italy and Belgium to identify *"the best approach to implement a group offer with regard to Renewable Energy Systems (RES)"* (Test-Achats/Test-Aankoop et al., 2015). The sample consisted of a target group mainly composed by intenders and thinkers and a basic level of adopters. 5012 respondents were gathered. According to the responses, the two aspects that a user most values concerning renewable energy solutions (RES) are how much money could be saved if they had a RES compared to their current energy source and total running costs. These two aspects are common in the four countries in which the survey was conducted.

For Spain, Italy and Portugal the least important information needs were information about performance warranties and the possibility to personalise the offer. For Belgium, the least important information was a tool to provide personalised solution and payment possibilities.

A major study on prosumers commissioned by DG Justice (GfK Belgium Consortium, 2017) has carried out a similar analysis and has included market enquiries in, amongst other Member States, Germany, France, the Netherlands and UK (Figure 8). This study also identified that the main driver that leads an end-user to invest in solar PV systems is saving money. Environmental impact and government subsidies play also an important role. The choice and purchase of PV systems from the end-users perspective would depend on price, aesthetics and payback time (GfK Belgium Consortium, 2017).

Concerning the product characteristics of PV solar panels, (GfK Belgium Consortium, 2017) the researchers conducted an experiment to identify which characteristics or combinations of characteristics were considered most important to the end-user when buying a PV system. The sample consisted of respondents owning a house with PV systems but interested in purchasing a PV system. Selected product features included:

- aesthetics,
- costs per solar panel,
- inverter type,
- installation,
- efficiency,
- lifetime, and
- maintenance costs

Other factors to be considered included the resale value of the houses after the PV system installation.

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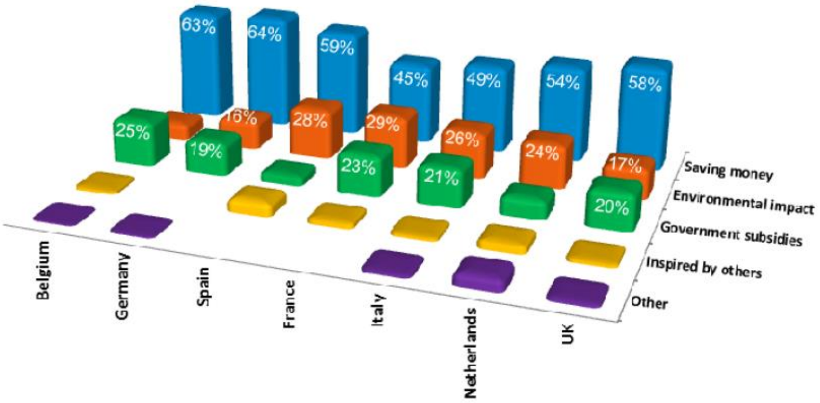
[23] A table summarizing that information can be found in (GfK Belgium Consortium, 2017): Table 1 - Definition of residential prosumers (page 37).

[24] http://www.pv-financing.eu/wp-content/uploads/2016/10/4.-Collective-self-consumption-in-France.pdf

Figure 8. Main drivers for residential prosumers to invest in solar PV by country (GfK Belgium Consortium, 2017)



3.3.2. PV system design processes in the residential market

The main driver for procuring a PV system is saving money (Figure 8). Therefore the most important consumer requirement is to calculate the annual Energy output from PV system (AC) (Eout). Based on the annual Energy output (Eout) forecast and the subsidy scheme, the return on investment or money saved can be calculated.

This PV system energy output (Eout) is related to the Performance Ratio (PR), the reference yield (Yr) [hours/year] and the total PV array power rating in DC(P0) [kWp]. Therefore the following formula applies:

Eout [kWh/y] = PR x Yr[hours/y] x P0[kWp]

The factors that that could affect the Performance Ratio (PR), referred to as 'derate' factors - are therefore of high importance. A more complete overview of contributing derate factors is made in Task 3 of the Ecodesign Preparatory Study and with reference to the standard IEC 61724-1 [25]. Not all parameters within the PR will be under the control of the installer and therefore there will always remain some margin of uncertainty left between what can be forecasted during the quoting and the real output. Therefore quality programs and procurement specifications also tend to focus on what can be controlled under standard test conditions.

Potentially the most important part of the design process is therefore the energy yield forecast (Ey).. A high-quality system requires the selection of a reliable solar resource database, correct energy simulation, a good layout, and adequate electrical and mechanical dimensioning[26]. Depending on the size of the installation, type of mounting (roof-mounted or ground-mounted) and aim, several design aspects should be taken into consideration.

Design processes for small residential PV systems can be automated and linked to predefined packages of module/inverter combinations. Therefore already today many large retailers start to offer PV systems to the residential market[27, 28, 29]. Mostly they carry out the design procedure for free during the quoting procedure, mainly related to the analysing the roof orientation and shading risk. These retailers can also differentiate in the amount of service that is included in the package deal, e.g. provide loans, insurance, extended warranty, maintenance, etc. Analysis of which roofs are suitable can also be automated by processing satellite/airplane images and laser range sensor data for a complete region[30]. Consumer expectations can also bring into the design process a range of other considerations such as aesthetics (e.g. the appearance of modules or the visual effect of a system on a roofline) as well as considerations of longer term aspects such as access to modules for cleaning and inverters for repair/replacement (Which? 2018).

[25] Derate factors quantify individual sources of loss with respect to the nameplate's DC power rating (IEC 61724-1).

[26] http://www.etip-pv.eu/fileadmin/Documents/ETIP_PV_Publications_2017-2018/PV_Quality_report_ETIP_PV_SolarUnited_August_17.pdf

[27] http://ikea.solarcentury.com/

[28] https://www.vattenfall.de/de/sonnendach.htm

[29] https://www.engie-electrabel.be/nl/energie-besparen/zonnepanelen/opbrengst

[30] https://vito.be/en/media-events/press-releases/how-suitable-is-your-roof-for-the-installation-of-solar-panels-or-a-solar-boiler-see-for-yourself-on-the-solar-map

From the user perspective various system design aspects may be of concern due to their influence on performance. The choice of the inverter is an important aspect. String inverters are usually cheaper but since they connect the panels in series, if one of the panels fails, it will impact in the whole system. Micro-inverters, usually more expensive, don't have this drawback and any problems will be potentially better identified through the power-monitoring system. The location of the inverter is another important aspect to take into account. Being placed near the panels minimises possible energy losses due to long cabling. The heat from solar irradiation however may have a negative impact on its performance. The colour of the panels, besides the aesthetic aspect, may or not influence their performance. Black panels without front surface busbars might, for example, see their efficiency decreased due to an associated temperature rise.

The choice between roof mounted or integrated, depends on the type of construction: for new constructions, BIPV is an option, but it can be more expensive and for old construction the only option may be BAPV. In the case of retrofitting, it will be dependent on the depth of modifications: for example, replacement of roofs might allow the installation of BIPV. It is important to highlight that one advantage of BIPV is related to their positioning: they sit flush with the roof which leaves no room for birds to nest underneath. Birds nesting is a problem reported by several PV owners and hence the importance of making them aware of this possible situation ("Make the most of your solar panels - Which?," n.d.).

Additionally, and although PV panels might be self-cleaning through the rain when the roof has the right incline, some additional actions might be required if there are birds, trees or even a high amount of traffic in the area.

3.3.3. System and product tests required by subsidy schemes

Given the importance of subsidy schemes such as feed-in tariffs to the growth of the EU PV market, the qualification requirements for equipment, systems and installers are of particular relevance as they impose requirements on all equipment, suppliers and contractors used. In this section the requirements of Italy, the UK, France and Belgium are briefly reviewed.

The countries reviewed make reference to existing type approval quality standards such as IEC 61215 for crystalline modules and IEC 61646 for thin film modules. Some novel findings from this review are as follows:

- Italy established a Performance Ratio target with field testing requirement which has driven a focus on installed performance.
- France has established an award criteria for the embodied GWP the modules to be used in the points system for capacity auctions.
- France has focussed on performance criteria in support of product and system warranties. These include coverage of:
    - The durability of the mounting system
    - Waterproofing of the main system components e.g. junction boxes
    - The halogen content of cables

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

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

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

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

- IEC standards

    - IEC 61215 for crystalline modules

    - IEC 61646 for thin film modules

- A warranty for 10 years against manufacturing defects

- Adherence of the manufacturer to a system or a consortium that will ensure the recycling of the modules at the end of life

- Confirmation of the execution of periodic factory inspections and product verifications in support of compliance with the above technical standards (IEC 61215/61646/62108)

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

3.3.3.2. Microgeneration Certification Scheme (UK)

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

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

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

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

– a measurement of the deflection of the sample,

– application of relevant glazing quality standards from a listing,

– consideration of imposed, static and live loads that the product may be exposed to in the field, and

– application of factory methods to achieve correct lamination in accordance with EN ISO 12543.

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

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

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

3.3.3.3. BAPV and BIPV product warranties (France)

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

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

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

- A calculation note on the mechanical resistance of the component parts of the mounting system (fixing clips, rails, screws, etc.) and on the climatic loads that may be applied to the modules.
- Justifications based on test results of the waterproofing of the main system components.
- Justifications based on test results of the resistance and durability of the component parts and their materials according to their ageing under environmental conditions (e.g. temperature, UV, humidity).
- Junction boxes according to EN 50548, which covers a range of environmental protection aspects, including water ingress and ambient temperature range, as well as resistance to ageing and corrosion.

Classification of fire cables according to national standard NF C 32-070 which contains the need for reporting on halogen content in conformance with IEC 60754-1.

3.3.3.4. Qualiwatt feed-in tariff (Belgium)

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

- a copy of the certificate of competence for the installer of the solar photovoltaic systems issued by the RESCERT body;
- a copy of a Factory Inspection Certificate (FIC) which identifies the site of the photovoltaic modules used were produced;
- evidence that photovoltaic modules used are certified according to:
  - IEC 61215 for crystalline modules
  - IEC 61646 for thin film modules
  - IEC 61730 when panels are integrated or superimposed on a building.

The certifications must be carried out by an accredited testing laboratory according to ISO 17025 by BELAC or another national accreditation body enjoying mutual recognition with BELAC.

3.3.4. System and product tests made by selected consumer organisations

An analysis has been made of the different types of information and tests that three selected *consumer organisations* carry out to support residential consumers in installing PV systems. Alongside the information provided by governments and their associated subsidy schemes, consumer organisations represent an important source of impartial information and guidance.

There are also international initiatives that developed collaboratively[31] PV system testing for their member consumer organizations. In principle what consumer organisations do is very close to what some retailers are doing [32] [33], the key difference is that they are also the contractor and single point of service. In many cases retailers and/or installers make proposals or quotes free of charge.

3.3.4.1. Test-Achats (Belgium)

The Belgian consumer organisation 'for example provides extensive support to their members for purchasing PV systems (Test-Achats/Test-Aankoop, 2015). They audit PV module manufacturers and check production samples on uniformity, compliance with the rated power, soldering errors with electroluminescence camera, visual errors in the back sheet laminates

[31] http://www.international-testing.org/

[32] https://www.ikea.com/gb/en/ikea/solar-panels/

[33] https://www.eon.de/de/pk/solar/aura/photovoltaikanlagen.html

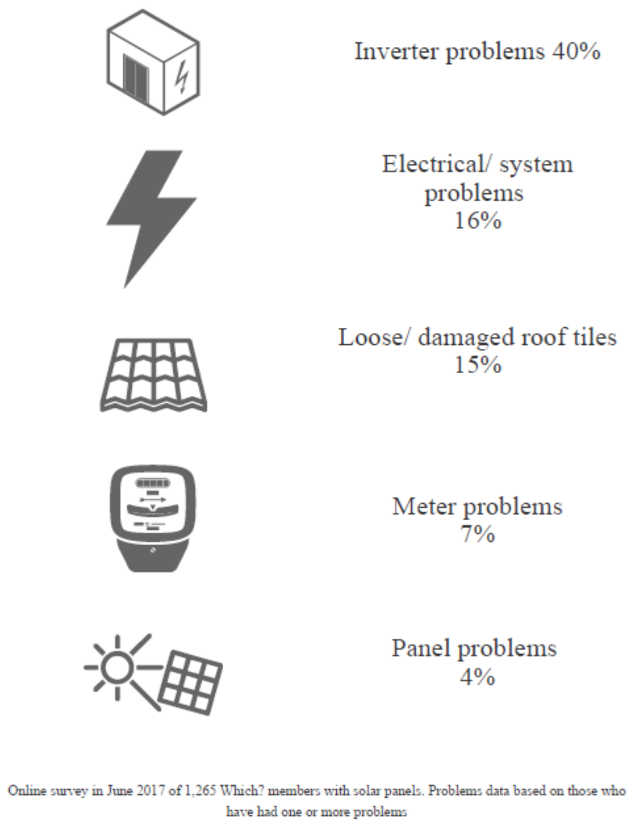
or frames and the quality system in place. They also offer group purchase promotions in which they audit the production accordingly. Moreover their requirements are that:

- PV modules must comply with IEC 61215 (crystalline cells) or IEC 61646 (thin film cells) IEC 61730 (BAPV) with a third party certification (BELAC, TUV, ..), as detailed in Task 1.
- They refer to a reference contract proposed by the local authorities[34] for installers (Service Public Wallonie, 2015), see a later section in this task for more details.
- Minimum warranty in modules and inverter of 10 years.
- At least one of the installers must have followed the Rescert PV installer course[35].
- During installation the consumer organisation will perform regular audits.
- IEC 61215 for crystalline modules
- IEC 61646 for thin film modules

3.3.4.2. Which? (United Kingdom)

The British consumer organisation Which?[36] provides similar information to its members consisting of module manufacturer audits and inspection combined with expert advice for selecting a PV systems. They also carry out surveys of their members to identify problems and issues to address (see Figure 9)

Figure 9 Top five solar system problems identified by a survey of Which? members



[35] https://www.rescert.be/fr/certificats-possibles

[36] https://www.which.co.uk/reviews/solar-panels/article/best-solar-panel-brands/solar-panel-brand-reviews

3.3.4.3. OCU (Spain)

The Spanish consumer organization OCU recommends a selection of tested PV systems or kits[37], which are preselected combinations of modules with inverters which are then given a scoring or rating based on their tested performance. Metrics that are scored include deviation from manufactured claimed performance and the number of cell defects.

3.4. Public procurement criteria and requirements for PV systems

During the procurement process a public authority will select a contractor for installing the PV system. The entity responsible for on-site system installation based on the intended design, equipment specifications is called herein the contractor. The Contractor can thus be seen as one of the entities with the greatest impact on the quality of the asset in terms of safety and actual system performance (Doyle et al., 2015).

The procurement process can vary according to the ownership. In the particular case of public authorities and green procurement, or Green Public Procurement, it means the process whereby public authorities seek to procure goods, services and works with *'a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured'*[38]. It is one of the objectives of this study to explore the potential for GPP criteria for PV modules, inverters and systems.

3.4.1. EU Green Public Procurement (GPP) criteria

EU GPP criteria aim at facilitating public authorities the purchase of products, services and works with reduced environmental impacts. The use of the criteria is voluntary. The criteria are formulated in such a way that they can be, if deemed appropriate by the individual authority, integrated into its tender documents.

There are four main types of GPP Criteria:

a. **Selection criteria (SC)** assess the suitability of an economic operator to carry out a contract and may relate to:
   - (a) suitability to pursue the professional activity;
   - (b) economic and financial standing;
   - (c) technical and professional ability.

b. **Technical specifications (TS)**, the required characteristics of a product or a service including requirements relevant to the product at any stage of the life cycle of the supply or service and conformity assessment procedures;

c. **Award criteria (AC)**, qualitative criteria with a weighted scoring which are chosen to determine the most economically advantageous tender. The criteria are linked to the subject-matter of the public contract in question and may comprise, for instance:
   - Environmental performance characteristics, including technical merit, functional and other innovative characteristics;
   - organisation, qualification and experience of staff assigned to performing the contract, where the quality of the staff assigned can have a significant impact on the level of performance of the contract; or

[37] https://www.ocu.org/vivienda-y-energia/gas-luz/test/comparar-kits-fotovoltaicos

[38] http://ec.europa.eu/environment/gpp/what_en.htm

- after-sales service and technical assistance, delivery conditions such as delivery date, delivery process and delivery period or period of completion.

Award criteria shall be considered to be linked to the subject-matter of the public contract where they relate to the works, supplies or services to be provided under that contract in any respect and at any stage of their life cycle, including factors involved in:

- (a) the specific process of production, provision or trading of those works, supplies or services; or
- (b) a specific process for another stage of their life cycle,

even where such factors do not form part of their material substance.

d. **Contract performance clauses (CPC)**, special conditions laid down that relate to the performance of a contract and how it shall be carried out and monitored, provided that they are linked to the subject-matter of the contract.

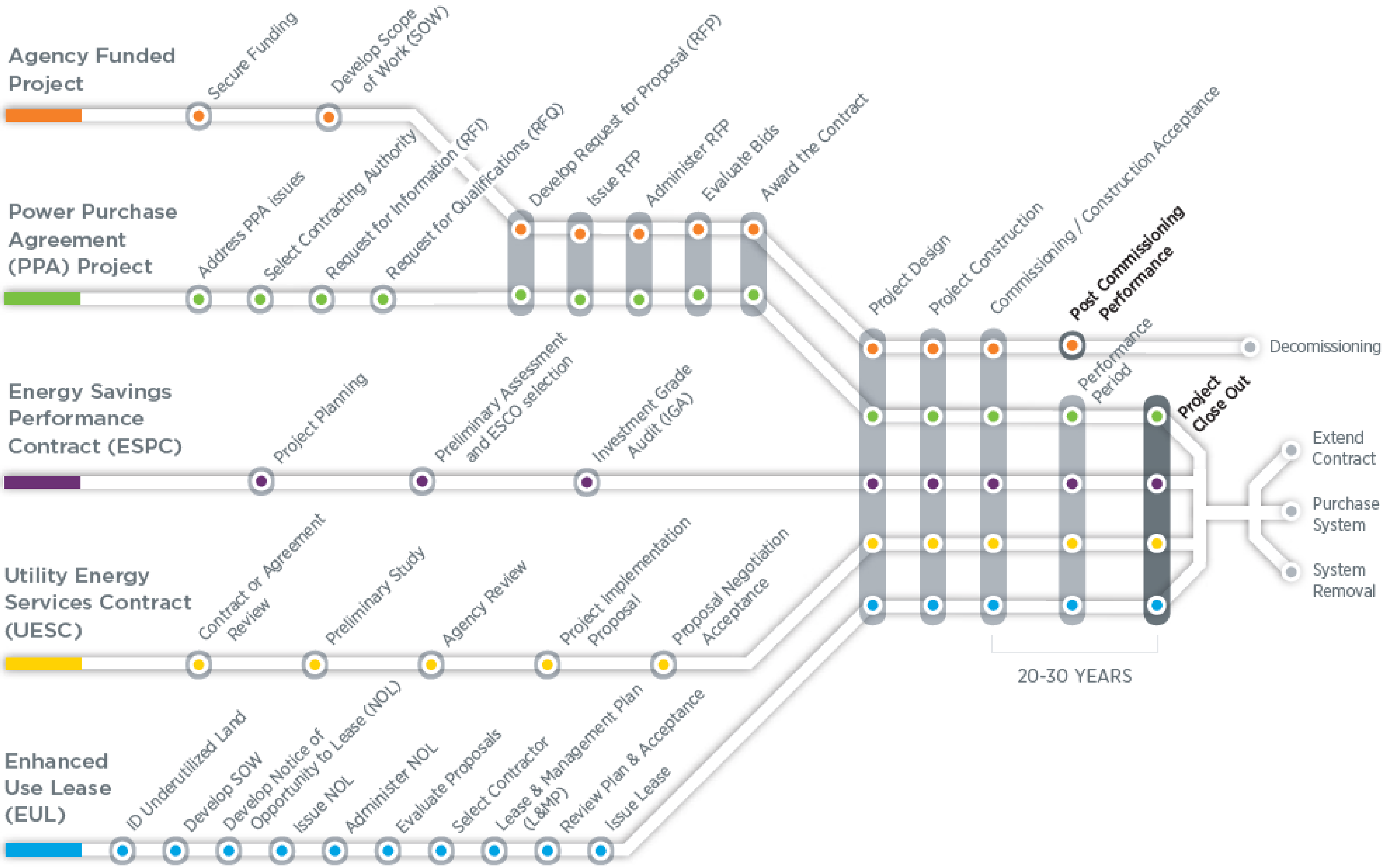
The criteria are split into Technical Specifications and Award Criteria. For each set of criteria there is a choice between two ambition levels:

- The Core criteria are designed to allow for easy application of GPP, focussing on the key area(s) of environmental performance of a product and aimed at keeping administrative costs for companies to a minimum.
- The Comprehensive criteria take into account more aspects or higher levels of environmental performance, for use by authorities that want to go further in supporting environmental and innovation goals.

The structure of the tender process is also linked to the preferred type of contractual arrangement, as illustrated by recent EU GPP criteria for Office Buildings (European Commission 2016). Figure 10 is taken from a guide developed for public authorities by the US Department of Energy and illustrates the different contracting routes that can be followed. Although the diagram is in a US context, the same broad options are available in a EU context.

Careful consideration of the contracting route is important because it may have implications for the types of GPP criteria that can be used, and when they will be applied during the bidding and contract execution process.

Figure 10 Diagram illustrating different financing and contractual arrangements for public procurement (Source: US DoE, 2010)



3.4.2. Public procurement examples and models

3.4.2.1. Findings from an OJEU tenders search

The Office Journal of the EU's tenders database was consulted in order to review the types of criteria that are set when publishing calls for tender for PV systems. Relatively few European public tenders for solar PV systems were found to be published[39], with 46 tender documents for a period from 7/2015 until 4/2018. The most active country was Poland followed by France, Germany, UK, Ireland, Italy and Switzerland. Note that public authorities can also procure green electricity but it seems that they do not often procure and/or own the PV systems used to generate this electricity themselves.

Examples of Award Criteria were based on the price per kWp but sometimes combined with extra points[40]. For example in the case of Main-Kinzig(D) the following were specified: a longer warranty on modules and inverter, installation time, reaction time in case of failure and how long spare parts are kept for repair of the inverter. Repair response times and installation time are sometimes specified only in the Contract Performance Clauses instead of the Award Criteria.

Another Tender (Monthey-Switzerland) combined the price (35%) with the forecasted AC output power (35%) combined with the judging on the technical quality of the proposal (10%), the project management (10%) and previous references (10%).

Note that in these examples elements such as project management and references that are usually Selection Criteria were found to have been taken into account in the Award Criteria.

Important in all the tenders reviewed were the minimum quality requirements and/or the valuation of quality, which was related to performance but also trained staff.

3.4.2.2. Facilitating energy services and roof contracts

Apart from directly procuring a PV installation there are also other procurement routes that are designed to attract private capital investment in solar PV opportunities. A special form of public procurement is using an Energy Service Company (ESCO) with Third Party Ownership. This can be done by roof contracting to a Third party, for example in Germany the Berliner Energy Agentur[41] and the city of Freiburg are doing this.

In Belgium the Distribution Company offers ESCO services to the local municipalities for their buildings[42] meaning that they organise the tendering, servicing an financing. Finally, public authorities can simply also procure green electricity. A hybrid of this approach is being used in some cases due to the absence of feed in tariff subsidies. For example in the case of Portsmouth City Council in the UK where Power Purchase Agreements (PPAs) have been used [43].

3.4.2.3. Facilitating communities of self-consumption

In both the UK (Reading) and in Germany (Freiburg) renewable energy investment co-operatives have been established to finance systems that have been installed on a range of public and community buildings [44] [45]. In France a project in Brittany

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[39] OJEU Tenders Electronic Daily, http://ted.europa.eu/TED/

[40] http://www.versorgungsservice-main-kinzig.de/Ausschreibung-2018.2031.0.html

[41] Berlin Energy Agency, http://www.berliner-e-agentur.de/en/services/photovoltaic-contracting

[42] http://www.eumayors.eu/about/covenant-community/signatories/key-actions.html?scity_id=5310

[43] Solar power portal, *Solar PPAs and the public sector*, 7th July 2016

https://www.solarpowerportal.co.uk/blogs/solar_ppas_and_the_public_sector_7834

[44] Reading Community Energy Society, readingenergy.coop

[45] see FESA, www.fesa.de *and* Regiosonne, www.regiosonne.solar-monitoring.de)

has been piloting the role of public authorities in establishing communities of self-consumption whereby the electricity generated by systems installed in a local area is pooled and shared.

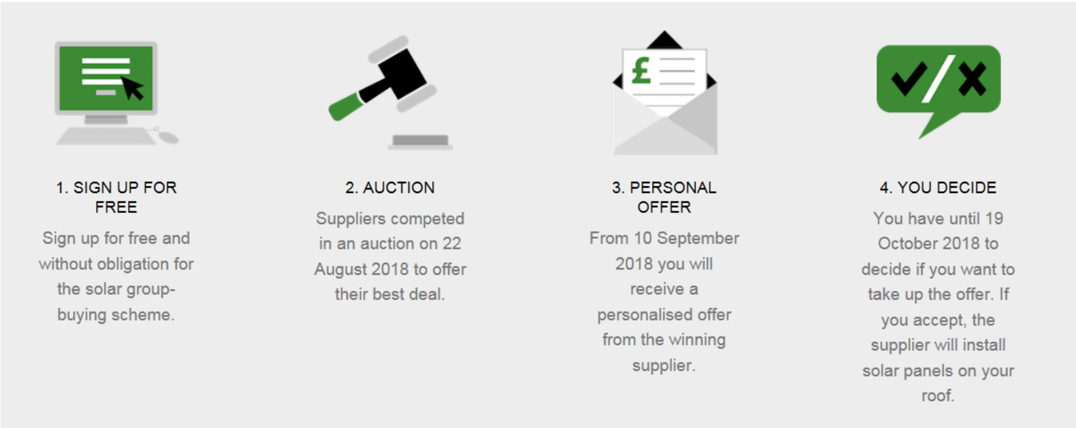
3.4.2.4. Facilitating residential systems - reverse auctions

As was highlighted in the Task 3 report of the Ecodesign Preparatory Study, increasing residential deployment of solar PV systems is a major challenge. Households wishing to install a solar PV system face a number of possible barriers, depending on the local context in each Member State. These include access to information and an initial point of contact with installers. Moreover, in the absence of subsidy regimes there are less economic incentives and prices may be artificially high if the market is less developed.

One approach to elimination of barriers to residential deployment is the concept of a 'reverse auction'. This concept is currently being demonstrated by the 'Solar Together London' initiative of the Mayor of London in the UK [46]. It consists of a two part group buying process that is managed by the public authority – the registration of households interested in installing a system on their home followed by a subsequent supplier shortlisting and tender process to select an installation company that can service the registered households. The public tender included quality specifications for the systems offered to households, including monitoring systems and an extended guarantee for each system. The guarantee includes a 10 year warrantee for modules and inverters and a 25 year performance guarantee for module degradation.

The auction process also has as a principle objective a reduction in the unit price of each system. A price reduction of 35% on market rates is claimed for the first auction round based on installations for 4,000 households. This is based on the economies of scale and certainty that can be provided by the household registration process.

Figure 11. The London reverse auction process as seen from the perspective of a household



Source: Solar Together London (2018)

4. Technical analysis

In this section a summary is provided of the technical analysis of improvement potential that was made in Task 4 of the Ecodesign Preparatory Study. A range of technical improvements were identified and analysed for:

- photovoltaic modules at wafer, cell and product level,

[46] Mayor of London, *Mayor expands solar panel scheme after 4,000 sign up to first phase*, 29th June 2018, https://www.london.gov.uk/press-releases/mayoral/mayor-expands-solar-panel-scheme

- inverters at product and component level, and
- systems in respect of design, operation and maintenance practices.

In order to facilitate the modelling of future improvement potential of each of the products, a range of design improvement options were identified that may be candidates to be either a Best Available Technology (BAT) or Best Not Yet Available Technology (BNAT) at product level.

4.1. Module improvement options

The standard product has been identified as a multisilicon module based on back contact cells also known as Back Surface Field (BSF) metallisation. With a cell efficiency of 14.7% this technology accounted for the majority (more than 70%) of module products on the market in 2016/7 and is projected to maintain significant market share past 2020.

In terms of improvement in the module and cell efficiency, as well as life-cycle environmental impacts, possible candidates for the Best Available Technology (BAT) at module and cell level are CIGS and CdTe thin films, as well as modules based on PERC/PERT, back contact, heterojunction and bifacial crystalline silicon cell designs. Although the cell efficiency and degradation rate of CIGS and CdTe appear to be inferior to the crystalline silicon cell technologies identified, initial evidence suggests that their life cycle performance for the functional unit of 1 kWh may be superior.

As well as module efficiency and life cycle impacts it also important to consider the Energy Packback Time (EPBT) – the relationship between the energy used to produce a module and primary energy it can generate. This can range, indicatively for a standard polycrystalline module, from 0.7 years to 2.0 years depending on the climate zone within Europe. In some Member States, or even between regions within Member States, the lower potential yield from modules results in a longer energy payback (see Figure 12). It is therefore important in lower yield locations to minimise energy use in the production stage of a module product.

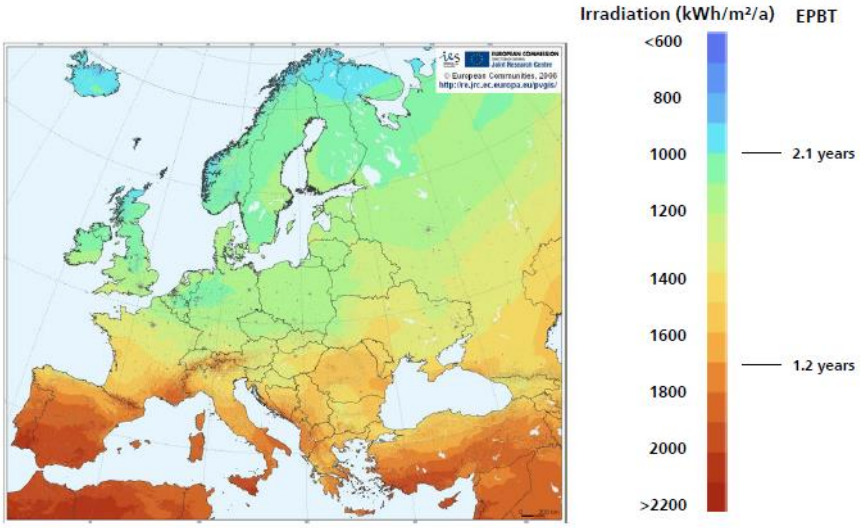


Figure 12. Map of European solar irradiation and indicative Energy Payback Times (EPBT)

Source: JRC (2017)

Additional module design options that could be combined with the aforementioned cell designs primarily relate to interconnections, encapsulation and backsheets:

- Interconnections: Electrical efficiency can be improved by using thinner busbars, multi wire design or electro-conductive backsheets to eliminate busbars, and the use of half cells. A trade-off exists between some of these options in which the use of silver can be reduced whilst more lead must be introduced into solder compounds and metallisation paste. Lead-free compounds are understood to have been demonstrated at commercial-scale but more information is required on their durability and the extent of their application field.

- Encapsulation: In relation to encapsulation, material selection can contribute to the reduction of water ingress and permeation, resulting in subsequent chemical reactions that can result in performance degradation. These material options may therefore improve module performance along the lifetime.
- Backsheet: Material selection can influence the durability, recyclability and water permeability of a module. The fire protection properties must also be taken into consideration and in this respect there appears to be a trade-off between cost, durability and the potential need for flame retardants – although more information is needed about the latter.

Opportunities also exist to reduce failure and performance degradation mechanisms at a number of stages in the process of bringing a product to market. These include, in addition to those already noted in relation to encapsulants, the potential at the following stages:

- Product design stage: Implement accelerated life testing routines that combine different simulated environmental testing conditions in order to provide feedback to the design and material selection processes. This may result in multiple improvements rather than a single identifiable design option;
- Manufacturing stage: Minimise manufacturing defects by implementing a series of factory quality testing and inspection routines. These are to some extent already reflected in a number of IEC and EN standards;
- Transport stage: Minimise transport damage by considering the packaging and protocols used to ship products and to distribute modules to installation sites;
- Use stage: Ensure that bypass diodes can be accessed and readily exchanged in order to minimise total or partial power loss.

Whilst warrantied product performance providing extended coverage of manufacturing defects and more stable long term efficiency is currently offered by some manufacturers, these have limited validation based on standardised product testing and performance in the field. This is particularly the case for PERC/PERT and bifacial cells, which have had limited deployment in the field. Proxies for improved performance could include accelerate life testing with multiple stress factors applied to a single product.

Candidates for the Best Not Yet Available Technology (BNAT) include modules consisting of crystalline silicon cells created by lift-off or epitaxial growth – thereby reducing the primary energy used to produce silicon wafers - or where the crystalline silicon cell is in a tandem formation with perovskite thin films – offering a further improvement in cell efficiency.

4.2. Inverter improvement options

The Ecodesign Preparatory Study has analysed representative inverters according to their application field – 1 string inverter (residential segment), 3 string inverter (commercial segment) and central inverter (utility scale segment). Improvement options relating to the residential segment will be of the most relevance to the EU Ecolabel and the commercial segment for Green Public Procurement.

With digitalisation the Euroefficiency of inverters has improved to the point that there is less scope to differentiate the performance of products. A performance of 97.5% can be seen in the market as a base case euroefficiency. Only micro-inverters and inverters forming part of hybrid battery storage systems can be seen to perform worse.

As a component of the Euroefficiency, Maximum Power Point Tracking (MPPT) is an important variable. The most important improvement measures identified are at product level:

- Micro-inverters offer benefits at system level because of their module-level Maximum Power Point Tracking (MPPT) and enhanced reliability that is intended to match the lifespan of the modules to which they are attached. Further evidence of the additional steps take to achieve products that have an extended design life is required;
- Inverters that incorporate wide band gap metal-oxide-semiconductor field-effect transistors (MOSFET) which are able to maintain high performance at higher operating temperatures. They could allow for a reduction in the bill of materials and a reduction in thermally induced failures, although the possible trade-off from using more energy intensive silicon carbide or gallium nitride semi-conductors requires further analysis.

Whilst it is understood that central and commercial scale inverters are commonly repaired and that their primary components can be replaced in order that they approach their estimated design life (cited as 20-30 years), more information is needed on the potential for repair and replacement of components identified as the common cause of failures and which have recommended replacement cycles – namely main circuit board, AC contactors, fuses, capacitors and fans. The potential to diagnose operating system errors is also important, including the possibility to upgrade firmware.

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 entered the commercial segment of the market in 2018 their market share and application field is still very limited..

The complementary role of optimisers installed at module-level in providing the function of Maximum Power Point Tracking (MPPT) can also be highlighted.

4.3. Photovoltaic system improvement options

The Ecodesign Preparatory Study has analysed representative systems for the market segments of residential (3 kW), commercial (20 kW) and utility scale (1.5 MW). Improvement options relating to the residential segment will be of the most relevance to the EU Ecolabel and the commercial segment for Green Public Procurement.

4.3.1. Identification of the Best Available Technology (BAT)

The possible candidates for system-level BAT focus mainly address the potential to transfer optimised performance improvement practices from the utility scale segment to the residential and commercial segment where Performance Ratios are typically less optimised and maintenance routines more limited.

The focus for system design improvements should extend to support better operation & maintenance practices. Energy yield can be optimised by addressing derating factors with the Performance Ratio such as soiling, and by diagnosing failures in the inverters and on the AC side of the power supplied. The two main improvement options that have been identified are as follows:

- Optimised design and yield forecasting: The use of more dynamic simulation yield modelling and forecasting software with a higher probability of accuracy (e.g. P90 exceedance level). This could include installation of a class C monitoring system on inverters to later monitor the yield with a high granularity.
- Optimised monitoring and maintenance: The potential to follow-up module and inverter failure identification with the repair of key components should be addressed. The use of remote field inspection in order to make fault diagnosis is also a possibility. This could include the application of IR imaging across multiple residential systems.

In terms of system components, the installation of bifacial modules that have the potential to enhance the energy yield by 5-15% in combination with the treatment of roof surfaces to improve reflectance, as well as the incorporation of single axis trackers to improve the yield of large roof and ground-based systems by up to 25% can be options.

An additional option for consumers that wish to maximise self-consumption is the inclusion of battery electrical storage. This is not yet been considered to be a potential BAT as the battery will create an additional environmental burden and the potential trade-off between this burden and the displacement of electricity generation at peak times, which may or may not have a higher grid CO_2 emissions factor depending on the nature of the generating capacity dispatched to meet peak demand in each Member State.

For the end of life phase of a PV system a decommissioning plan is becoming a requirement for large systems. Facilities and processes are now being developed to handle modules and ensure proper treatment according to WEEE Directive requirements as waste arising increase into the future. The state of the art is represented by a first stage mechanical dismantling to recover bulk materials such as glass and aluminium followed in some cases by chemical processing of the semiconductor. More information is still needed on inverter end of life routes.

4.3.2. Best practice in risk mitigation and reduction in Life Cycle Costs

The concept of Levelised Cost of Electricity (LCOE) is widely used in the electricity sector to express the total Life Cycle Cost (LCC) of delivering electricity to the grid. The difference between LCOE and LCC is that it is normalised to the unit of power generated, kWh. This enables comparisons between different power generation options.

LCOE is defined by the European Photovoltaic Technology Platform as the average generation cost, i.e., including all the costs involved in supplying PV at the point of connection to the grid. The PV LCOE, expressed in €/kWh in real money, can be defined by equation:

$$LCOE = \frac{CAPEX + \sum_{t=1}^{n}[OPEX(t)/(1 + WACC_{Nom})^{t}]}{\sum_{t=1}^{n}[Utilisation_0 \cdot (1 - Degradation)^{t} / (1 + WACC_{Real})^{t}]}$$

where

t = time (in years)

n = economic lifetime of the system (in years)

CAPEX = total investment expenditure of the system, made at t=0 (in €/kWp)

OPEX (t) = operation and maintenance expenditure in year t (in €/kWp)

$WACC_{Nom}$ = nominal weighted average cost of capital (per annum)

$WACC_{Real}$ = real weighted average cost of capital (per annum)

$Utilisation_0$ = initial annual utilisation in year 0 without degradation (in kWh/kWp)

Degradation = annual degradation of the nominal power of the system (per annum)

and $WACC_{Real} = (1 + WACC_{Nom}) / (1 + Inflation) - 1$

where Inflation is the annual inflation rate.

A number of private initiatives and European Union funded projects have made analyses of the project life cycle for implementation of solar PV systems with a view to identify how to:

- optimise the potential to generate solar power,
- minimise risks to loss of income from and,
- minimise the LCOE along the life cycle of a project.

These include the IEA PVPS programme [47], the European Photovoltaic Technology Platform [48], Solar Bankability [49] and PV Finance [50].

The Solar Bankability project is of particular relevance as the recommendations are based on analysis of due diligence, operation and maintenance records for a range of PV system scales. The outcomes of the project focus on project planning to minimise technical project risks to the economic operation of a system, with a focus on the LCOE. Table 7 provides an overview of the main technical gaps in risk management identified by the project.

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[47] International Energy Agency, *Technical assumptions used in PV financial models – review of current practices and recommendations*, Photovoltaic Power Systems Programme, Report IEA-PVPS T13-08:2017

[48] European PV Technology Plaftorm, *PV LCOE in Europe 2014-2030*, PV LCOE working group., March 2015

[49] Solar Bankability, *Recommendations for minimising technical risks of PV project development and PV plant operation* (2017), Merged deliverable D1.2 and D2.2.

[50] PV Finance, http://www.pv-financing.eu/

Table 7 Most common mistakes in the present day technical inputs for PV financial models

Risk	Phase/field	Identified critical technical gaps
Year-0	Procurement/ product selection and testing	1. Insufficient EPC technical specifications to ensure that selected components are suitable for use in the specific PV plant environment of application. 2. Inadequate component testing to check for product manufacturing deviations. 3. Absence of adequate independent product delivery acceptance test and criteria.
	Planning/ lifetime energy yield estimation	4. The effect of long-term trends in the solar resource is not fully accounted for. 5. Exceedance probabilities (e.g. P90) are often calculated for risk assessment assuming a normal distribution for all elements contributing to the overall uncertainty. 6. Incorrect degradation rate and behaviour over time assumed in the yield estimation. 7. Incorrect availability assumption to calculate the initial yield for project investment financial model (vs O&M plant availability guarantee).
	Transportation	8. Absence of standardised transportation and handling protocol.
	Installation/ construction	9. Inadequate quality procedures in component un-packaging and handling during construction by workers. 10. Missing intermediate construction monitoring.
	Installation/ provisional and final acceptance	11. Inadequate protocol or equipment for plant acceptance visual inspection. 12. Missing short-term performance (e.g. PR) check at provisional acceptance test, including proper correction for temperature and other losses. 13. Missing final performance check and guaranteed performance. 14. Incorrect or missing specification for collecting data for PR or availability evaluations: incorrect measurement sensor specification, incorrect irradiance threshold to define time window of PV operation for PR/availability calculation.
Risks during operation	Operation	15. Selected monitoring system is not capable of advanced fault detection and identification. 16. Inadequate or absence of devices for visual inspection to catch invisible defects/faults. 17. Missing guaranteed key performance indicators (PR, availability or energy yield). 18. Incorrect or missing specification for collecting data for PR or availability evaluations: incorrect measurement sensor specification, incorrect irradiance threshold to define time window of PV operation for PR/availability calculation.
	Maintenance	19. Missing or inadequate maintenance of the monitoring system. 20. Module cleaning missing or frequency too low.

Source: Solar Bankability (2017)

From the analysis made a set of eight priority mitigation measures have been identified based on their Cost Priority Number (CPN) and potential impact on LCOE. These can be grouped into preventative and corrective measures, with the combined effect estimated to have the potential to reduce annual potential economic losses (measured as CPN) by more than 80%:

Preventative

1 Quality testing of modules and inverters,

2 Design review and construction monitoring to improve design and workmanship,

3 Energy Performance Contractor (EPC) qualification,

Corrective

4 Implementation of advance monitoring systems for early fault detection/diagnosis,

5 Basic monitoring of system alarms and notifications,

6 Advanced inspection to detect defects,

7 Visual inspection to detect visible changes,

8 Spare part management to minimise downtime and repair/substitution.

Improvement options identified in Task 4 of the Preparatory Study can potentially be overlaid onto these measures in order to specify requirements. For example, module quality testing standards such as EN 61215, repair operations for an inverter that are recommended in order to can achieve a notional technical design life.

5. Screening of life cycle environmental impacts

The aim of this section is to systematically assess the environmental impacts that are associated with the three products to be addressed within the scope.

A screening of existing LCA literature has been made in order to identify 'hot-spots' for environmental impacts along the life cycle. These may relate to specific material flows/inputs, components or emissions. A preliminary analysis has then been made of the potential for EU Ecolabel and/or GPP criteria to address these hot spots.

The main requirement of the EU Ecolabel and Green Public Procurement is that criteria should be based on scientific evidence and should focus on the most significant environmental impacts during the whole life cycle of products. The purpose of this section is to respond to this requirement by using the best available scientific evidence to identify the environmental "hot spots" in the life cycle of Photovoltaic Modules, Inverters and Systems. This evidence can also be used to cross check and complement the results that emerged from the MEErP analysis of the base cases.

5.1.1. Selection of LCA studies for further analysis

In the first step, relevant Life Cycle Assessment (LCA) literature regarding the environmental assessment and improvement potential of Photovoltaic Modules, Inverters and Systems, was identified and critically reviewed for the robustness of the results (methodology, data quality, age etc.).

This section presents an overview of existing LCA studies together with an initial screening categorising them according to the following quality criteria:

- Subject of the studies: The analysed products should have representative features of the product group, sub-categories, technologies or specifications.
- Time-related coverage of data: This refers to the year the inventory data of the analysis is based on; studies should ideally be less than 4 years old (publication year 2015 or later).
- Comprehensiveness and robustness: this refers to which environmental impacts are considered in the study? The impact Categories should be comprehensive, ideally following recognised LCA methodologies, and scientifically. Ideally studies are cradle-to-grave.

A literature search has been performed with the aim of identifying relevant literature. An overview of this screening has been made and is available in Annex C. For all papers, the following information is available:

– General information: Year of publication, Authors, Journal/source, Title, Region

– Life cycle stages considered: Manufacture, Use, End-of-life, System boundaries

– Technical aspects: Technology, Functional unit, Lifetime, Capacity, Type of system

– Methodological aspects: Environmental impact categories, Assessment method, Main database used, Software, Data quality and data quality rating

– Results and interpretation: Hot spots, Technology comparison

– Notes

In total 30 recent studies have been identified. The comparative LCA studies seem to be most relevant for further analysis as in comparative assessments the same methodology is followed to analyse different systems.

The six studies identified to be of suitable quality for detailed analysis are:

- Wyss F., Frischknecht R., de Wild-Scholten M., Stolz P. 2015. PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots.
- Frischknecht R., Itten R., Sinha P., de Wild-Scholten M., Zhang J., Fthenakis V., Kim H.C., Raugei M., Stucki M. 2015. Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, International Energy Agency (IEA) PVPS Task 12, Report T12-04:2015.
- UNEP. 2016. Green Energy Choices: The benefits, risks, and trade-offs of low-carbon technologies for electricity production. Report of the International Resource Panel. E.G.Hertwich, J. Aloisi de Larderel, A. Arvesen, P. Bayer, J. Bergesen, E. Bouman, T. Gibon, G. Heath, C. Peña, P. Purohit, A. Ramirez, S. Suh.
- Lecissi E., Raugei M., Fthenakis V. 2016. The Energy and Environmental Performance of Ground-Mounted Photovoltaic Systems—A Timely Update. Energies 9, 622; doi:10.3390/en9080622.
- Chatzisideris M., Espinosa N., Laurent A., Krebs F. 2016. Ecodesign perspective of thin-film photovoltaic technologies: A review of life cycle assessment studies. Solar Energy Materials & Solar Cells.
- Tschümperlin L. Stolz P., Frischknecht R. . 2016 Life cycle assessment of low power solar inverters (2.5 to 20 kW)

5.1.2. Detailed analysis of the selected LCA studies

In this detailed analysis we will look at the base parameters of the selected studies (investigated products and type of system), the goal and scope and functional unit, system boundaries and life time. Next, information on impact categories and impact assessment, assumptions, data and data quality is are identified. In the final part of the analysis, the results of the identified studies are discussed.

5.1.2.1. Base parameters of the selected studies

Some details of the products investigated in the selected studies are outlined in Table 8.

Table 8: Description of the investigated studies

Study	**Products investigated**	**Type of system/capacity**
Wyss et al. 2015	CdTe, CIS, microcrystalline -Si[51], multicrystalline-Si, monocrystalline-Si Modules and cabling Sensitivity assessment with inverter	3 kWp integrated in roof, 3 kWp mounted on roof and 570 kWp open ground
Frischknecht et al. 2015	mono-and multi-crystalline Si, CdTe and high concentration (HC) PV additional inventory data describing different mounting structures, electrical components (cabling, inverter, transformer)	93 kWp slanted-roof installation, single-Si laminates; 280 kWp flat-roof installation, single-Si modules; 156 kWp flat-roof installation, multi-Si modules; 1.3 MWp slanted-roof installation, multi-Si modules; 324 kWp flat-roof installation, single-Si modules; 450 kWp flat-roof installation, single-Si modules; 569 kWp open ground installation, multi-Si modules; 570 kWp open ground installation, multi-Si modules
UNEP. 2016	Poly Si, CdTe, CIGS, inverters, transformers, wiring, mounting and construction	Ground and rooftop mounted systems

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

Lecissi et al. 2016	Mono-c-Si, multi-c-Si, CdTe, CIGS PV modules, including BOS (mechanical and electrical components such as inverters, transformers, and cables).	Fixed-Tilt Ground-Mounted Photovoltaic Systems and comparison to 1-Axis Tracking Installations
Chatzisideris et al. 2016	Review paper of 31 thin-film PV LCA studies covering the technologies: CdTe; CIGS; a-Si; nc-Si; CZTS; Zn_3P_2; PSC; OPV; DSSC; QDPV; GaAs	Review paper of 31 LCA studies with a focus on BIPV applications, thus thin-film PV systems.
Tschümperlin L. et al. 2016	Average European inverter 2.5 kW; Average European inverter 5 kW; average European inverter 10 kW and average European inverter 20 kW.	Inverters of 2.5 kW, 5 kW, 10 kW and 20 kW.

The selected studies are five comparative life cycle assessment studies and one review paper. The comparative studies all look at system level. The BOS is included in all studies, sometimes only partly (e.g. Wyss et al. (2015) include the inverter in a sensitivity assessment). The review paper from Chatzisideris et al. (2016) reviewed 31 thin-film LCA studies. They concluded that only a small part of the investigated studies included the BOS. The technologies covered by the selected papers are Poly Si, Mono Si, micromorphous Si, CdTe, CI(G)S and HCPV. The review paper from Chatzisideris et al. (2016) looked at different thin-film applications. The study from Tschümperlin et al. (2016) looked only at inverters.

5.1.2.2. Goal and scope

The goal and scope of the studies should be compliant to the goal and scope of this report section, being to identify the environmental "hot spots" in the life cycle of Photovoltaic Modules, Inverters and Systems based on the best available scientific evidence. The goal and scope of the selected studies can be divided into two broad categories:

- Studies that focus on an individual photovoltaic technology or system component. The goals of the study typically include hotspot analysis analyses for product improvement options, reporting and or documenting product performance, benchmarking products usually with a functional equivalent.
- Studies assessing photovoltaic systems in a context perspective, typically at meso and large-scale. These studies are primarily associated with goals oriented towards policy analysis or decision- and policy-making at urban, national or regional scales.

Most of the analysed studies fall into the first category with the exception of one study (UNEP 2016). The selected studies are mainly comparative life cycle assessments (Wyss et al. 2016, UNEP. 2016 and Lecissi et al. 2016). The paper from Chatzisideris et al. (2016) is a review paper on different thin film technologies. The scope of the study from Frishknecht et al. 2015 is compiling life cycle inventory data on the manufacturing. See Table 9 below.

Table 9: Goal and scope of the studies considered

Study	**Goal of the study**	**Scope of the study**
Wyss et al. 2015	Pilot the use of the PEF methodology in order to determine how to use it as the basis for product category rules for photovoltaic modules.	To analyse the whole life cycle of five subcategories of PV modules used in photovoltaic systems. The LCA follows the PEF methodology, from cradle to grave (product stage, construction stage, operation stage and end-of-life stage)
Frischknecht et al. 2015	To present the latest consensus LCA results among the authors, PV LCA experts in North America, Europe and Asia. At this time consensus is limited to five technologies for which there are well-established and up-to-date LCI data: mono- and multi-crystalline Si, CdTe, CIGS, and high concentration PV (HCPV) using III/V cells. The	To provide updated life cycle inventory data of five subcategories of PV modules used in photovoltaic systems and of the BOS. To provide inventory data for different sizes of PV power plants in Europe.

	LCA indicators shown herein include Energy Payback Times (EPBT), Greenhouse Gas emissions (GHG), criteria pollutant emissions, and heavy metal emissions. To present LCI data for the above mentioned technologies including detailed inputs and outputs for manufacturing of the cell, wafer, module and BOS.	
UNEP. 2016	To provide a comprehensive comparison of greenhouse gas mitigation potential of various energy generation technologies, including hydro, solar, geothermal and wind and it examines the environmental and human health impacts of these options and their implications for resource use.	High level comparison of different technologies. Details regarding the followed methodology are not provided in the report.
Lecissi et al. 2016	Update of life cycle assessment (LCA) and net energy analysis (NEA) perspectives for the main commercially relevant large-scale PV technologies as of today, namely: single-crystalline Si (sc-Si), multi-crystalline Si (mc-Si), CdTe, and CIGS providing input for long-term energy strategy decisions.	To compare commercially relevant large scale PV technologies from cradle to grave. The comparative life cycle assessment following ISO 14040 and ISO 14044 and the IEA guidelines.
Chatzisideris et al. 2016	To investigate how results of past LCA studies of thin-film PVs can be used to identify bottlenecks and opportunities for technological improvement and mitigation of environmental impacts and to highlight the value the value of using LCA as a strategic decision-support by identifying and critically reviewing ecodesign aspects of LCA studies across thin-film technologies.	Review paper of LCA studies BIPV applications and thus thin-film PV systems with focus on ecodesign aspects of the studies (so not only climate change and energy related indicators) and all life cycle stages (not only production, to avoid burden shifting).
Tschümperlin et al. 2016	The objective of this study is to compile life cycle inventories of different power scales of solar inverters. Compiling this new life cycle inventory is necessary due to significant changes in the technology used in inverters the past few years.	To generate life cycle inventories for inverters and to compare the environmental impacts caused by the solar inverters analysed in this study with the environmental impacts calculated based on the already existing life cycle inventory of a 2.5 kW inverter for the life cycle stages manufacturing (incl. raw material production) and disposal.

5.1.2.3. Functional unit, system boundaries and life time

According to ISO 14040/44, the functional unit refers to a quantified performance of a product system for use for comparisons on the basis for functional equivalence in LCA studies. The system boundary describes which processes are taken into account in the LCA analysis and which processes are not. The lifetime is the reference duration that the products to be analysed will be in service.

The functional unit is 1 kWh of electricity generated in Wyss et al. (2016), Frischknecht et al. (2015) and UNEP (2016). Lecissi et al. (2016) express the results per kWp and per kWh. The paper from Chatzisideris et al. (2016) is a review paper of 31 different studies.

All papers consider the product stage while the majority exclude the end of life stage. Wyss et al. (2016) considers the entire life cycle excluding end-of-life while UNEP (2016) only considers the dismantling part of the end-of-life stage. The review paper from Chatzisideris et al. (2016) identified 6 studies covering the entire life cycle, 10 studies covering production and use stage, 13 studies covering only the production and 2 studies which cover production and end-of-life.

Table 10 provides an overview of the functional unit, system boundaries and life time considered in the selected LCA studies.

Table 10: Functional unit, System boundaries and life time in the studies considered

Study	Functional unit	System boundaries	Life time
Wyss et al. 2015	1 kWh (Kilowatt hour) of DC electricity generated by a PV module	Product stage, construction stage, operation stage and end-of-life stage. Modules and cabling are included, the impact of the inverter is investigated in a sensitivity assessment	Service life of 30 years
Frischknecht et al. 2015	1 kWh of electricity fed into the grid.	Included in the product system are the modules, the mounting system, the cabling, the inverters, and all further components needed to produce electricity and supply the grid.	Modules: 30 years for mature module technologies, may be lower for foil-only encapsulation; Inverters: 15 years for small plants; 30 years with 10% part replacement every 10 yrs. for large size plants; Transformers: 30 yrs.; Structure: 30 yrs. for roof-top and facades, and between 30-60 yrs. for ground mount installations on metal supports; Cabling: 30 yrs. (Fthenakis, 2011)
UNEP. 2016	Results are expressed per unit of power production (1 kWh).	The assessment covers production, construction, maintenance and dismantling	Not mentioned
Lecissi et al. 2016	Results are expressed per kWp and per kWh	Production, system operation and maintenance. End of life (EOL) management and decommissioning of the PV systems were not included including manufacturing, operation and maintenance	30
Chatzisideris et al. 2016	Review paper: depends on the study	Review paper of 31 studies, depends on the study: 6 studies cover the entire life cycle; 10 studies cover production and use stage; 13 studies cover only the production and 2 cover production and end-of-life	Review paper: depends on the paper
Tschümperlin et al. 2016	One solar inverter of a given power output with a life time of 15 years	The product system includes the supply of materials and energy used in the production and mounting, the production processes, packaging and the disposal of packaging material and of the product itself after the use phase.	15

5.1.2.4. Impact categories and impact assessment

Wyss et al. (2015) calculated the 15 mandatory PEF environmental impact categories complemented by three additional categories, being renewable cumulative energy demand, non-renewable cumulative energy demand and nuclear waste.

Frischknecht et al. (2015) report greenhouse gas emissions and two energy related parameters (Primary energy demand and Energy payback time).

The life cycle inventory established in Frischknecht et al. (2015) can however be used to calculate other environmental impact categories as well. UNEP (2016) reports carbon footprint, human health related environmental impacts (ionizing radiation, photochemical oxidant formation, particulate matter, human toxicity, ozone depletion), ecosystem related environmental impacts (freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, terrestrial acidification, terrestrial ecotoxicity) and results for land occupation and resource use. Lecissi et al. (2016) report 5 impact categories, global warming potential, cumulative energy demand, acidification potential, ozone layer depletion and energy pay-back time.

The papers reviewed by Chatzisideris et al. (2016) report many different environmental impacts (see Table 11). Tschümperlin et al. report the environmental impacts of inverters for six impact categories previously identified as most relevant for PV electricity generation (Stolz et al. 201652): global warming, human toxicity (cancer effects), human toxicity (non-cancer effects), particulate matter, freshwater ecotoxicity, mineral, fossil and renewable resource depletion.

The majority of studies use the ecoinvent database and SimaPro software. The impact categories, method used, database used and software used for life cycle impact assessment are detailed in Table 11.

Table 11: Impact categories, impact assessment method, database and software in the studies considered

Study	**Impact categories**	**Method**	**Database**	**Software**
Wyss et al. 2015	15 impact categories: Gobal Warming; Ozone depletion; Human toxicity, cancer; Human toxicity, non-cancer; Particulate matter; ionizing radiation; Photochemical Ozone formation; Acidification; Eutrophication, terrestrial; Eutrophication, aquatic; Ecotoxicity, freshwater; Land transformation; Resource depletion, water; Resource depletion, mineral, fossil, renew;. 3 additional indicators: Renewable cumulative energy demand, Non-renewable cumulative energy demand and Nuclear waste	Impact assessment methods according to PEF Guide	Ecoinvent 2.2 – with some adaptations	SimaPro 7.3.3
Frischknecht et al. 2015	Primary energy demand, Energy payback time, Greenhouse Gas emissions	For GHG: IPCC method (Fthenakis, 2011)	Ecoinvent v2.2	Not mentioned in the report
UNEP. 2016	Carbon footprint, human health (ionizing radiation, photochemical oxidant formation, particulate matter, human toxicity, ozone depletion), ecosystems	Not mentioned, high level report	Not mentioned in the report	Not mentioned in the report

[52] Stolz P., Frischknecht R., Wyss F. and de Wild Scholten M. (2016) PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots, version 2.0. treeze Ltd. commissioned by the Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation", Uster, Switzerland.

	(freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, terrestrial acidification, terrestrial ecotoxicity), land occupation, resource use			
Lecissi et al. 2016	Cumulative Energy Demand, Global warming, Acidification, Ozone depletion One additional indicator:Energy payback time	CML	ecoinvent 3.1	SimaPro 8
Chatzisideris et al. 2016	Primary energy demand, Global warming, Acidification Ozone depletion, Photochemical Ozone formation, Eutrophication, Ecotoxicity freshwater, Terrestrial ecotoxicity, Human toxicity, cancer; Human toxicity, non-cancer, Respiratory in-organics, ionising radiation, Land use, Agricultural land occupation, urban land occupation, natural land transformation, resource depletion water, Abiotic depletion non fossil, Abiotic depletion fossil, Solid waste, Cumulative energy demand	Eco-indicator 95/99, CML and ReCiPe were the most commonly used LCIA methodologies among the reviewed LCA studies.	Not relevant – review paper	Not relevant – review paper
Tschümperlin et al. 2016	Global warming, human toxicity (cancer effects), human toxicity (non-cancer effects), particulate matter, freshwater ecotoxicity, mineral, fossil and renewable resource depletion.	ILCD midpoint 2011 (only selected impact categories – see previous column)	Ecoinvent 2.2	SimaPro v8.0.6

5.1.2.5. Assumptions

Table 12 lists some of the main assumptions made in the selected LCA papers and provides assumptions made on average yield, degradation rate, irradiation level, performance ration and average efficiency.

Wyss et al. (2015) report an average yield of 975 kWh/kWp and a degradation rate of 0.7% per year. Average yield and degradation rate are not mentioned in the other publications. The irradiation rate used by Wyss et al. (2015) is 1090 kWh/m^2/yr. This is the annual average yield of optimally oriented modules in Europe, weighted according to the cumulative installed photovoltaic power when excluding degradation effects (Wyss et al., 2015).

Frischknecht et al. (2015) use an irradiation of 1700 kWh/m^2/yr, representative for Southern European (Mediterranean) conditions. Lecissi et al. (2016) calculated results for three different levels which are representative of irradiation on a south-facing, latitude-tilted plane in Central-Northern Europe (1000 kWh/(m^2_yr)), Central-Southern Europe (1700 kWh/(m^2_yr)), and the Southwestern United States (2300 kWh/(m^2_yr)). Wyss et al. (2015), Frischknecht et al. (2015) and Lecissi et al. (2016) report efficiencies which are in these comparative LCA studies always lower for thin film compared to Si technologies.

The study from Tschümperlin et al (2016) investigates inverters. The assumptions listed in Table 12 are not relevant for inverters.

Table 12: Assumptions taken in the different studies considered

Study	**Average yield**	**Degradation rate**	**Irradiation**	**Performance ratio**	**Average efficiency**

Wyss et al. 2015	975 kWh/kWp	0.7% per year	1090 kWh/m²/yr	/	CdTe: 14% CIS: 10.8% Micro-Si: 10% Multi-Si: 14.7% Mono-Si: 15.1%
Frischknecht et al. 2015	/	/	1700 kWh/m²/yr	0.75	Multi-Si: 14.2% Mono-Si: 14.5% CdTe: 11.3%
UNEP. 2016	/	/	/	/	/
Lecissi et al. 2016	/	/	1000 kWh/m²/yr; 1700 kWh/m²/yr 2300 kWh/m²/yr	0.8	Sc-Si PV: 17% mc-Si: 16% CdTe PV: 15.6% CIGS PV: 14%
Chatzisideris et al. 2016	/	/	/	/	/
Tschümperlin et al. 2016	Not relevant, inverters	Not relevant, inverters	Not relevant, inverters	Not relevant, inverters	Not relevant, inverters

5.1.2.6. Data quality requirements and data sources

Data quality level and sources of primary and secondary data should be documented. The time-related, geographical and technological representativeness of the selected LCA studies are summarised in Table 13. This table also contains information on data sources of primary and secondary data.

The foreground data provided in Frischknecht et al. (2015) are less than 10 years old. The data used by Wyss et al. (2016) are less than 5 years old, except for input data on CIGS, which are from 2010. Lecissi et al. (2016) collected foreground data for CdTe. The other data are taken from the IEA task 12 report (Frischknecht et al. 2015). The data presented in Frischknecht et al. (2015) are company specific data (e.g. data from FirstSolar for CdTe; data from Amonix for HCPV) or average data based on input from several companies (for mono and multi Si data from 11 companies collected during the Crystalclear project). Regarding the geographical representativeness, regionalized data have been used in Wyss et al. (2015), Frischknecht et al. (2015) and Lecissi et al. (2016). The foreground data collected by Tschümperlin et al. (2016) are most likely less than 5 years old.

Table 13: Time-related, geographical and technological representativeness of data and data sources of primary and secondary data in the studies considered

Study	Time-related representativeness	Geographical representativeness	Technological representativeness	Data sources of primary data	Data sources of secondary data
Wyss et al. 2015	Inventory data describing the supply chain of the monocrystalline-Si, and multicrystalline-Si PV modules were provided by leading manufacturers representative of 2012. Inventory data describing the supply chain of thin film PV modules stem from FirstSolar (CdTe), Oerlikon Solar (now TEL, micromorphous silicon) representative of 2012. Avancis and Solar Frontier (CIGS). The CIGS inventory data are from 2010 and published by SmartGreenScans in 2014 (de Wild-Scholten 2014). All data come with uncertainty information.	Europe, regionalised electricity mixes have been used within the supply chain	Data collected from leading manufacturers during the study, CIGS inventory data were from 2010. Representative for current technology (at the time of the study)	Manufacturers. For CIGS: publication from SmartGreenScans	ecoinvent
Frischknecht et al. 2015	Primary data: The LCI datasets presented in this report correspond to the status in 2011 for crystalline Si, 2010-2011 for CdTe, 2010 for CIGS..	Crystalline Si-PV modules: data from 11 companies from the CrystalClear project; CdTe PV: First Solar's CdTe PV manufacturing plant in Perrysburg (USA);	Data collected from leading manufacturers.	Crystalline Si-PV modules: 11 commercial European and U.S. photovoltaic module manufacturing; CdTe: First Solar	ecoinvent
UNEP. 2016	No information on time related representativeness of input data	No information on geographical representativeness in the publication	Regionalised electricity mixes are used	Not mentioned	Not mentioned
Lecissi et al. 2016	CdTe modules: foreground data on the production provided directly by First Solar, BOS CdTe ground mounted system: foreground data provided by First Solar c-Si PV and CIGS technologies:IEA-photovoltaic power systems (PVPS) Task 12 Report from 2015 The efficiencies of all the PV technologies as well as the electric mixtures used in the Si supply chain and for PV module production have been updated to reflect the current (2015) situation	Real geographic location of each component has been considered.	Data collected from leading manufacturers	CdTe: First Solar, BOS: First Solar c-Si PV and CIGS technologies: IEA-photovoltaic power systems (PVPS) Task 12 Report from 2015	Ecoinvent 3.1

Chatzisideris et al. 2016	Not relevant, review paper	Not relevant, review paper	Not relevant, review paper	Not relevant, review paper	Not relevant, review paper
Tschümperlin et al. 2016	Primary data are collected from three European inverter manufacturers. The year for which the data are representative is not mentioned, but the study is published in 2016 and the aim of the study was to compile a life cycle inventory for inverters.	Europe, data provided by three European manufacturers	Data collected for current technology (2016) from three European manufacturers. Inverter mass has been extrapolated to the power outputs of 2.5 kW, 5 kW, 10 kW and 20 kW using a non-linear formula proposed by Caduff et al. (2011)[53]: $M = 6.03 * P^{0.68}$ (where M = Mass and P = Power output)	Primary data collected from three European manufacturers. The data gathered differ considerably in the level of detail. Only one manufacturer provided data for each component mounted on their print board assembly. The data for the print board components have been taken directly from one single manufacturer. This is mentioned in the study as a clear limitation of the study.	Ecoinvent 2.2

[53] Caduff M., Huijbregts M. A. J., Althaus H.-J. and Hendriks A. J. (2011) Power-Law Relationships for Estimating Mass, Fuel Con-sumption and Costs of Energy Conversion Equipments. In: Environmental Science & Technology, 45(2), pp. 751-754.

5.1.3. Results of the selected LCA studies

PEF screening report (Wyss et al., 2015) and PEFCR (Technical Secretariat, 2018).

Depending on the PV technology the environmental impacts vary depending on the application. The overall normalised and weighted results show that CdTe modules have the lowest impact (2.02 10-6 pt/kWh), followed by CIS (3.29 10-6 pt/kWh), micro Si (4.73 10-6 pt/kWh), multi Si (5.68 10-6 pt/kWh), and finally mono Si (9.28 10-6 pt/kWh)[54]. Within each technology, the roof-mounted systems cause the lowest impacts per kWh of electricity produced, followed by the ground-mounted systems. The latter cause the highest environmental impact of the systems analyzed. These differences are due to the land use, the mounting system and the cabling.

Based on the outcomes and findings of all environmental footprint screening studies, the method for weighting has been updated after the publication of the screening study. During the PEF PV screening study an anomaly on the characterisation factor for indium has been identified. This anomaly was responsible for the high contribution of CdTe modules to the impact category mineral, fossil, renewable resource depletion. Using the updated method in the PEFCR 2018 has lead to different results compared to the results published in the screening report.

The environmental performance of a kWh of DC electricity produced with the average PV module mix in Europe and most impact categories are mainly influenced by the production of the modules, with the exception of human toxicity cancer effects, freshwater ecotoxicity and eutrophication as well as cumulative energy demand (CED) renewable (see Figure 13). However, it is to be noted that these impact categories are not reported in the updated PEFCR 2018.

In the case of CIS and CdTe PV modules, the production and the construction stages are the most significant life cycle stages on average for all impact categories. The impact category that dominates the environmental impact is climate change followed by the resource use (minerals and metals), resource use (fossils) and particulate matter.

For the silicon based PV technologies, the production stage is the most relevant life cycle stage on average for all impact categories. The environmental impacts of Chinese electricity production contribute strongly to the weighted result in addition to the supply of mineral resources.

The use phase across all technologies was not found to be significant for the majority of impact categories except for the CED renewable (harvested solar energy). The end-of-life stage contributes to overall impacts between 0 % to 5 % while the potential benefits from recycling can result in a credit of -17 % for human toxicity, cancer effects, shortly followed by freshwater eutrophication, ionising radiation and water resource depletion.

The production of 1 kWh DC electricity with an average residential scale PV system mounted on a rooftop causes on average 65 grams of CO_2-eq and requires 0.795 MJ of non-renewable primary energy. The particulate matter emissions amount to 86.9 mg per kWh and 1 kWh of DC electricity produced with PV modules requires 32.1 mg Sb-eq of abiotic resources and consumes 72.5 g water-eq of water.

[54] Points are dimensionless unit derived from the normalisation of the impact category results based on normalisation factors to which a weighting is both technical and political.

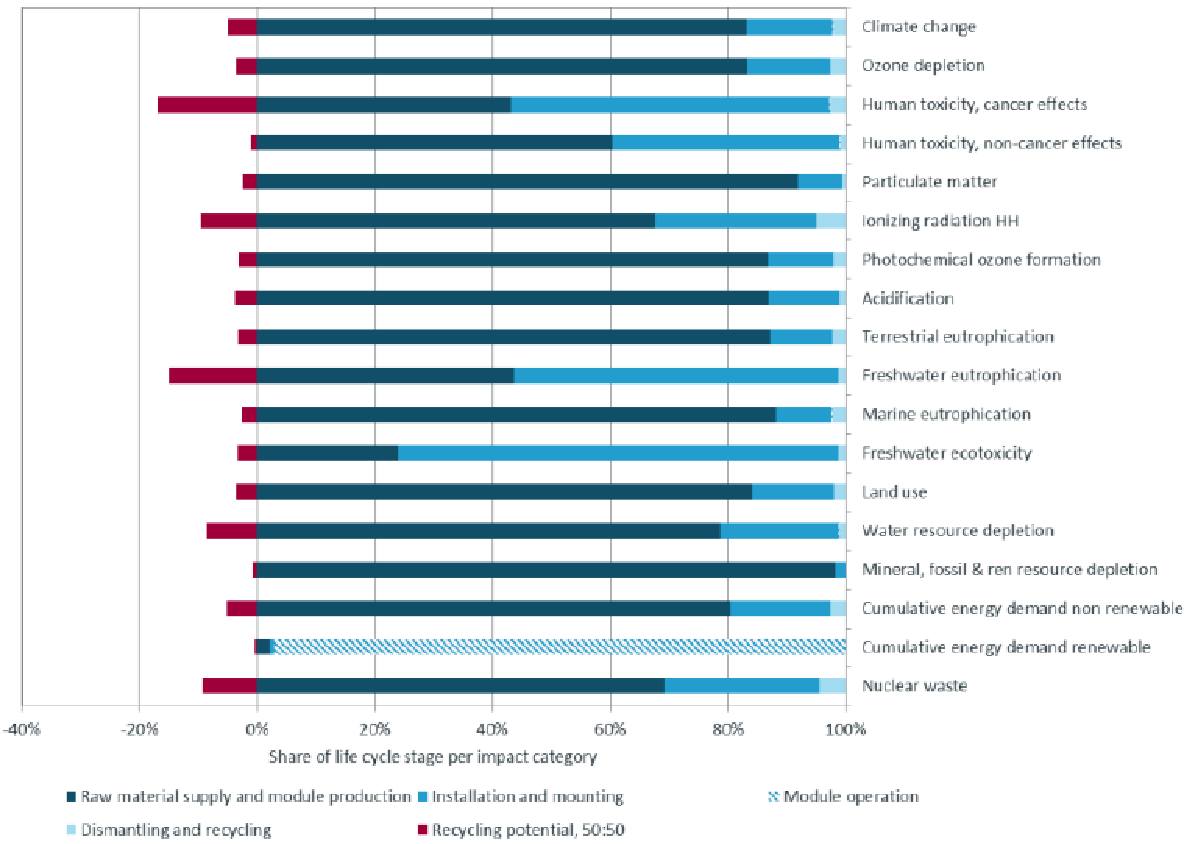

Figure 13 (taken from Wyss et al., 2015): Environmental impact results (characterized, indexed to 100 %) of 1 kWh of DC electricity produced with a residential scale (3 kWp) PV system with average PV modules mounted on a slanted roof. The potential benefits due to recycling are illustrated relative to the overall environmental impacts from production to end-of-life.

<u>IEA, PVPS task 12 (Frischknecht et al., 2015)</u>

A strong focus of this study was the relationship between the primary energy consumed during the production stage of the modules and primary energy generated in the use stage. In order to relate these figures the energy payback time is calculated. Figure 14 gives the energy payback time (EPBT) estimates of three major commercial PV module types, i.e. mono-Si, multi-Si, and cadmium telluride (CdTe). The EPBT for a typical rooftop installation in south Europe, (i.e., irradiation of 1700 kWh/m^2/yr), corresponds to 1.7 years, 1.7 years and 0.8 years for mono-Si, multi-Si, and CdTe PV technologies, respectively. The impact of the BOS is not very important for the three investigated systems. For mono-Si and multi-Si the largest share of the impact is generated during production of the Si feedstock and ingot/crystal and wafer production. For CdTe, the largest impact comes from laminate production.

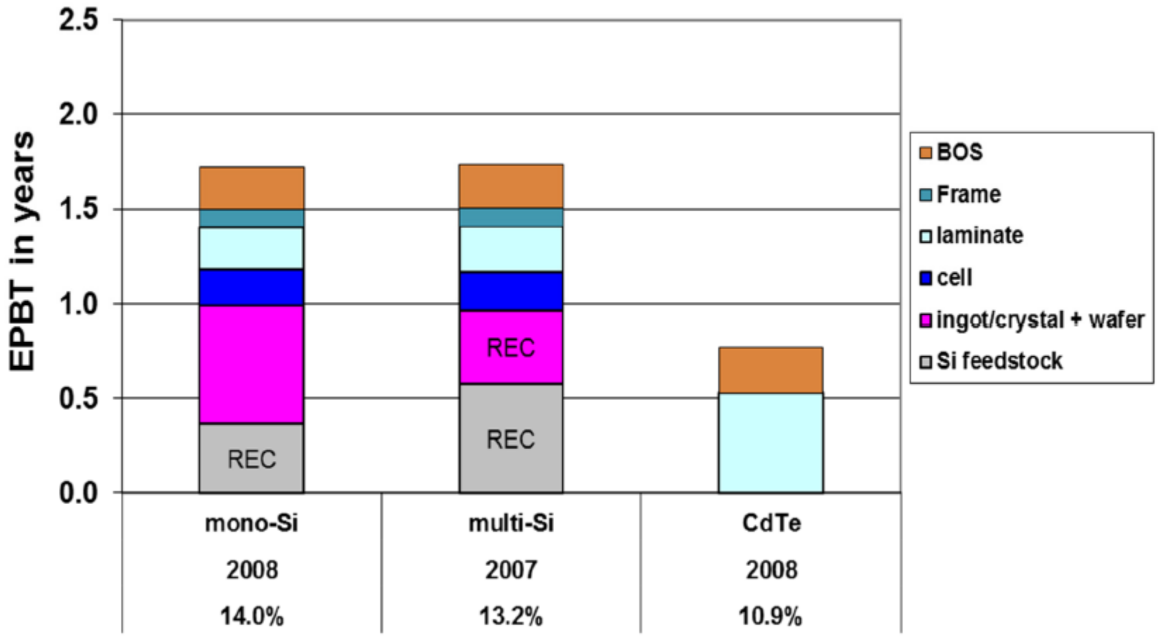

Figure 14: (taken from Frischknecht et al. 2015) Energy payback time (EPBT) of rooftop mounted PV systems for European production and installation under Southern European irradiation of 1700 kWh/m2/yr and performance ratio of 0.75. Data adapted from de Wild Scholten (2009) and Fthenakis et al. (2009). They were harmonized for system boundary and performance ratios, according to IEA Task 12 LCA Methodology Guidelines. REC corresponds to REC product-specific Si production; the corresponding LCI data are not publicly available.

UNEP (2016)

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

When looking at the life cycle of the PV systems, UNEP (2016) identified that energy use during the manufacturing process contributes the most to climate change, particulates and toxicity. The largest contributors to metal use in PV systems are the inverters, transformers, wiring, mounting and construction.

On the comparison of PV technologies, UNEP (2016) writes that generally thin film technologies show lower environmental impacts than crystalline silicon. Crystalline silicon requires a greater quantity of electricity and has higher direct emissions during production of metallurgical grade silicon, polycrystalline silicon wafers and modules.

UNEP also analyses the use of critical raw materials in PV. They mention that PV uses substantial amounts of silver as a conductor for cell electrodes. Thin film technologies rely on semiconductor layers composed of by-product metals, namely cadmium, tellurium, gallium, indium and selenium. As the thin film technologies using these elements capture larger market shares, they may encounter shortages if the recovery of these metals from primary copper and zinc production is not increased. Metal supply shortage is a particular concern for tellurium in CdTe technology. Due to the toxicity of the involved metals, proper recovery and recycling is important.

Figure 1: Life-cycle GHG emissions of different energy technologies, in gCO2e/kWh, reflecting application of the technology in Europe [12].

The numbers for future years reflect a reduction of emissions expected due to technical progress and the reduced emissions in the production of equipment following the implementation of a mitigation scenario.

12 Data for other regions is available in the full report. Abbreviations: CdTe – Cadmiumtelluride, CIGS – Copper Indium Gallium Selenide, Poly-Si – Polycrystalline Silicon, CCS – CO2 Capture and Storage, IGCC – Integrated Gasification Combined Cycle, GB – Gravity-Based Foundation.

Figure 15: (taken from UNEP 2016) Life-cycle GHG emissions of different energy technologies, in g CO_{2e}/kWh, reflecting application of technology in Europe

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

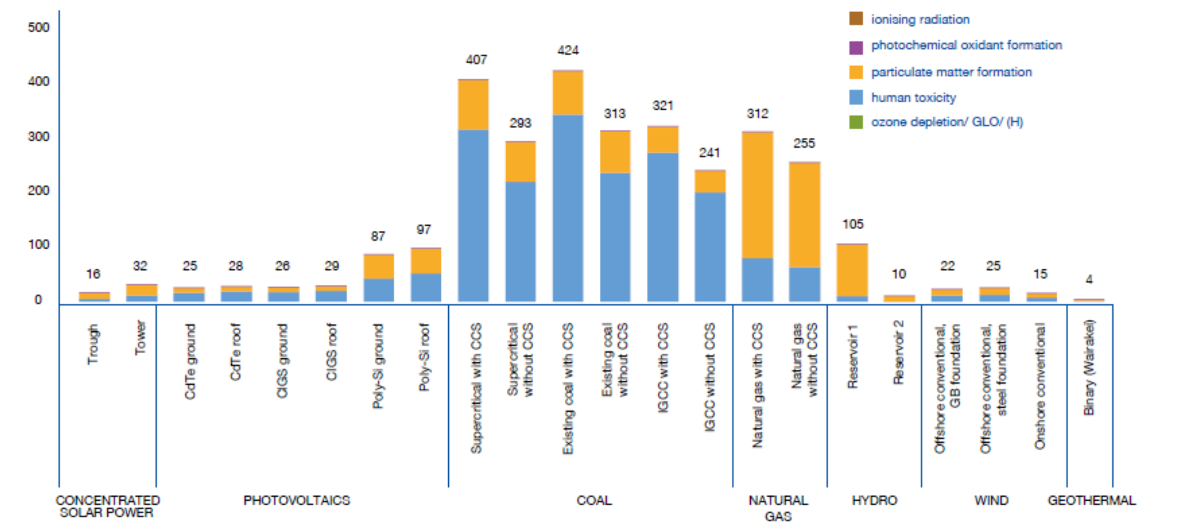

Figure 16: (taken from UNEP 2016) Human health impact in disability adjusted life years (DALY) per 1 TWh of electricity generated, for Europe 2010.

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

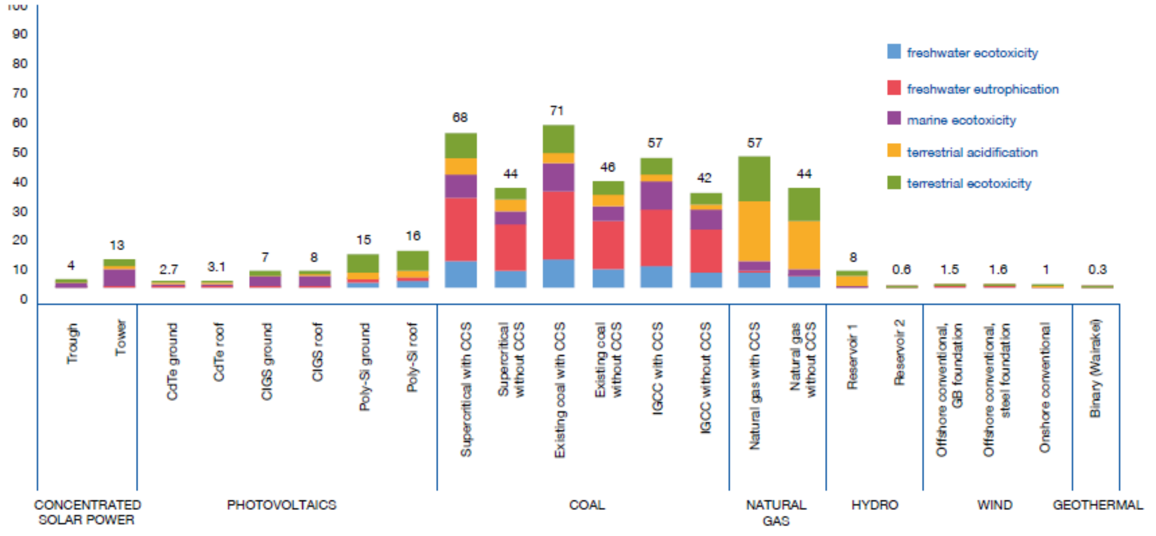

Figure 17: (taken from UNEP 2016): Ecosystem impacts in species-year affected per 1000 TWh of electricity following different damage pathways, reflecting Europe 2010.

Figure 5: Bulk material and non-renewable energy requirements per unit power produced.[28]

Fossil technologies have high cumulative non-renewable energy demand (CED) and low bulk material requirements.

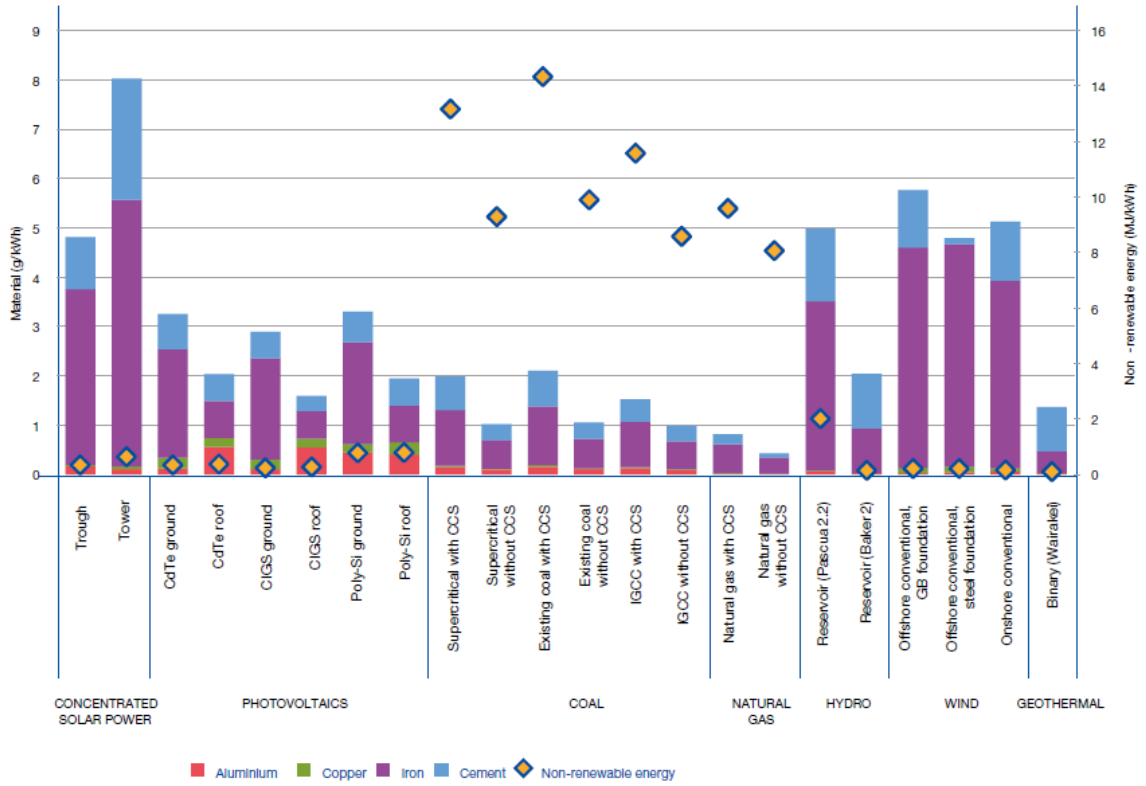

Figure 18: (taken from UNEP 2016) Bulk material and non-renewable energy requirements per unit power produced.

Lecissi et al., 2016

Lecissi et al. 2016 calculated the energy pay-back time (EPBT) for 4 fixed-tilt ground mounted installations. The EPBT range from 0.5 years for CdTe PV at high-irradiation (2300 kWh/(m2/yr)) to 2.8 years for sc-Si (mono-crystalline) PV at low-irradiation (1000 kWh/(m2/yr)) (see Table 14). The Global warming potential (GWP) per kWhel varies between ~10 g for CdTe PV at high irradiation, and up to ~80 g for Chinese sc-Si PV at low irradiation. In general, the results point to CdTe PV as the best performing technology from an environmental life-cycle perspective, also showing a remarkable improvement for current production modules in comparison with previous generations.

The results clearly show that the most impacting step for crystalline Si technologies is from solar grade Si supply to finished PV cells, which includes ingot/crystal growth and wafer and cell production. The BOS contribution is generally fairly low, with the partial exception of the acidification potential results, which are negatively affected by the comparatively large amounts of copper and aluminium required. For CdTe PV and CIGS PV, the contribution of the BOS becomes relatively more important, due to the lower impact of the PV module production compared to crystalline Si.

Finally, Lecissi et al. 2016 determined that one-axis tracking installations can improve the environmental profile of PV systems by approximately 10% for most impact metrics.

Table 14: Energy pay-back time calculated by Lecissi et al. 2016

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

Irradiation and Grid Efficiency (η)	sc-Si PV	mc-Si PV	CdTe PV	CIGS PV
1000 kWh/(m^2·yr); η = 0.3	2.8	2.1	1.1	1.9
1700 kWh/(m^2·yr); η = 0.3	1.6	1.2	0.6	1.1
2300 kWh/(m^2·yr); η = 0.3	1.2	0.9	0.5	0.8

Chatzisideris et al., 2016

Chatzisideris et al. (2016) observed that an LCA study might produce considerably different results for some impact categories if it disregards the disposal stage. The disposal stage can entail benefits due to the recyclability of certain materials.

Equally important to considering the entire PV life cycle, LCA studies must include all environmental impact categories to identify the most problematic ones and avoid burden-shifting from one impact category to another one. Chatzisideris et al. (2016) illustrate this statement with the results of a study from Serrano-Luján. In this study the impact of electricity generated by a CdTe PV system was lower than the impact of electricity from Spain's average electricity mix in 9 impact categories. The results were higher for metal depletion category than the results of Spain's average electricity mix. The reason stems from the use of copper, lead and steel for the CdTe modules and BOS.

Based on normalised results presented in some of the reviewed papers, Chatzisideris et al. (2016) identified toxicity impacts and resource depletion as important impact categories for thin-film PV.

Conclusions on hot spots at module level could only be made by Chatzisideris et al. (2016) for primary energy demand. This is because most of the reviewed papers only made a hot spot analysis for this indicator. Primary energy demand consumed by the production of thin-film modules was mainly the result of electricity demanding processes rather than materials with a high-embedded energy. Across technologies, these are mainly metal deposition processes with vacuum conditions and high temperatures such as ITO sputtering and layer deposition. Only a few studies were found to identify materials with embedded energy as hotspots with the highest contribution to energy demand. These include Al as encapsulation or framing material. In metal-free or ITO-free technologies, main contributors to energy demand are plastics: PET as substrate and encapsulation barriers.

Across thin-film technologies, the contribution of BOS to environmental impacts can be significant, ranging from 3% to 95% depending on the impact category. For CdTe systems cradle to grave, the reported contribution ranges from 40 to 51% for the impact categories climate change, ozone depletion, photochemical ozone formation and acidification. These findings demonstrate the significant influence of BOS components on the environmental performance across impact categories.

Tschumperlin et 2016

Tschümperlin et al. (2016) compared the results obtained with the newly compiled inventories for low power inverters (2.5 kW, 5 kW, 10 kW and 20 kW) to existing inventory of a 2.5 kW inverter dating back to products over 10 years old.

They also analysed the main contributors to each of the seven impact categories modelled using the new inverters inventories. The hot spot is clearly the print board assembly, which is responsible for 59 % of the total result for the impact category climate change; 50% of the human toxicity cancer effects, 55% of the human toxicity non-cancer effects, 52 % of the total PM emissions, 67 % of the total freshwater ecotoxicity contribution and 75 % of the overall impact on resource depletion.

On the other hand, the energy used during production is at most responsible for 1.5% of any of the impact categories. Also, environmental impacts due to packaging, infrastructure, metal processing, transportation of raw materials and end of life treatment are small in all the considered impact categories.

When comparing the old 2.5 kW inverter with the new 2.5 kW inverter, the results are higher for the new inverter across all impact categories except for two impact categories: human toxicity cancer effects category, where the impacts are equal, and mineral, fossil and renewable resources, in which the old inverter has a higher contribution.

6. Other environmental or non-environmental impacts of relevance for EU Ecolabel certification and GPP

The aim of this section is to identify environmental impacts which are not explicitly identified through standard LCA tools and PEF, or non-environmental impacts of relevance (e.g. health or social related issues). These impacts are of particular relevance as the basis for the development of potential EU Ecolabel and GPP criteria.

The identification of environmental impacts which may not detected through standard LCA methods including the Commission's PEF method, or non-environmental impacts of relevance (e.g. health or social related issues), is also made. The former is particularly necessary in order to determine whether workable criteria can be developed that fulfil the Ecolabel Regulation's requirement for a criteria addressing hazardous substances in final products sold to consumers.

6.1.1. Hazardous substances in solar photovoltaic products

This section focuses on substances that may be present in the final product and does not consider substances used in manufacturing as e.g. catalysts, cleaning agents.

The Ecolabel Regulation (EC) 66/2010 contains in Article 6(6) and 6(7) specific requirements that ecolabelled products shall not contain hazardous substances. The implications of these requirements, which are based on definitions laid down in the REACH regulation (EC) No 1907/2006 and in the CLP Regulation (EC) 1272/2008, are briefly explored in the subsequent sections.

6.1.2. REACH Candidate List substances

Article 6(6) of the Ecolabel Regulation refers to substances which meet the criteria described in Article 57 of the REACH Regulation (EC) No 1907/2006. Article 57 provides the criteria for Substances of Very High Concern that may then be included in the Candidate List. The criteria for being an SVHC are as follows:

- Classified with Hazard Classes 1A and 1B for carcinogenicity, germ cell mutagenicity and reproductive toxicity according to the CLP Regulation;

- Persistent, bioaccumulative and toxic as defined by the criteria in Annex XIII;
- Substances identified on a case by case basis that may raise equivalent levels of concern.

Suppliers of solar photovoltaic modules and inverters are required to comply with the REACH regulation (EC) No 1907/2006. The inclusion of a substance in the Candidate List triggers additional duties for EU manufacturers and importers:

  - Any producer and/or importer of an article or component containing a 'Candidate List' SVHC in a concentration above 0.1 % (w/w) or in quantities in the produced or imported articles above 1 tonne per year has the duty to notify the European Chemical Agency (ECHA).
  - Suppliers must provide the recipient of the article (downstream users) with sufficient information to allow safe use of the article. This information also needs to be provided to consumers within 45 days of a request.

The Candidate List is dynamic, with proposals for SVHC's submitted by Member States being entered onto the list prior to evaluation by ECHA. As of November 2018 the list contains a total of 191 substances[55].

The IEC 62474 substance declaration list[56] is understood to be used by the solar photovoltaic industry as a tool to pre-screen the Candidate List for relevance. The IEC list is referred to in the criteria of the NSF/ANSI 457 Sustainability Leadership Standard for Photovoltaic Modules. The standard has criteria requiring use of IEC 62474 and the disclosure of substances on the Candidate List if they are present in products.

A consortium comprising CEA Tech and Fraunhofer ISE made a preliminary screening of hazardous substances in solar PV products for the EU Ecolabelling Board in 2015. In regard to Candidate List substances they concluded based on screening of the list at the time that only one family of substances and another specific substance were used within the PV industry:

  - Phthalates: These type of substances are mainly used as plasticisers in module connector cables, in particular where the sheathing is made of PVC. Phthalates of relevance are DMEP, DIPP, DPP, DnPP and DnHP.
  - Cadmium sulphide: This substance forms part of the semi-conductor layer in both CIGS and CdTe technologies. The concentration is understood in both cases to be below 0.1% w/w.

Subsequent to this screening the substances lead, lead monoxide and diarsenic trioxide have been added to the list and are of relevance to the product group. The inclusion of lead is of high relevance to both modules and inverters being used in solder and metallisation pastes at concentrations that may exceed 0.1%.

Long chain perfluorinated compounds (PFCs) such as PFOA, may be present as impurities (100-200ppm) in the fluoropolymer PVDF, which is used in ~50% of module backsheets produced globally. According to ECHA's restriction report, long chain PFCs are no longer used in the EU for PVDF manufacturing but they are used in China, where most of the PVDF for backsheets is produced.

6.1.3. Substances classified with CLP hazards

In addition to SVHCs, Article 6(6) of the Ecolabel Regulation refers to substances that *'meet the criteria for classification as toxic, hazardous to the environment, carcinogenic, mutagenic or toxic for reproduction (CMR)'* according to the CLP Regulation (EC) No 1272/2008. For the purposes of ecolabel criteria development the screening threshold for substances classified as such is 0.1% for articles. The hazards to screen are presented in Table 15.

Recognising that progress by manufacturers to substitute or eliminate the use of hazardous substances may vary between products groups, Article 6(7) recognises that in certain circumstances there may be a technical or environmental justification for still using a substance restricted by Article 6(6). In practice therefore, criteria should reflect those products that can demonstrate the state of the art in minimising the presence of hazardous substances.

The hazard screening approach adopted during product criteria development generally focusses on substances that fulfil a necessary function. Following on from initial screening by the CEA Tech/Fraunhofer ISE consortium, the relevance of the

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

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

substances that provide the function of plasticisers, flame retardants and dirt repellents are briefly reviewed in this in subsequent sub-sections.

Table 15: Restricted hazard classifications and their hazard categorisation

Acute toxicity	
Category 1 and 2	**Category 3**
H300 Fatal if swallowed (R28)	H301 Toxic if swallowed (R25)
H310 Fatal in contact with skin (R27)	H311 Toxic in contact with skin (R24)
H330 Fatal if inhaled (R23/26)	H331 Toxic if inhaled (R23)
H304 May be fatal if swallowed and enters airways (R65)	EUH070 Toxic by eye contact (R39/41)
Specific target organ toxicity	
Category 1	**Category 2**
H370 Causes damage to organs (R39/23, R39/24, R39/25, R39/26, R39/27, R39/28)	H371 May cause damage to organs (R68/20, R68/21, R68/22)
H372 Causes damage to organs (R48/25, R48/24, R48/23)	H373 May cause damage to organs (R48/20, R48/21, R48/22)
Respiratory and skin sensitisation	
Category 1A	**Category 1B**
H317: May cause allergic skin reaction (R43)	H317: May cause allergic skin reaction (R43)
H334: May cause allergy or asthma symptoms or breathing difficulties if inhaled (R42)	H334: May cause allergy or asthma symptoms or breathing difficulties if inhaled (R42)
Carcinogenic, mutagenic or toxic for reproduction	
Category 1A and 1B	**Category 2**
H340 May cause genetic defects (R46)	H341 Suspected of causing genetic defects (R68)
H350 May cause cancer (R45)	H351 Suspected of causing cancer (R49)
H350i May cause cancer by inhalation (R49)	
H360F May damage fertility (R60)	H361f Suspected of damaging fertility (R62)
H360D May damage the unborn child (R61)	H361d Suspected of damaging the unborn child (R63)
H360FD May damage fertility. May damage the unborn child (R60, R60/61)	H361fd Suspected of damaging fertility. Suspected of damaging the unborn child (R62/63)
H360Fd May damage fertility. Suspected of damaging the unborn child (R60/63)	H362 May cause harm to breast fed children (R64)
H360Df May damage the unborn child. Suspected of damaging fertility (R61/62)	
Hazardous to the aquatic environment	
Category 1 and 2	**Category 3 and 4**
H400 Very toxic to aquatic life (R50)	H412 Harmful to aquatic life with long-lasting effects (R52/53)
H410 Very toxic to aquatic life with long-lasting effects (R50/53)	H413 May cause long-lasting effects to aquatic life (R53)
H411 Toxic to aquatic life with long-lasting effects (R51/53)	
Hazardous to the ozone layer	
EUH059 Hazardous to the ozone layer (R59)	

Plasticisers

Plasticisers are used primarily in cable sheathing but may also be present in other soft plastics used in the encapsulation of a module. As was already identified in section x.y, a number of low molecular weight phthalate plasticisers have been identified as Substances of Very High Concern because of their classification as being toxic for reproduction and, in some cases, as endocrine disruptors.

Phthalate-free plasticisers and cable sheathing materials have been developed. Material substitutes include thermoplastic elastomers (TPE) and Ethyl Vinyl Acetate (EVA). Safer plasticiser substitutes include TOM and DOTP. Plasticisers derogated in other EU Ecolabel product groups, therefore representing alternatives that at the time of criteria voting were deemed to be acceptable, are listed in Table 16.

Table 16. Plasticiser alternatives that have been derogated for us in other EU Ecolabel product groups

Plasticiser	**CAS No**	**Hazard group**
Derogated for use in external power cords and power packs, external casings and internal cables		
Trioctyl trimetallate (TOM/TOTM)	3319-31-1	Not classified
Dioctyl terephthalate (DOTP)	6422-86-2	Not classified
Hexamoll DINCH	166412-78-8	Not classified
DIDP	68515-49-1	Not classified
DINP	28553-12-0	Not classified.

Flame retardants

Flame retardants are primarily understood to be used in polymer back sheet materials of modules in order to provide fire protection in line with standards such as IEC 61730 and UL 723/790. This is particularly the case for Building Integrated PV products, which must meet more exacting fire protection requirements. More information is needed to verify whether they are used in the junction boxes of modules and in any of the electronic components of inverters, with possible locations including power supply units and printed circuit boards.

However, at a module level, to ensure compliance with IEC 61730-2, a burning brand and flame spreading test are executed. It is understood that all commercially available backsheets when they form part of the modules are able to pass these tests without the use of additional flame retardants. An additional safety concern arises because the fluoro-polymer backsheets can emit corrosive and harmful fluorinated gases.

In relation to back sheet materials themselves if they are required to meet a fire safety test, the use of flame retardants or not is understood to be dependent on the chosen polymer. Their use is not necessary in the case that the back sheet material has a high melting point, such as in the case of fluorpolymers (e.g. PVF, PVDF), or may be necessary in lesser quantities where the thickness of the material creates a barrier (e.g. PET). For other types of polymer they will need to be considered.

Flame retardants derogated in other EU Ecolabel product groups and therefore representing alternatives that at the time of criteria voting were deemed to be acceptable, are listed in Table 17 and Table 18. These flame retardants are potentially relevant for internal electrical components of an inverter and for a module junction box. The type of flame retardants currently used in back sheet materials require further identification with stakeholder input. It is understood that the use of inorganic flame retardants may have implications for the properties a polymer back sheet.

In terms of cables, PINFA identify the most significant alternatives to PVC material or brominate chemistries as metal hydroxides, including aluminium hydroxide (ATH), aluminium oxide hydroxide (AOH) and magnesium hydrovide (MDH). Intumescent systems based on phosphate chemistry are also identified as having been adopted by industry.

The substitutes available will depend on the chosen material for the cable sheath. Metal phosphinates are detailed as solutions for Thermoplastic Elastomers (TPE's), co-polyester elastomers and thermoplastic urethanes. The addition of nitrogen synergists such as melamine cyanate and melamine polyphosponate can be used to improve performance to fire protection standard IL94 V0.

Table 17. Flame retardants alternatives for circuitry that have been derogated for us in other EU Ecolabel product groups

Flame retardant	**CAS No**	**Hazard group**
Derogated for use in Printed wiring boards, power supply units, internal connectors and sockets.		
Dihydrooxaphosphaphenanthrene (DOPO) CAS No	35948-25-5	Group 3: H411, H412
Fyrol PMP (Aryl Alkylphosphinate)	63747-58-0	Group 3: H413
Magnesium hydroxide (MDH) *with zinc synergist*	1309-42-8	Group 3: H413
Ammonium polyphosphate	68333-79-9	Group 3: H413
Aluminium hydroxide (ATH) *with zinc synergist*	21645-51-2	Group 3: H413
Bisphenol A Bis (diphenyl Phosphate)	5945-33-5	Not classified

The benefits of these alternative Flame Retardant systems are understood to include a substantial reduction in smoke when compared to halogenated materials or retardants. Their disadvantage is understood to be the high concentrations and filler material required.

Table 18. Flame retardants alternatives for cables that have been derogated for us in other EU Ecolabel product groups

Flame retardant	**CAS No**	**Hazard group**
Flame retardants *derogated for use in external power cables and power packs*		
Aluminium hydroxide (ATH) *with zinc synergist*	21645-51-2	Not classified
Magnesium hydroxide (MDH) *with zinc synergist*	1309-42-8	Group 3: H413
Bisphenol A Bis (diphenyl Phosphate)	5945-33-5	Not classified
Ammonium polyphosphonate	68333-79-9	Group 3: H413

Water and dirt repellents

The application of repellent coatings to module glass can reduce the accumulation of dust and dirt on the surface, thereby reducing performance losses[57].

Although such coatings are declared to have a long life-span based on environmental and accelerated life testing parameters – for example, 1,000 bi-monthly cleaning cycles – their possible degradation and migration into the environment may warrant further consideration.

An initial screening suggests that repellent properties are combined with Anti Reflective coatings. Chemistries which have been used as AR coatings include zinc oxide and silicon dioxide. It is understood that titanium dioxide and zinc dioxide are applied as anti-soiling coatings, together with morphological texturing of the glass surface to aid run-off. Fluorinated organic compounds are also understood to be used, but they are generally applied in order to renew or maintain the anti-soiling properties, having therefore a shorter lifetime.

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

The substitution of repellents in other EU Ecolabel product groups has focussed on the long chain length fluorinated repellents PFOS and PFOA, both of which raised concerns due to their persistency in the environment. They are as a result now the subject of restrictions under REACH. It is not clear the extent to which these chemistries are applied to module glass. According to research by the Danish EPA looking at textiles less persistent alternatives such as silicon or paraffin based repellents may still be classified as hazards so alternative chemistries must be reviewed carefully [58]. It is understood that the fluorinated compounds used to renew or maintain anti-soiling properties can be substituted by silicone repellents.

6.1.4. Substances restricted by the RoHS Directive

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

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

In terms of the product scope considered by this study, photovoltaic modules (referred to below as panels) are specifically excluded according to the following definition:

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

Despite this exclusion it is understood that manufacturers in the sector differentiate themselves by claiming the absence of substances restricted under RoHS - such as lead, cadmium and phthalates.

In this section the potential to minimise the use of lead and cadmium is therefore briefly reviewed against the background of current usage:

Lead

Lead is present at <0.003 wt.% in the metallization paste of wafer-based and thin film solar cells and is used to enable a contact formation. It is also present in the tin-lead alloy coating of the copper ribbons used to string together crystalline silicon cells in modules. The thickness of this coating depends on the number of ribbons and their thickness. The weight per module has been estimated to be in the range of 0.05% - 0.25% wt. indicating that it may be present at a concentration greater than the EU Ecolabel screening threshold of >0.1%.

[58] The Danish Environmental Protection Agency, Alternatives to perfluoroalkyl and polyfluoro-alkyl substances (PFAS) in textiles, Survey of chemical substances in consumer products No. 137, 2015.

The CEA Tech and Fraunhofer ISE screening study claimed that there was sufficient evidence at the time that lead-free soldering (using SnAgCu alloys) and silver pastes were feasible alternatives[59]. The presence in the market of RoHS compliant modules with declared lead concentrations <0.1 wt.% and lead-free modules was identified.

The commercialisation of lead-free module specifications by manufacturers Sunpower, Panasonic and Mitsubishi was also cited. It is to be further cross-checked whether a shift to solders with a higher silver content results in any burden shifting between product stage environmental impacts.

Cadmium

The thin film technologies CdTe and CIGS both contain cadmium in their semi-conductor layers. CdTe modules contain cadmium telluride and may contain cadmium sulphide, resulting in a total cadmium content of around 0.05 wt.%, although it is to be noted that end of life recovery processes allow for up to 95% of this material to be recycled in a close loop. CIGS modules may also contain cadmium sulphide but data could not be found on the concentration. It is understood that both products can be manufactured without cadmium sulphide in their buffer layers. Two CIGS manufacturers - Solar Frontier and Steon - claim that they manufacture modules with cadmium concentrations of less than 0.01%.

6.1.5. Hazardous substances in manufacturing processes

In this sub-section two types of hazards that have been a focus of attention at solar photovoltaic module production sites are briefly reviewed – fluorinated gases with a high Global Warming Potential (GWP) and exposure to silicon tetrachloride.

6.1.5.1. High GWP (Global Warming Potential) production emissions

Fluorinated gases such as sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3) with a high Global Warming Potential (GWP) relative to CO_2 are used in production processes for mass produced thin film products such as televisions and displays and have been identified since several years as being used in thin film photovoltaic production processes [60]. Available information suggests that CF_4 was used in edge isolation and C_2F_6, SF_6 and/or NF_3 for reactor cleaning after deposition of silicon nitride or film silicon. It was suggested at the time that their use was likely to increase due to a shift from wet to dry processing.

The NSF/ANSI 457 Sustainability Leadership Standard for Photovoltaic Modules includes a specific *requirement* relating to the 'avoidance or reduction of high global warming potential (GWP) gas emissions resulting from photovoltaic module manufacturing' suggesting that these emissions are still of relevance. High GWP gases of relevance are identified as including nitrous oxide (N_2O) and fluorinated greenhouse gases (F-GHGs) and it is noted that these may be used in manufacturing or reactor cleaning operations. The requirement can be met by ensuring that such gases are not emitted or that *'specifically designed abatement systems are installed, operated, and maintained'*.

However, analysis of the processes contributing to the life cycle environmental impacts for the representative CdTe and CIGS modules modelled in the Ecodesign Preparatory Study suggest that the overall contribution of these gases to the GWP impact category is not significant.

6.1.5.2. Exposure to silicon tetrachloride by-product

Silicon-Tetrachloride[61] is a intermediate product of crystalline silicon production[62] for the production of silane and trichlorosilane. It is highly toxic, to humans, animals and plants, and has to be converted to solid waste before disposal to landfill. Reports from China also suggest that rapid expansion of production has in the past led to the pollution of rivers [63].

[59] P. Schmitt*, P. Kaiser, C. Savio, M. Tranitz, U. Eitner , Intermetallic Phase Growth and Reliability of Sn-Ag-Soldered Solar Cell Joints, Energy Procedia 27 (2012) 664 – 669

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

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

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

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

However, it is understood that there is now an economic impetus to recover this by-product. This is because it can be used as a raw material for further polysilicon production and also to manufacturer fibre optics [64]. Further information is required to confirm the abatement strategies adopted by the sector.

6.1.5.3. Use of Critical Raw Materials

Critical Raw Materials are defined by the European Commission as *'raw materials of high importance to the economy of the EU and whose supply is associated with high risk*'. Task 1 identified the following CRMs as having potential relevance to the solar photovoltaic product group - antimony, cobalt, borate, indium, gallium, silicon metal and tantalum. An overview of those raw materials listed as CRM is presented in Figure 19.

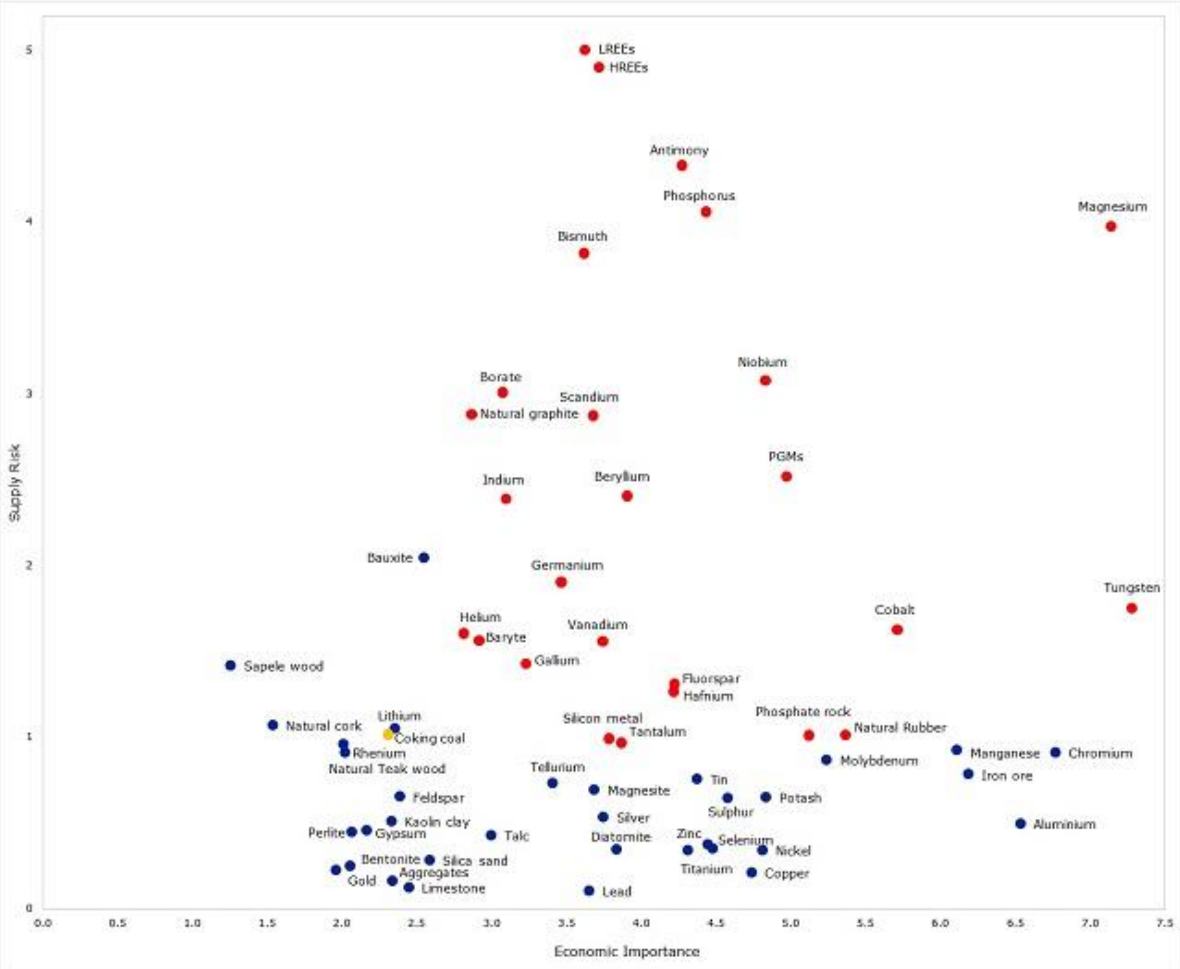

Figure 19 The 2017 list of Critical Raw Materials (in red) to the EU

(HREEs = Heavy Rare Earth Elements, LREEs = Light Rare Earth Elements, PGMs = Platinum Group Metals)

Source: European Commission (2018)

[64] Ye Wan *et al, The preparation and detection of high purity silicon tetrachloride with optical fibres level*, 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* 207, 012018

Further work on CRM management and the circular economy has identified indium, gallium and silicon metal as being of particular relevance to the solar photovoltaic product group. A high potential (95%) for economically feasible recycling has been identified.

The CIS and CIGS thin film cell design are of particular relevance given that indium and gallium are fundamental to their semi-conductor designs. The potential for the recycling of silicon wafers manufactured from silicon metal was discussed in Task 4 of the Ecodesign Preparatory Study and faces significant economic and technical barriers.

6.1.6. Social and ethical issues

Use of minerals from conflict zones

Solar photovoltaic products may contain a number of scarce mineral resources such as tin and tantalum which have been identified as being obtained from conflict areas. The Commission has defined conflict areas as:

> '*areas in a state of armed conflict, fragile post-conflict as well as areas witnessing weak or non-existing governance and security, such as failed states, and widespread and systematic violations of international law, including human rights abuses*.'

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

Initiatives by the electronics industry to address this issue were stimulated by the US Dodd-Frank Act which requires disclosure of the source of metals. Corporate initiatives generally focus on improving working conditions as opposed to the black listing locations. Verification has tended to be linked to participation in a range of projects that have been established in conflict areas. The Responsible Minerals Assurance Process (RMAP) and the Conflict Free Sourcing Initiative (CFSI) also provide verification routes that focus on specific points in the supply chain for minerals.

Example projects on the ground include those working to establish traceability systems at a general level - such as the Public-Private Alliance for a responsible minerals trade and Solutions for Hope - and those focussed on specific minerals, such as the Conflict-free tin initiative, the Tin Source Initiative and the Tantalum Initiative.

7. Preliminary evaluation

7.1. Identification of lifecycle hotspots

Life cycle assessment has the potential to generate valuable information and knowledge for policy makers, as insights can be gained by applying LCA into the development of policy criteria. A systematic LCA review has been conducted with a focus on the information needs of the policy tools. However, to be of relevant use, a LCA study should report the values, or give an interpretation of the results per components/substances, in order to support hotspot identification or allow for conducting it. This is specifically useful to develop in a later stage criteria for EU Ecolabel as an example. Product environmental footprint category rules (PEFCRs) have been a complementary source for the identification of hotspots for photovoltaic modules, **Error! Reference source not found.**Table 19 shows a summary of the analysis conducted to translate the findings form the LCA review for module inverters and systems into possible criteria.

- Modules
    - For Si-based technologies a number of hotspots have been identified. Ingot manufacturing or wafer production is the process that has the largest contribution to the environmental impact categories.

  - For thin-film technologies, the metal deposition together with flat glass production have been pointed out as the process/component having the largest share to the total impact of the module manufacturing
  - For all module technologies, the electricity demand in the supply chain of aluminium and copper production (at construction stage) can exert a large influence on the environmental impact
- Inverters
  - For inverter products the main contributor to the environmental impact is the integrated circuit of the printed circuit board.
- Systems
  - The electricity demand in the supply chain of aluminium and copper production for the mounting structure and cabling can as well have a large impact at system level. The balance of system in thin-film installations is a hotspot detected from the literature review,

Table 19. Summary table of hotspots to be translated into criteria for EU Ecolabel.

Product	PV tech/ System size	Hotspots LCA	Measures and verification (suitability)	Scoping improvement potential	Technical requirement	Verification	Precedents
	Si tech	Ingot/wafer production	1) Use of less energy intensive manufacturing processes, 2) Silicon ingot slicing, e.g. change of laser cutting, lift-off, kerfless (epitaxial), diamond wire sawing for multicrystalline	1) A change of processes that consume less energy could lower the primary energy consumed up to x%, and 2) that measure could reduce the losses from slicing up to x% and minimising the silicon needed for the same energy output	1) Reduction in primary energy from ingot/wafer manufacturing, 2) Reduction in GWP from silicon slicing	1 and 2) Primary energy and GHG emissions reporting standard production specific , e.g. ISO 14064, 50001 Energy Management System	NSF 457 (7.1.1 required criteria)
	Si tech	Grid electricity mix	Change of site to a location with a lower grid emissions factor	The change of the electricity mix used for the production could lower the GWP up to approx. 100%	Reduction in GWP from production stage electricity use	GHG emissions reporting standard production specific , e.g. 14064	French national PV capacity auction, where there is an annex explaining the method to calculate GHG emissions and compare them against a benchmark
Modules	all techs	Silver metallization paste	1) Use of less silver metallization paste, 2) Substitute silver by copper plating	A reduction down to 50 mg per cell is expected to be possible by 2028	Report the amount of silver per m^2 or per Wp of module.	No standard procedure. It could be an information requirement, similar to ROHS requirement	-
	Thin film	Metal deposition in thin films	Use of less energy intensive step/process	The primary energy consumed by the deposition process could be reduced and toxicity impacts and resource depletion would be as well reduced as a result	Reduction in primary energy from metal deposition processes	Primary energy reporting according to I50001 Energy Management System. EPBT calculation?	NSF 457 (8.1 required criteria), Blue Angel proposal
		Extraction of cadmium and tellurium	Reduce the consumption of Cd and Te	Two CIGS manufacturers - Solar Frontier and Steon - claim that they manufacture modules with 'RoHS compliant' cadmium concentrations of less than 0.01%. First solar claim a 50% reduction semiconductor intensity since 2009	1) Reduction of cadmium or tellurium content, 2) Circular loop recovery process for semiconductor materials	1) No standard procedure. It could be an information requirement, similar to ROHS requirement. 2) Modules must be covered by a producer responsibility scheme which ensures a minimum level of recovery, or a minimum recycled content	NSF 457 (9.1.1 End of life management & design for recycling and 9.1.2 Publicly available record of annual recycling and recovery achievement (corporate) and 6.1 (6.1.1 + 6.1.2)

	Thin film	Flat glass production	Use of thinner glass, change the type, facilitate recycling or reuse	In series 6 of first solar, the front glass has reduced the thickness from 3.2 to 2.8 mm and for the back glass from 3.2 to 2.2 mm. Lowering also the environmental impact of transport	1) Glass thickness for specific grade 2) Ease of separation of lamination from glass	1) Verification of glass specification, 2) Dismantling tests to show the separation	UBA WEEE criteria: proposals from WG3 PV modules 3.1 on unloading storage and handling, 3.9. on preferable recycling of glass as flat or container glass
	All techs	Life time and degradation	extended lifetime and lower failure rates	An increase in the degradation rate from 0.5% to 0.7% would lower the energy yield 7% meaning that environmental impacts would rise proportionally another 7%. Comparing a base case (25y, 0.5% degradation) to a case where lifetime is 30 years and the degradation rate increases to 0.7%), the environmental impacts produced are 15 % higher compared to the base case.	1) Stablish a technical lifetime defined according to the yield (>80% at 30y) or 2) Degradation target, e.g. lower than 0.5%. Or take a degradation rate and translate it into a technical lifetime	1) Minimum set of data provided by JRC C2 Ispra	-
	All techs	Energy payback time	1) Use of less energy intensive manufacturing processes, 2) Change in geographical location	The lower the primary energy in the production stage, the higher the energy payback time. Variation in the southern to northern affects the EPBT, as the system yield strongly depends on the radiation of the location. Multicrystalline silicon modules installed in a reference system can have 8 years or 4.31 years if they are installed in Helsinki or Sevilla[65] respectively.	1) To maintain an EPBT below a certain threshold for a given climate conditions, 2) To include it in an Energy label	No standard exists to calculate the primary energy during the manufacturing stage. There is a standard EN 15804 and ISO carbon emissions reporting for construction products. A third party verification against those standards and a certain quality of data could be use.	NSF 457 (7.1.1 required criteria) French national PV capacity auction, where there is an annex explaining the method to calculate GHG emissions and compare them against a benchmark
Inverters	R&C	Print board assembly	1) Avoiding toxic elements such as cadmium, mercury, beryllium,	Limit the content of hazardous substances or improve the	1) Avoiding toxic elements such as cadmium, mercury, beryllium,	No standard exist on the content of hazardous	Ecodesign regulations for washing

[65] For a MSi module 14.7% efficiency, 30 years lifetime, and a performance ratio of 75%

			arsenic, lead and chromium. 2)Lead-free soldering techniques	supply of these materials by recovering as much as possible from the WEEE, would have positive impacts especially in the marine aquatic ecotoxicity, the freshwater aquatic ecotoxicity	arsenic, lead and chromium. 2)Lead-free soldering techniques 3) Give recommendations for the ease of disassembly for end of life treatments	substances in PCBs. 1) Declaration of content of substances from a list of targeted substances 2) Declaration of no Lead content 3) Declaration of protocols for the disassembly and recycling	machines/DWs/fridges/TVs/servers WEEE directive applies to PCBs larger than 10 cm^2
Systems	R,C,U all techs	Electricity demand in the supply chain of aluminium and copper production (construction stage)	Use of less or no framing and mounting structure, use of less cabling	Possible reduction in the amount of cabling and structure by e.g. having dual junction box design (e.g. Q cells claim up to 87% cable saving), alternative frame materials or use of lighter structure, or integrated PV (substitution of roof structure by modules).	Amount of cabling form module/module connections. For the framing material it could be captured by the GWP of the whole module. Integrated modules could be another proposal but how to credit the integration?	In general hardly feasible to capture in criteria. Integrated modules would be a proposal but how to credit the integration? 1) Declaration of cabling material, 2) GHG emissions reporting standard production specific , e.g. 14064	-
	U	BOS in thin film technologies	Use of lighter structures or more sustainable materials	Share of the BOS in the total impact could be lower	Possible reduction in the amount of cabling and structure by e.g. having dual junction box design (to check first solar series 6), or use of lighter structure, or integrated PV (substitution of roof structure by modules)	In general hardly feasible to capture in criteria. Integrated modules would be a proposal but how to credit the integration? 1) Declaration of cabling material, 2) GHG emissions reporting standard production specific , e.g. 14064	-
		Consumption of copper from the electrical installation as well as aluminium from the mounting structure	Recycled content or recovery processes	In this impact category the resource consumption of copper from the electrical installation as well as aluminium from the mounting structure are responsible for the high variability. Across all impact categories the variability can be from 0-67%	1) Ease of dismantling and recovery , 2) Recycled content	1) Declaration of protocols of dismantling 2) Systems must be covered by a producer responsibility scheme which ensures a minimum level of recovery, or a minimum recycled content	-

Table 20. General criteria area proposals and benchmark methods for Ecolabel

Criteria area	**Possible criteria**	**Benchmark methods**
Life cycle primary energy/GWP	1) Reporting the life cycle energy 2) Acting on individual components: a) ingot manufacturing a1) reduce energy/gwp a2) reduce losses per wafer b) Reduce the energy used in the flat glass production c) Purchase of green electricity mix 3) Life cycle performance	1) Report according to . ISO 14064 normalised to the site yield 2a1) Keep to a certain level the kWh/wafer 2a2) Keep to a certain level the kWh/wafer 2b) thicckess by grade specification 2c) Coverage of 50% of the demand by certificates at the production site 3) Energy payback time under certain values
Circular economy/Material efficiency	1) Ease of dismantling flat glass 2) Reduction of semiconductor materials content 3) Recycle content of materials of concern, e.g. Cd, In, Ga, Te	
Lifetime	Maintenance of performance in terms of degradation (setting an expected technical lifetime)	1) declared degradation rate, 2) how many years the performance would be maintained at 80%
Hazardous substances	Content limitation in lead, cadmium and phthalates	
To be validated by further modelling and supported evidence in the Ecodesign Preparatory Study		
Circular economy/Material efficiency	1) Design for repairability and recycling in inverter products 2) Design for recycling of PV modules	1) There may be potential to differentiate based on design life disclosure, e.g. by stating the repair cycle 2) Protocol for dismantling

7.2. Assessment of the evidence for the EU Ecolabel

7.2.1. Contribution to EU policy objectives

In order to evaluate whether the EU Ecolabel could make a positive contribution to specific EU environmental policy objectives a matrix of EU policy measures has been compiled in *Table 21*. Policy measures of relevance to the product group have been identified from those described in section 1.2.1. Then for each policy measure the need and scope for contribution to policy objectives has been evaluated.

Table 21 Evaluation from an EU policy perspective of the need and potential for an EU Ecolabel intervention

Policy measure	**Policy objectives and actions of relevance to the product group**	**Is there a role for such a voluntary policy intervention?**	**Does the potential exist in the market to differentiate product performance?**
Energy Union Framework Strategy *and* accompanying new Electricity market rules	Citizens take ownership of the energy transition, benefit from new technologies to reduce their bills, [and] participate actively in the market.	Moderate for all products, citizens would be given additional information with which to make better choices in terms of maximising the yield whilst minimising environmental impacts.	*Not apparent yet, pending the full results of the design options evaluation.*
	Guaranteeing consumers' rights to the self-consumption of electricity.		
	The establishment of legal frameworks for 'local energy communities' to engage in generation, distribution and supply.	No role, outside of the scope of this policy instrument.	-
Renewable Energy Directive 2009/28/EC and the proposed recast	Increased deployment of solar PV as a contributor to EU energy strategy renewables targets for 2030	Moderate to limited role for all products, it could give further visibility to PV solutions and promote higher yield solutions.	A differentiation exists between the highest and lowest efficiency module products. Differentiation is more limited between inverter products.
	Member States make available certification schemes or equivalent qualification schemes for installers.	Limited role for PV systems, it could give further visibility to the need for quality design and installation.	-
	Buildings shall obtain minimum levels of energy from renewable sources	No role, outside of the scope of this policy instrument.	-
	New public buildings and existing buildings subject to major renovation shall fulfill an exemplary role	Moderate for PV systems, it could enable better choices in terms of maximising the yield whilst minimising environmental impacts.	*Not apparent yet, pending the full results of the design options evaluation.*

	Empowerment of citizens to self-consume and store renewable electricity	Limited to moderate, citizens would be given additional information with which to make better choices in terms of maximising the yield whilst minimising environmental impacts.	*Not apparent yet, pending the full results of the design options evaluation.*
Recast Energy Performance of Buildings Directive 2010/31/EU (EPBD) and 2018 update	Ensure [at national level] that all new buildings are 'nearly zero energy' (NZEB) by 2020.	No role, outside of the scope of this policy instrument.	-
	A stronger focus on renovation and decarbonisation of the existing building stock.	Moderate, it could enable better choices in terms of maximising the yield whilst minimising environmental impacts.	*Not apparent yet, pending the full results of the design options evaluation.*
	Enhance the ability of occupants and the building itself to react to comfort or operational requirements, take part in demand response and contribute to the optimum, smooth and safe operation of the various energy systems…	Limited, in the case of a criterion on smart monitoring capabilities for systems.	-
Construction Products Regulation (EU) No 305/2011	Use in the design, construction and demolition of buildings to facilitate more sustainable resource use: (a) reuse or recyclability of the their materials and parts after demolition; (b) durability; (c) use of environmentally compatible raw and secondary materials.	Moderate, in the case that module and inverter criteria on dismantling and durability are defined.	For modules there has been limited work to date on design for dismantling. There may be potential to differentiate based on degradation rate. For inverters there may be potential for ease of dismantling to be investigated further. There may be potential to differentiate based on design life disclosure e.g. by stating the repair cycle.
Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)	The restriction of the use of certain hazardous substances in electrical and electronic equipment	Moderate to strong, in the case that module criteria define compliance with the RoHS thresholds for some/all of the substances restricted.	For modules there appears to be potential based on variations in lead, cadmium and phthalates. -
	Secondary market operations for EEE shall from 2019 be compliant with the Directive.	Limited, as it is not clear the extent to which remanufactured products could comply or would be a target market for the EU Ecolabel.	

Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE),	Products shall achieve an overall collection rate of 85% by 2019	Limited, it could provide visibility and impetus in the case that a criterion.is set on manufacturers to provide a take back route.	-
	From the 15th August 2018 EEE category 4 products shall achieve an 85% recovery rate and an 80% re-use and recycling rate.	Limited to moderate, in the case that: – criteria are set that encourage modules, inverters and system components to be better designed for recycling/depollution. – criteria are set that require a certain level of performance from take back scheme recovery facilities.	For modules there are only some limited examples of design for recycling. For inverters there is no information.
	'Proper treatment' of solar photovoltaic 'panels' (modules) under EEE category 4(b).		
	Verification of proper treatment and depollution is supported by the EN 50625 standards series.		For modules there are some technologies that can achieve a high level of recovery, including for the semi-conductor material.
	Member States shall encourage co-operation between product manufacturers and recyclers in order to facilitate the re-use, dismantling and recycling of WEEE at product, component and material level.		
EU action plan for the Circular Economy	Promote the reparability, upgradability, durability, and recyclability of products (by developing product requirements)	Moderate to strong, as an instrument to stimulate innovative designs in the case that criteria are set on repairability, recyclability and durability	For modules there has been limited work to date on design for recycling and dismantling. There may be potential to differentiate based on degradation rate. For inverters there may be potential for design for repairability and recycling to be investigated further. There may be potential to differentiate based on design life disclosure e.g. by stating the repair cycle.
	Specifically consider proportionate requirements on durability and the availability of repair information and spare parts (under eco-design).	Moderate to strong, it could complement any Ecodesign measures on durability, repairability and information as a pull in the market.	See the previous row.
	Efficient use and recycling of Critical Raw Materials	Moderate to strong, in the case that criteria are set to address the CRM content of modules and inverters.	Would require a focus on silicon wafer and CIGS semi-conductor recovery, for both of which there is limited evidence of progress. For inverters tantalum is relevant but more information is needed about ease of recovery from PCBs.

7.2.2. Evaluation of the potential new product group for EU Ecolabel

In this section the evidence gathered in this report is reviewed in order to answer the evaluation questions for a potential new EU Ecolabel product group. It is to be noted that to date photovoltaic products have been proposed in 2016 as a new product group by a private sector consortium.

- **Feasibility of definition and scope:** *Is it possible to clearly define and classify the product/sub-products as the basis for a criteria scope?*

  Yes, the scope and definition is currently proposed as being that which has been defined for the Ecodesign Preparatory Study. However, as modules and inverters are for the most part business-to-business products it is not clear if they would be appropriate as EU Ecolabel products. Instead PV DIY (Do It Yourself) kits or installed systems could be labelled, with criteria set to address their main components. The point in the supply of systems to retail consumers at which the kit or set of components should be labelled would need to be clearly defined, also in terms of who would be the EU Ecolabel applicant and license holder, as well as who would communicate any change in the composition of the kit of package of components over time.

  Furthermore, there could be the potential to narrow the PV system scope to focus on the sub-5kW residential scale and to also create the potential to label DIY kits made up of modules and inverters. The rationale for a narrower focus is that this is the scale that retail consumers would look to purchase an EU Ecolabelled system. Moreover, the wider Preparatory Study has highlighted the need to transfer best practices in the design, installation and maintenance of PV systems from larger scale commercial systems to smaller residential systems.

- **Existence of other ecolabels and schemes:** *Is there an existing basis in the EU or internationally for product group criteria?*

  Yes, the NSF/ANSI 457 standard for modules and the Blue Angel ecolabel criteria set for inverters. The Cradle to Cradle certification has also been awarded to a number of module products.

  While the above referred to standards and certifications all have criteria that could be reflected in an EU Ecolabel criteria set, to the best of our knowledge, the only one of these that has currently been awarded to products is Cradle to Cradle. Whilst this certification does not have specific PV criteria, only ones for general applicability to a range of products, the criteria could already provide verification material for possible EU Ecolabel criteria on chemicals, production site GWP emissions and circular design, as well as social fairness.

- **Market significance:** *Could the EU Ecolabel criteria be effectively targeted at mainstream products that can be clearly identified from market data?*

  Unclear at this stage, there are no specific products that in their design would achieve all of the identified improvement potential. There are, however, some products that can achieve combinations of the identified improvement potential. Care would therefore need to be taken to configure the overall criteria set in order to ensure there were sufficient possible license holders from the outset.

  In order to build some flexibility into how different products could achieve the label there could be merit in exploring a points=based system as used by the NSF/ANSI 457 standard. Such a system is used on some EU Ecolabel product groups and consists of mandatory minimum criteria and optional criteria. Applicants must achieve a points threshold by combining the minimum and optional criteria.

- **Visibility:** *Would the product group provide a high level of consumer visibility for the EU Ecolabel?*

  Potentially, since it is a high profile green product but in reality the degree of visibility for the EU Ecolabel may depend on the point of sale for the PV system or components e.g. if it is marketed in IKEA for instance.

- **Potential uptake:** *What existing indications are there of the potential uptake?*

  There has been an industry consortium proposal for an EU Ecolabel for PV modules. This suggests that there are potential verifiers and some manufacturers interested and ready to bring products forward for labelling. Some major manufacturers have been involved with development of the NSF/ANSI 457 standard and have certified module products with Cradle to Cradle.

- **Alignment with legislation and standards:** *Could the Ecolabel make a positive contribution to specific EU environmental policy objectives?*

  Yes, the analysis suggests that it could have a moderate to strong contributing role in implementation of some of the main objectives of Energy Union Framework Strategy, the Construction Products Regulation, the RoHS Directive, the WEEE Directive and the EU action plan for the Circular Economy.

- **Environmental impacts analysis;** *Can practical, verifiable criteria be identified that are based upon and could address LCA hot spots and non-LCA issues that are of significance?*

  The analysis of the potential to translate hot spots into criteria was able to identify 5 broad categories of potential:

  – Those that have a metric and standardised method(s) but for which establishing a benchmark will be difficult e.g. life cycle GWP emissions.

  – Those that have a metric but no standardised method(s) has yet been identified e.g. silver content of a module.

  – Those that have a specific activity and accompanying metric but for which no standardised method(s) has yet been identified e.g. semi-conductor recovery rate.

  – Those that don't have a clear metric together with the basis for performance benchmarks,

  – Those for which an initial threshold can be identified

7.3. Assessment of the evidence for Green Public Procurement

7.3.1. Contribution to EU policy objectives

In order to evaluate whether the EU GPP criteria could make a positive contribution to specific EU environmental policy objectives, a matrix of EU policy measures has been compiled in Table 22. Policy measures of relevance to the product group have been identified from those described in section 1.2.1. Then for each policy measure the role for GPP in contributing to policy objectives has been evaluated.

Table 22 Evaluation from an EU policy perspective of the need and potential for an EU GPP intervention

Policy measure	**Policy objectives and actions of relevance to the product group**	**Is there a role for such a voluntary policy intervention?**
Energy Union Framework Strategy *and* accompanying new Electricity market rules	Citizens take ownership of the energy transition, benefit from new technologies to reduce their bills, [and] participate actively in the market.	Strong role, in the case of establishing community or city-wide 'reverse auction' procurement framework to enable citizens to purchase systems or electricity.
	Guaranteeing consumers' rights to the self-consumption of electricity.	No role, outside of the scope of this policy instrument.
	The establishment of legal frameworks for 'local energy communities' to engage in generation, distribution and supply.	Strong role, could lead the procurement of systems or the establishment of frameworks.

Renewable Energy Directive 2009/28/EC and the proposed recast	Increased deployment of solar PV as a contributor to EU energy strategy renewables targets for 2030	Strong role, both in terms of: • Making available public buildings and housing roofs/land • Investing in new systems facilitating citizens to purchase systems.
	Member States make available certification schemes or equivalent qualification schemes for installers.	Limited to moderate, for direct purchase it could enhance quality of installations through Selection Criteria and similarly in the case of reverse auctions but with potentially wider impact.
	Buildings shall obtain minimum levels of energy from renewable sources	Moderate to strong, starting with public buildings/social housing and with potentially wider impact e.g. community and citizen installations
	New public buildings and existing buildings subject to major renovation shall fulfill an exemplary role	Strong, potential for direct contribution.
	Empowerment of citizens to self-consume and store renewable electricity	Strong role, in the case of establishing community or city-wide 'reverse auction' procurement framework to enable citizens to overcome a range of barriers to the purchase of systems or electricity.
Recast Energy Performance of Buildings Directive 2010/31/EU (EPBD) and 2018 update	Ensure [at national level] that all new buildings are 'nearly zero energy' (NZEB) by 2020.	Moderate to strong, starting with public buildings/social housing and with potentially wider impact e.g. community and citizen installations
	A stronger focus on renovation and decarbonisation of the existing building stock.	Strong, potential for direct contribution.
	Enhance the ability of occupants and the building itself to react to comfort or operational requirements, take part in demand response and contribute to the optimum, smooth and safe operation of the various energy systems…	Moderate, alongside procurement of Building Energy Management Systems (BEMS)
Construction Products Regulation (EU) No 305/2011	Use in the design, construction and demolition of buildings to facilitate more sustainable resource use: (a) reuse or recyclability of the their materials and parts after demolition; (b) durability; (c) use of environmentally compatible raw and secondary materials.	Moderate, in the case that module and inverter criteria on dismantling and durability are defined.

<table>
<tr><td rowspan="2">Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)</td><td>The restriction of the use of certain hazardous substances in electrical and electronic equipment</td><td>Moderate to strong, in the case that module criteria define compliance with the RoHS thresholds for some/all of the substances restricted.</td></tr>
<tr><td>Secondary market operations for EEE shall from 2019 be compliant with the Directive.[66]</td><td>Limited, as it is not clear the extent to which remanufactured products could comply or would be a target market for EU GPP criteria.</td></tr>
<tr><td rowspan="5">Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE),</td><td>Products shall achieve an overall collection rate of 85% by 2019</td><td>Limited, it could provide visibility and impetus in the case that a criterion.is set on manufacturers to provide a take back route.</td></tr>
<tr><td>From the 15th August 2018 EEE category 4 products shall achieve an 85% recovery rate and an 80% re-use and recycling rate.</td><td rowspan="4">Limited to moderate, in the case that:
– criteria are set that encourage modules, inverters and system components to be better designed for recycling/depollution.
– criteria are set that require a certain level of performance from take back scheme recovery facilities.
Requirements are set for how the decommissioning of systems is carried out</td></tr>
<tr><td>'Proper treatment' of solar photovoltaic 'panels' (modules) under EEE category 4(b).</td></tr>
<tr><td>Verification of proper treatment and depollution is supported by the EN 50625 standards series.</td></tr>
<tr><td>Member States shall encourage co-operation between product manufacturers and recyclers in order to facilitate the re-use, dismantling and recycling of WEEE at product, component and material level.</td></tr>
<tr><td rowspan="3">EU action plan for the Circular Economy</td><td>Promote the reparability, upgradability, durability, and recyclability of products (by developing product requirements)</td><td>Moderate to strong, as an instrument to stimulate innovative designs in the case that criteria are set on repairability, recyclability and durability</td></tr>
<tr><td>Specifically consider proportionate requirements on durability and the availability of repair information and spare parts (under eco-design).</td><td>Moderate to strong, it could complement any Ecodesign measures on durability, repairability and information as a pull in the market.</td></tr>
<tr><td>Efficient use and recycling of Critical Raw Materials</td><td>Moderate to strong, in the case that criteria are set to address the CRM content of modules and inverters.</td></tr>
</table>

[66] RoHS restrictions apply at the point of placing on the market for the first time, after that, the equipment can be resold without having to comply with possible new restrictions. Remanufactured products would have to comply only if they could be classified as a new product, i.e. if the original performance, purpose or type would be changed or if it would be marketed under a new name.

7.3.2. Evaluation of the potential new product group for GPP

In this section the evidence gathered in this report is reviewed in order to answer the evaluation questions for a potential new EU GPP criteria for the product group. It is to be noted that to date photovoltaic products have not been identified as a priority product group for EU GPP criteria development by any stakeholder or Member States.

Step 1: Contribution to objectives

- Reduction of the environmental impact (CO2 reduction, energy/resource efficiency, air pollution, etc.) of products, services or works
- Stimulation of innovation
- Cost reduction

The technical analysis and screening of life cycle environmental impacts has shown that the product group has the potential to contribute to meeting environmental objectives in two broad ways:

- Support greater deployment and yield optimisation of solar photovoltaic power with the associated reduction in environmental impacts through displacement of fossil fuel energy sources..
- Reduce or manage environmental impacts along the life cycle of solar photovoltaic systems and components such as energy consumption at the production stage, material efficiency during the use phase and recyclability at the end of life..

Moreover, GPP can contribute towards achievement of grid parity for the LCOE of solar electricity by promoting best practices in design optimisation and component selection. In the process this has the potential to stimulate innovation in module and inverter design as well as system solutions such as smart monitoring.

The specific ways in which GPP criteria could contribute are identified in **Error! Reference source not found.** under Step 4 of this evaluation

Step 2: Determine the added value of GPP to existing policy instruments

The next step is to determine the added value of GPP to existing policy instruments like:

- Covenants
- GPP
- Ecolabel
- Ecodesign
- Directives
- Subsidies
- Fiscal instruments
- Communication

The potential contribution of GPP criteria to the added value of existing policies has been evaluated and is shown in *Table 22*. A strong role has been identified for a number of policies such as:

- Citizen engagement in the energy transition promoted via reverse auctions (the Energy Union Framework Strategy),
- Increased deployment of solar energy by a more active role on the part of public authorities (Renewable Energy Directive 2009/28/EC and the new Directive (EU) 2018/2001
- Decarbonising of the existing building stock through a more active role on the part of public authorities (Recast Energy Performance of Buildings Directive 2010/31/EU (EPBD) and 2018 update)

- Reduction in the presence of hazardous substances in electrical equipment (RoHS Directive 2011/65/EU)
- Promotion of more repairable, durable and recyclable products (EU Action Plan for a Circular Economy)
- Ensuring that for any given geographical location the energy yield is maximised and the energy payback time and LCOE is minimised

Step 3: Determine if GPP is the most effective instrument to achieve the objectives

The next step is to decide if GPP is among the most effective instruments to reach the objectives (go/no go moment). For this decision there are the following questions:

1. If by means of procurement public authorities have considerable direct or indirect influence on the sustainable objectives of the product group concerned.
2. If the influence of public authorities is small, you can further ask if there are other policy objectives (such as acting as role model) to include the product group in GPP.
3. Does it seem possible to translate the objective(s) into legally admissible and technically achievable procurement instrument/criteria.

The public sector has a substantial stock of buildings and land on which solar PV could potentially be installed. Once a decision has been made to procure solar PV systems the potential influence on the design and specification of components is direct in most cases. In the case of reverse auctions or the procurement of electricity this influence can be extended to third party, citizen installations.

The proposal presented in *Table 22* has mapped from EU studies that have analysed project delivery and risk mitigation. This suggests a combined focus on product (e.g. quality), works (e.g. protocols) and services (e.g. maintenance). There could be a case for guidelines that take a procurer through the various steps along a project life cycle. From a cost and risk mitigation, perspective a proposal of technically achievable and legally admissible criteria is made in **Error! Reference source not found.**.

Step 4: Determine the best form of GPP implementation

If you decide, that GPP is an effective instrument, choose the best way to implement it. Elements can include::

- Product criteria (mainly for products*)
- Functional criteria (mainly for works*)
- Process criteria (mainly for services*)
- Support systems for procurers
- Guidelines
- Trainings
- Examples

(* = in general, but there are many exceptions)

These elements should relate to the product group in question.

Table 23. Determination of potential types of GPP criteria as related to project phases and risk mitigation

Project phase		**Risk mitigation**	**Potential type of GPP criteria**
Preventative	Selection/testing	Module and inverter factory quality and performance testing	Selection Criteria for factory quality (e.g. IEC 62941, EN 62788) Technical Specifications for modules and inverters (e.g. EN 61215, EN 62093) Award criteria based on declared module degradation rate
	Design and yield estimation	Quality of design yield estimate and associated modelling data and assumptions Quality of electrical engineering design to mismatch and other losses	Selection Criteria for the field experience of the design team/EPC contractor Award criteria based on an estimate of the Performance Ratio (with reference to IEC 61724) Award criteria based on energy payback time (dependent on climate/location)
	Transportation to site	Protocols to minimise damage of modules through mishandling	Selection Criteria evidencing the use of such protocols Technical Specification requiring specific actions within a protocol
	Installation/construction	EPC qualification for competencies of field workers Advanced monitoring systems for early detection and diagnosis of faults Procedures to minimise damage of modules through mishandling	Selection Criteria for the field experience of the design team/EPC contractor Technical Specification for the monitoring systems Technical Specification requiring specific actions within a protocol
Corrective	Operation & maintenance	Basic monitoring routines to detect failures and deviations Advanced monitoring routines including visual inspection and IR/electroluminescence sensing Spare part management to minimise costs of downtime and increase likelihood of fulfilling design life.	Technical Specification/Award Criteria for the granularity of monitoring system (e.g. IEC 61724-1) Technical Specification based on planning to respond to inverter manufacturers recommended repair cycle
	Decommissioning	Definition of dismantling procedures and end of life routes	Technical Specification/Award Criteria requiring specific actions within a protocol and/or provision of specific EoL services

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