Product Environmental Footprint Category Rules (PEFCR)

PHOTOVOLTAIC MODULES USED IN PHOTOVOLTAIC POWER SYSTEMS FOR ELECTRICITY GENERATION

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Acronyms

AC	Alternating Current
AF	Allocation Factor
APAC	Asia & Pacific
AR	Allocation Ratio
B2B	Business to Business
B2C	Business to Consumer
BoC	Bill of Components
BoM	Bill of Materials
BP	Bonne Pratique
CdTe	Cadmium Telluride (PV Technology)
CF	Characterization Factor
CFF	Circular Footprint Formula
CFF-M	Circular Footprint Formula – Modular form
CI(G)S	Copper-Indium-Gallium-Selenide (PV Technology)
CPA	Classification of Products by Activity
DC	Distribution Centre
DC	Direct Current (Electricity)
DNM	Data Needs Matrix
DQR	Data Quality Rating
EA	Economic Allocation
EC	European Commission
EF	Environmental Footprint
EI	Environmental Impact
EoL	End-of-Life
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HD	Helpdesk
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
JRC	Joint Research Centre
kWh	Kilowatt Hour
kWp	Kilowatt Peak
LCDN	Life Cycle Data Network
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LT	Lifetime
micro-Si	Micromorphous Silicon (PV Technology)
mono-Si	Monocrystalline Silicon (PV Technology)
multi-Si	Multicrystalline Silicon (PV Technology)
NDA	Non-Disclosure Agreement
NGO	Non-Governmental Organisation
NMVOC	Non-methane volatile compounds

P	Precision
PCR	Product Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
PV	Photovoltaic
RF	Reference Flow
RP	Representative Product
SB	System Boundary
SC	Steering Committee
SMRS	Sustainability Measurement & Reporting System
SS	Supporting study
TAB	Technical Advisory Board
TeR	Technological Representativeness
TiR	Time Representativeness
TS	Technical Secretariat
UNEP	United Nations Environment
UUID	Universally Unique Identifier
WEEE	Waste Electrical and Electronic Equipment

Definitions

Activity data – This term refers to information which is associated with processes while modelling Life Cycle Inventories (LCI). In the PEF Guide it is also called “non-elementary flows”. The aggregated LCI results of the process chains that represent the activities of a process are each multiplied by the corresponding activity data[1] and then combined to derive the environmental footprint associated with that process (see Figure 1). Examples of activity data include quantity of kilowatt-hours of electricity used, quantity of fuel used, output of a process (e.g. waste), number of hours equipment is operated, distance travelled, floor area of a building, etc. In the context of PEF the amounts of ingredients from the bill of material (BOM) shall always be considered as activity data.

Aggregated dataset – This term is defined as a life cycle inventory of multiple unit processes (e.g. material or energy production) or life cycle stages (cradle-to-gate), but for which the inputs and outputs are provided only at the aggregated level. Aggregated datasets are also called "LCI results", “cumulative inventory” or “system processes” datasets. The aggregated dataset can have been aggregated horizontally and/or vertically. Depending on the specific situation and modelling choices a "unit process" dataset can also be aggregated. See Figure 1[2].

Application specific – It refers to the generic aspect of the specific application in which a material is used. For example, the average recycling rate of PET in bottles.

Benchmark – A standard or point of reference against which any comparison can be made. In the context of PEF, the term ‘benchmark’ refers to the ***average*** environmental performance of the representative product sold in the EU market. A benchmark may eventually be used, if appropriate, in the context of communicating environmental performance of a product belonging to the same category.

Bill of materials – A bill of materials or product structure (sometimes bill of material, BOM or associated list) is a list of the raw materials, sub-assemblies, intermediate assemblies, sub-components, parts and the quantities of each needed to manufacture an end product.

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[1] Based on GHG protocol scope 3 definition from the Corporate Accounting and Reporting Standard (World resources institute, 2011).
[2] Source: UNEP/SETAC “Global Guidance Principles for LCA Databases”

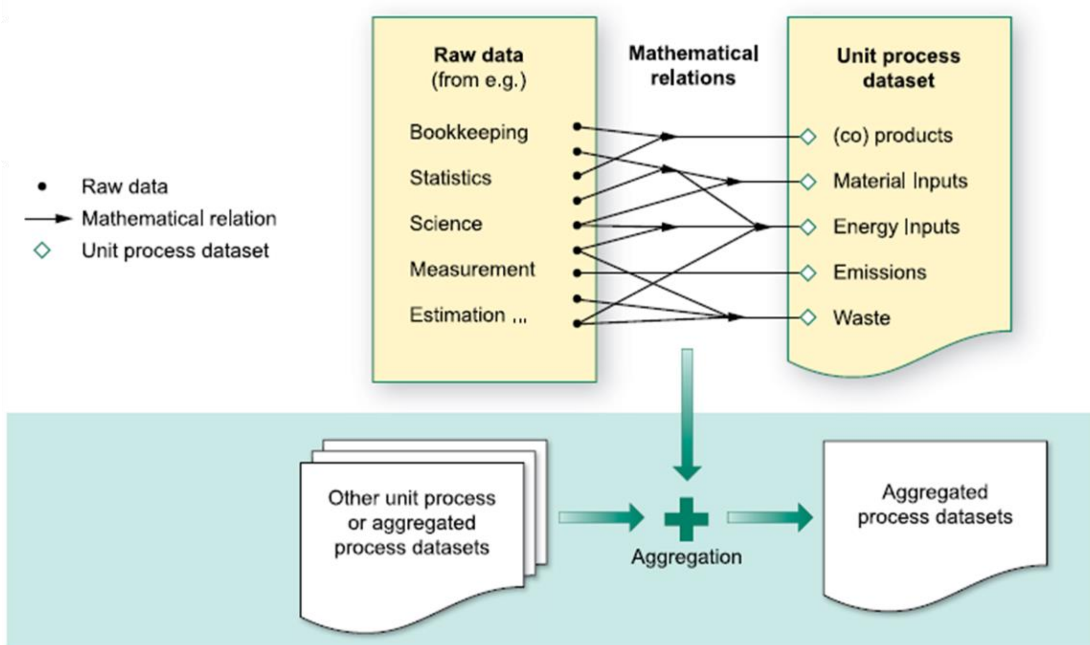

Figure 1 Definition of a unit process dataset and an aggregated process dataset

Business to Business (B2B) – Describes transactions between businesses, such as between a manufacturer and a wholesaler, or between a wholesaler and a retailer.

Business to Consumers (B2C) – Describes transactions between business and consumers, such as between retailers and consumers. According to ISO 14025:2006, a consumer is defined as "an individual member of the general public purchasing or using goods, property or services for private purposes".

Commissioner of the EF study – Organisation (or group of organisations) that finances the EF study in accordance with the PEF Guide, PEFCR Guidance and the relevant PEFCR, if available (definition adapted from ISO 14071/2014, point 3.4).

Company-specific data – It refers to directly measured or collected data from one or multiple facilities (site-specific data) that are representative for the activities of the company. It is synonymous to "primary data". To determine the level of representativeness a sampling procedure can be applied.

Comparative assertion – An environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function (adapted from ISO 14025:2006).

Comparison – A comparison, not including a comparative assertion, (graphic or otherwise) of two or more products based on the results of a PEF study and supporting PEFCRs or the comparison of one or more products against the benchmark, based on the results of a PEF study and supporting PEFCRs.

Data Quality Rating (DQR) – Semi-quantitative assessment of the quality criteria of a dataset based on Technological representativeness, Geographical representativeness, Time-related representativeness, and Precision. The data quality shall be considered as the quality of the dataset as documented.

Direct elementary flows (also named elementary flows) – All output emissions and input resource use that arise directly in the context of a process. Examples are emissions from a chemical process, or fugitive emissions from a boiler directly onsite. See Figure 2.

Disaggregation – The process that breaks down an aggregated dataset into smaller unit process datasets (horizontal or vertical). The disaggregation can help making data more specific. The process of disaggregation should never compromise or threat to compromise the quality and consistency of the original aggregated dataset

EF communication vehicles – It includes all the possible ways that can be used to communicate the results of the EF study to the stakeholders. The list of EF communication vehicles includes, but it is not limited to, labels, environmental product declarations, green claims, websites, infographics, etc.

EF report – Document that summarises the results of the EF study. For the EF report the template provided as annex to the PECFR Guidance shall be used. In case the commissioner of the EF study decides to communicate the results of the EF study (independently from the communication vehicle used), the EF report shall be made available for free through the commissioner's website. The EF report shall not contain any information that is considered as confidential by the commissioner, however the confidential information shall be provided to the verifier(s).

EF study – Term used to identify the totality of actions needed to calculate the EF results. It includes the modelisation, the data collection, and the analysis of the results.

Electricity tracking[3] – Electricity tracking is the process of assigning electricity generation attributes to electricity consumption.

Elementary flow – Material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation.

Environmental aspect – Element of an organization's activities or products or services that interacts or can interact with the environment (ISO 14001:2015)

External Communication – Communication to any interested party other than the commissioner or the practitioner of the study.

Foreground elementary flows – Direct elementary flows (emissions and resources) for which access to primary data (or company-specific information) is available.

Independent external expert – Competent person, not employed in a full-time or part-time role by the commissioner of the EF study or the practitioner of the EF study, and not involved in defining the scope or conducting the EF study (adapted from ISO 14071/2014, point 3.2).

Input flows – Product, material or energy flow that enters a unit process. Products and materials include raw materials, intermediate products and co-products (ISO 14040:2006).

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[3] http://www.e-track-project.org/

Intermediate product – An intermediate product is a product that requires further processing before it is saleable to the final consumer.

Lead verifier – Verifier taking part in a verification team with additional responsibilities compared to the other verifiers in the team.

Life Cycle Inventory (LCI) – The combined set of exchanges of elementary, waste and product flows in a LCI dataset.

Life Cycle Inventory (LCI) dataset – A document or file with life cycle information of a specified product or other reference (e.g., site, process), covering descriptive metadata and quantitative life cycle inventory. A LCI dataset could be a unit process dataset, partially aggregated or an aggregated dataset.

Material-specific – It refers to a generic aspect of a material. For example, the recycling rate of PET.

Output flows – Product, material or energy flow that leaves a unit process. Products and materials include raw materials, intermediate products, co-products and releases (ISO 14040:2006).

Partially disaggregated dataset – A dataset with a LCI that contains elementary flows and activity data, and that only in combination with its complementing underlying datasets yield a complete aggregated LCI data set. We refer to a partially disaggregated dataset at level 1 in case the LCI contains elementary flows and activity data, while all complementing underlying dataset are in their aggregated form (see an example in Figure 2).

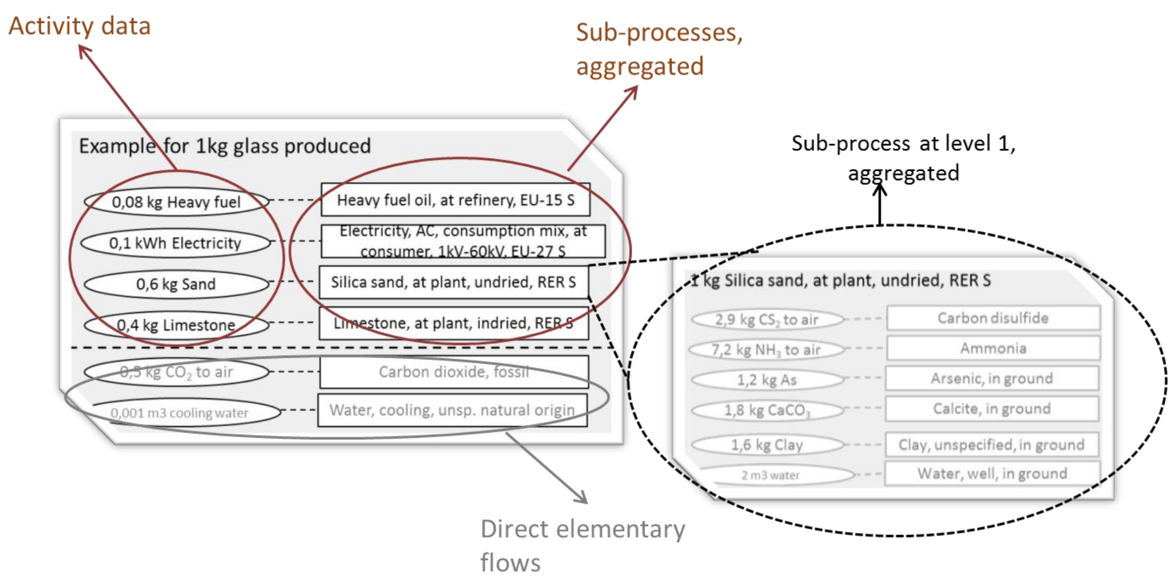

Figure 2 **An example of a partially aggregated dataset, at level 1. The activity data and direct elementary flows are to the left, and the complementing sub-processes in their aggregated form are to the right. The grey text indicates elementary flows**

PEFCR Supporting study – The PEF study done on the basis of a draft PEFCR. It is used to confirm the decisions taken in the draft PEFCR before the final PEFCR is released.

PEF Profile – The quantified results of a PEF study. It includes the quantification of the impacts for the various impact categories and the additional environmental information considered necessary to be reported.

PEF screening – A preliminary study carried out on the representative product(s) and intended to identify the most relevant life cycle stages, processes, elementary flows, impact categories and data quality needs to derive the preliminary indication about the definition of the benchmark for the product category/sub-categories in scope, and any other major requirement to be part of the final PEFCR.

Population – Any finite or infinite aggregation of individuals, not necessarily animate, subject to a statistical study.

Practitioner of the EF study – Individual, organisation or group of organisations that performs the EF study in accordance with the PEF Guide, PEFCR Guidance and the relevant PEFCR if available. The practitioner of the EF study can belong to the same organisation as the commissioner of the EF study (adapted from ISO 14071/2014, point 3.6).

Primary data[4] – This term refers to data from specific processes within the supply-chain of the company applying the PEFCR. Such data may take the form of activity data, or foreground elementary flows (life cycle inventory). Primary data are site-specific, company-specific (if multiple sites for the same product) or supply-chain specific. Primary data may be obtained through meter readings, purchase records, utility bills, engineering models, direct monitoring, material/product balances, stoichiometry, or other methods for obtaining data from specific processes in the value chain of the company applying the PEFCR. In this Guidance, primary data is synonym of "company-specific data" or "supply-chain specific data".

Product category – Group of products (or services) that can fulfil equivalent functions (ISO 14025:2006).

Product Category Rules (PCR) – Set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories (ISO 14025:2006).

Product Environmental Footprint Category Rules (PEFCRs) – Product category-specific, life-cycle-based rules that complement general methodological guidance for PEF studies by providing further specification at the level of a specific product category. PEFCRs help to shift the focus of the PEF study towards those aspects and parameters that matter the most, and hence contribute to increased relevance, reproducibility and consistency of the results by reducing costs versus a study based on the comprehensive requirements of the PEF guide.

Refurbishment – It is the process of restoring components to a functional and/or satisfactory state to the original specification (providing the same function), using methods such as resurfacing, repainting, etc. Refurbished products may have been tested and verified to function properly.

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[4] Based on GHG protocol scope 3 definition from the Corporate Accounting and Reporting Standard (World resources institute, 2011).

Representative product (model) – The “representative product” may or may not be a real product that one can buy on the EU market. Especially when the market is made up of different technologies, the “representative product” can be a virtual (non-existing) product built, for example, from the average EU sales-weighted characteristics of all technologies around. A PEFCR may include more than one representative product if appropriate.

Representative sample – A representative sample with respect to one or more variables is a sample in which the distribution of these variables is exactly the same (or similar) as in the population from which the sample is a subset

Sample – A sample is a subset containing the characteristics of a larger population. Samples are used in statistical testing when population sizes are too large for the test to include all possible members or observations. A sample should represent the whole population and not reflect bias toward a specific attribute.

Secondary data[5] – It refers to data not from specific process within the supply-chain of the company applying the PEFCR. This refers to data that is not directly collected, measured, or estimated by the company, but sourced from a third-party life-cycle-inventory database or other sources. Secondary data includes industry-average data (e.g., from published production data, government statistics, and industry associations), literature studies, engineering studies and patents, and can also be based on financial data, and contain proxy data, and other generic data. Primary data that go through a horizontal aggregation step are considered as secondary data.

Site-specific data – It refers to directly measured or collected data from one facility (production site). It is synonymous to “primary data”.

Sub-population – In this document this term indicates any finite or infinite aggregation of individuals, not necessarily animate, subject to a statistical study that constitutes a homogenous sub-set of the whole population. Sometimes the word "stratum" can be used as well.

Sub-processes – Those processes used to represent the activities of the level 1 processes (=building blocks). Sub-processes can be presented in their (partially) aggregated form (see Figure 2).

Sub-sample – In this document this term indicates a sample of a sub-population.

Supply-chain – It refers to all of the upstream and downstream activities associated with the operations of the company applying the PEFCR, including the use of sold products by consumers and the end-of-life treatment of sold products after consumer use.

Supply-chain specific – It refers to a specific aspect of the specific supply-chain of a company. For example the recycled content value of an aluminium can produced by a specific company.

[5] Based on GHG protocol scope 3 definition from the Corporate Accounting and Reporting Standard (World resources institute, 2004)

Type III environmental declaration – An environmental declaration providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information (ISO 14025:2006). The predetermined parameters are based on the ISO 14040 series of standards, which is made up of ISO 14040 and ISO 14044.

Unit process dataset – Smallest element considered in the life cycle inventory analysis for which input and output data are quantified (ISO 14040:2006). In LCA practice, both physically not further separable processes (such as unit operations in production plants, then called "unit process single operation") and also whole production sites are covered under "unit process", then called "unit process, black box" (ILCD Handbook).

Validation statement – Conclusive document aggregating the conclusions from the *verifiers* or the verification team regarding the EF study. This document is mandatory and shall be electronically or physically signed by the *verifier or in case of a* verification panel, by the lead verifier. The minimum content of the validation statement is provided in this document.

Verification report – Documentation of the verification process and findings, including detailed comments from the *Verifier(s)*, as well as the corresponding responses. This document is mandatory, but it can be confidential. However, it shall be signed, electronically or physically, by the *verifier or in case of a* verification panel, by the lead verifier.

Verification team – Team of verifiers that will perform the verification of the EF study, of the EF report and the EF communication vehicles.

Verifier – Independent external expert performing a verification of the EF study and eventually taking part in a verification team.

1 Introduction

The Product Environmental Footprint (PEF) Guide provides detailed and comprehensive technical guidance on how to conduct a PEF study. PEF studies may be used for a variety of purposes, including in-house management and participation in voluntary or mandatory programmes.

For all requirements not specified in this PEFCR the applicant shall refer to the documents this PEFCR is in conformance with (see chapter 2.7).

The compliance with the present PEFCR is optional for PEF in-house applications, whilst it is mandatory whenever the results of a PEF study or any of its content is intended to be communicated.

Terminology: shall, should and may

This PEFCR uses precise terminology to indicate the requirements, the recommendations and options that could be chosen when a PEF study is conducted.

- The term “shall” is used to indicate what is required in order for a PEF study to be in conformance with this PEFCR.
- The term “should” is used to indicate a recommendation rather than a requirement. Any deviation from a “should” requirement has to be justified when developing the PEF study and made transparent.
- The term “may” is used to indicate an option that is permissible. Whenever options are available, the PEF study shall include adequate argumentation to justify the chosen option.

2 General information about the PEFCR

2.1 Technical secretariat

Name of the organization	Type of organization	Name of the members	Participation since
Calyxo GmbH	Manufacturer of thin film PV modules	Dr. Jochen Fritsche	17.10.2013
ECN Solar Energy	Energy Research Centre of the Netherlands – Solar Energy	Dr. Carol Olson	17.10.2013
First Solar	Manufacturer of thin film and mono-Si PV modules	Andreas Wade	17.10.2013
IEA PVPS Task 12	International Energy Agency Photovoltaic Power Systems Programme Task 12 – Energy Research	Dr. Garvin Heath	17.10.2013
PVthin	International Thin Film Solar Industry Association	Andreas Wade	17.10.2013
SolarPower Europe	Photovoltaic Industry Association	Ioannis-Thomas Theologitis	17.10.2013
Total	Power plant planning and operation	Dr. Loïc Francke	17.10.2013
treeze Ltd.	LCA consultant	Dr. Rolf Frischknecht Philippe Stolz	17.10.2013
Yingli Green Energy	Manufacturer of mono-Si and multi-Si PV modules	Jean Tian	17.10.2013

2.2 Consultations and stakeholders

The process of the development of the PEFCR for photovoltaic electricity generation has been made accessible to interested stakeholders through the wiki page of this PEF pilot[6]. To date 187 stakeholders have registered on the webpage and are following the updates and the consultation processes. Three stakeholder consultations were held at different stages of the development of the draft PEFCR. The lists of stakeholder comments and the corresponding responses are available on the wiki page[6].

The first physical consultation meeting on the scope, representative product and the selection of the model for the PEF screening study took place on 9th April 2014 in Brussels. During the consultation a total number of 77 comments were received by 6 commenting stakeholders (First Solar, Total, Yingli Green Energy, Mariska de Wild-Scholten, DG Environment, Technical Helpdesk) and addressed in the final revision of the scoping document, which got approved by the Steering Committee.

The virtual consultation on the first draft of the PEFCR and the results of the PEF screening took place between 20th June and 19th July 2015, after approval of the PEF screening study by the Commission and the Steering Committee. During the first virtual consultation a total number of 59 comments were received by 7 commenting stakeholders (ADEME, Ecoinvent Board, Quantis, thinkstep, Bo Weidema, DG Environment, JRC) and addressed in the revision of the draft PEFCR, which got approved by the Steering Committee on 30th September 2015 in Brussels.

The second virtual consultation took place between 16th September and 14th October 2016. Four stakeholders (Solar Frontier, University of Palermo, PEF Metal Sheet, DG Environment) made a total number of 50 comments, which were addressed in a revised version of the PEFCR.

[6] https://webgate.ec.europa.eu/fpfis/wikis/display/EUENVFP/Stakeholder+workspace%3A+PEFCR+pilot+Photovoltaic+electricity+generation

2.3 Review panel and review requirements of the PEFCR

Name of the member	Affiliation	Role
Dr. Sangwon Suh	Professor, Corporate Environmental Management, Industrial Ecology, Life Cycle Assessment Bren School of Environmental Science & Management University of California 3422 Bren Hall Santa Barbara, CA 93106-5131, USA	*Chair of the review panel* *LCA expert with a focus on energy systems* Sangwon Suh is professor in industrial ecology and director of the CLiCC Program, an EPA-funded university-industry partnership that is developing a tool for rapid assessment of chemicals' environmental and human health impacts. He was trained as an environmental engineer and earned his PhD in industrial ecology at Leiden University in the Netherlands. Professor Suh's research focuses on the sustainability of the human-nature complexity through understanding materials and energy exchanges between them. Over the past twenty years, he contributed to the theoretical foundations and practical applications of life cycle assessment (LCA) and industrial ecology. Dr. Suh was appointed as a member of the International Resource Panel (IRP) by the United Nations Environmental Programme (UNEP) and served as the Coordinating Lead Author of the Assessment Report 5 by the Intergovernmental Panel on Climate Change (IPCC). He received the McKnight Land-Grant Professorship from the University of Minnesota's Board of Regents, Leontief Memorial Prize and the Richard Stone Prize from the International Input-Output Association (IIOA), the Robert A. Laudise Medal from the International Society for Industrial Ecology (ISIE), and Distinguished Teaching Award from the Bren school.

Name of the member	Affiliation	Role
Prof. Dr. Edgar Hertwich	Professor of Industrial Sustainability Yale School of Forestry & Environmental Studies 195 Prospect Street New Haven, CT 06511, USA	*Member of the review panel* *LCA expert with a focus on energy systems* Member of the International Resource Panel, leading the Working Group on the Environmental Impacts of Products and Materials. Contributed to the IPCC 5th assessment report as a lead author of the energy systems chapter and the methods annex, as well as a contributor to the Technical Summary and the Summary for Policy makers. Contributed to the Global Energy Assessment. Member of the editorial board of Environmental Science & Technology, the Journal of Industrial Ecology, and the Journal of Economic Structure. From 2003 to 2015, he directed the Industrial Ecology Programme and worked as professor in Energy and Process Engineering at the Norwegian University of Science and Technology in Trondheim, Norway. Before that, he was a research scholar at the International Institute of Applied Systems Analysis in Laxenburg, Austria.
Ugo Pretato	Senior Consultant and R & D Manager Studio Fieschi & Soci Srl Corso Vittorio Emanuele II 18 10123 Torino, Italy	*Member of the review panel* *LCA and PEF expert* Associate of the company since 2010, he is a graduate in forestry and holds an international master in Environmental Engineering (EPEA). Ugo has been working as a leading environmental consultant and LCA project manager at ANPA (now ISPRA). He has managed the environmental programs for the Olympic Winter Games of Torino in 2006 and held the positions of senior advisor at the Torino Energy Agency and scientific officer on Life Cycle Assessment at the European Commission JRC.

The reviewers have verified that the following requirements have been fulfilled:

- The PEFCR has been developed in accordance with the requirement provided in the PEFCR Guidance version 6.3, and where appropriate in accordance with the requirements provided in the most recent approved version of the PEF Guide, and supports creation of credible and consistent PEF profiles,

- The functional unit, allocation and calculation rules are adequate for the product category under consideration,
- Company-specific and secondary datasets used to develop this PEFCR are relevant, representative, and reliable,
- The selected LCIA indicators and additional environmental information are appropriate for the product category under consideration and the selection is done in accordance with the guidelines stated in the PEFCR Guidance version 6.3 and the most recent approved version of the PEF Guide,
- The benchmark(s) is(are) correctly defined, and
- Both LCA-based data and the additional environmental information prescribed by the PEFCR give a description of the significant environmental aspects associated with the product.

The PEFCR shall be reviewed again whenever important modifications are introduced by the Technical Secretariat and prior to the extension of the validity of the PEFCR.

The detailed review report is provided in Annex 3 of this PEFCR.

2.4 Review statement

This PEFCR has been developed in compliance with version 6.3 of the PEFCR Guidance, and with the PEF Guide adopted by the Commission on 9 April 2013.

The representative product(s) correctly describe the average product(s) sold in Europe for the product group in scope of this PEFCR.

PEF studies carried out in compliance with this PEFCR would reasonably lead to reproducible results and the information included therein may be used to make comparisons and comparative assertions under the prescribed conditions (see chapter on limitations).

2.5 Geographic validity

This PEFCR is valid for products in scope sold in the European Union + EFTA.

Each PEF study shall identify its geographical validity listing all the countries where the product object of the PEF study is sold with the relative market share. In case the information on the market for the specific product object of the study is not available, Europe + EFTA shall be considered as the default market, with an equal market share for each country.

2.6 Language

The PEFCR is written in English. The original in English supersedes translated versions in case of conflicts.

2.7 Conformance to other documents

This PEFCR has been prepared in conformance with the following documents (in prevailing order; the first two documents are the ones setting the conformance requirements, while there is partial conformance of this PEFCR with the other documents):

- PEFCR Guidance version 6.3
- Product Environmental Footprint (PEF) Guide; Annex II to the Recommendation 2013/179/EU, 9 April 2013. Published in the official journal of the European Union Volume 56, 4 May 2013
- IEA PVPS Task 12 Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity (2015b)
- Product Category Rules within the International EPD System IES (PCR CPC 171 & 173 2013)
- Product Category Rules within the European Standards on Environmental Product Declaration of construction works (EN 15804 2013)

3 PEFCR scope

The product category corresponds to the **production of photovoltaic modules used in photovoltaic power systems for electricity generation**. The product analysed is a photovoltaic module. “Photovoltaic module” is used as general term for panels (framed modules) and laminates (unframed modules).

A photovoltaic module basically consists of 48, 60 or 72 photovoltaic cells (156 x 156 mm² crystalline technology) or a monolithically integrated semiconductor layer (thin film technology), a substrate and a cover material (glass, plastic films), the connections (used for the interconnection of the cells), the cabling (used for the interconnection of the modules) and the frame (in case of panels). It is either mounted on a building or on the open ground. Mounting is considered as part of the product, but the inverter and the alternating current (AC) cabling (connection to the grid) are not part of the product analysed within this PEFCR. The life cycle inventories include the manufacturing, the operation and dismantling of the photovoltaic modules as well as the use of production equipment, facilities and the supply chain of the materials used. The photovoltaic module analysed is installed in Europe and the value chain of the module covers production worldwide (grouped in China, Europe, Asia & Pacific (APAC) and the USA).

Solar photovoltaic (PV) technology has developed strongly in a relatively short time. Many different technologies for panel production exist today. They differ in material consumption, efficiency, life expectancy and costs but also in their environmental performance. This PEFCR includes **five subcategories representing the following PV technologies**:

- Cadmium-Telluride photovoltaic modules (CdTe)
- Copper-Indium-Gallium-Selenide photovoltaic modules (CIS / CIGS)
- Micromorphous Silicon photovoltaic modules (micro-Si)
- Multicrystalline Silicon photovoltaic modules (multi-Si)
- Monocrystalline Silicon photovoltaic modules (mono-Si)

PV technologies have only been addressed in this PEFCR to the extent life cycle inventory data was available. This means that more advanced technology concepts, such as hetero- or multi-junction crystalline silicon cell architectures could not be included, even though market entry of these has happened to some extent. If sufficient quality data is available this PEFCR can also be applied to novel technology concepts.

The rated power of the module analysed according to this PEFCR should not be lower than 100 Watt and the size of the module should not be below 0.5 m^2. The module is installed in a grid-connected PV power plant, mounted on a slanted roof[7] and optimally oriented. The PV modules are compared on the basis of 1 kilowatt hour (kWh) of direct current (DC) electricity generated by a photovoltaic module given an average European irradiation weighted by the installed PV capacity per country in 2012[8] (functional unit). The reference flow is the photovoltaic module expressed in the maximum power output measured in kilowatt peak (kWp) under

[7] A PV system mounted on a slanted roof is the predominant application of PV modules in Europe and is therefore defined as the reference system, which shall be used for a comparison of different PV modules. The present PEFCR may also be applied to other PV installations such as open ground and roof-integrated PV systems.

[8] The European irradiation is calculated in subchapter 6.4 as the average irradiation in the EU and IEA PVPS member countries weighted with their cumulative installed photovoltaic capacity. The resulting average irradiation of 1’331 kWh/m^2 is representative for Europe since the countries with the highest installed photovoltaic capacity are considered.

standard conditions. The reference flow (kWp) is linked to the functional unit (kWh) by the inverse of the lifetime electricity production per kilowatt peak (see subchapter 3.3 and equation 1).

3.1 Product classification

The CPA code for the products included in this PEFCR is: 27.90 “Manufacturing of other electrical equipment”.

3.2 Representative product

The representative product is defined as an average photovoltaic module with similar rated power installed in Europe. The average photovoltaic module is a virtual product. The technologies included are mono- and multi-crystalline silicon, micromorphous silicon, CdTe and CIGS modules. The different photovoltaic technologies are analysed separately and finally merged to an average representative product. This supports individual hot spot analyses and enables the definition of technology specific benchmarks.

The technology mix and the bill of materials are presented in the sections 3.2.1 and 3.2.2, respectively.

The screening study is available upon request to the TS coordinator that has the responsibility of distributing it with an adequate disclaimer about its limitations.

3.2.1 Technology mix

The technology mix of the representative product was determined in the PEF scoping document (Frischknecht & Itten 2014) and in the PEF screening study (Stolz et al. 2016). Due to a lack of information on the technology specific annual or cumulative photovoltaic capacity installed in Europe, the average photovoltaic module is established using the global production volumes of the photovoltaic technologies addressed in this version of the PEFCR (CdTe, CIS, micro-Si, multi-Si, mono-Si) in 2012. Data on the actual production of photovoltaic modules according to FHI-ISE (2013)[9] were used to calculate the shares of the individual technologies in the representative product (Tab. 3.1). Ribbon-Si PV modules are excluded from the technology mix due to their small market share and because they are not addressed in the present version of the PEFCR.

[9] FHI-ISE (2013) cites the data originally published by Navigant consult 2012.

Tab. 3.1 Global PV module production in Gigawatt peak (GWp, the maximum power output of the modules) by technology, reference year 2012, based on FHI-ISE (2013)[9]

Technology	PV production in GWp	Share
single-Si	12.1	40.3%
multi-Si	13.5	45.0%
Ribbon-Si	0.1	0.3%
micro-Si	1.4	4.5%
CdTe	1.9	6.3%
CI(G)S	1.1	3.5%
Total	30.0	100.0%

Most of the crystalline silicon modules installed in Europe are framed (95 % according to an expert guess[10] reported in Jungbluth et al. (2010)). It is assumed that all CdTe modules are delivered unframed and that all micro-Si and CIS PV modules are framed. Tab. 3.2 shows the European technology mix of the different photovoltaic technologies (mono-Si, multi-Si, micro-Si, CdTe and CIGS) and module types (framed or unframed) based on data shown in Tab. 3.1.

Tab. 3.2 European photovoltaic technology mix based on FHI-ISE (2013)[9] and further information (see text) distinguishing technology and module type (framed/unframed)

Technology	Module type	PV production in MWp	Share	Producer / Product
mono-Si	framed	11'495	38.4%	Yingli PANDA, YLSYS800 & generic
	unframed	605	2.0%	generic
multi-Si	framed	12'825	42.9%	Yingli YGE Series & generic
	unframed	675	2.3%	generic
micro-Si	framed	1'350	4.5%	Oerlikon / Tel Solar
	unframed	-	0.0%	Oerlikon / Tel Solar
CdTe	framed	-	0.0%	First solar, Belectrict & generic
	unframed	1'900	6.4%	First solar, Belectrict & generic
CIGS	framed	1'050	3.5%	Solar frontier & generic
	unframed	-	0.0%	Solar frontier & generic
Total		29'900	100.0%	

3.2.2 Bill of materials

The materials photovoltaic modules usually consist of are compiled in Tab. 3.3. The average module per technology is modelled using specific data from de Wild-Scholten (2014; mono-Si, multi-Si and CIS), Flury et al. (2012; micro-Si), First Solar (CdTe) and Itten and Frischknecht (2014; mono-Si, multi-Si, CIS and CdTe). In

[10] Personal communication Pius Hüsser, Nova Energie, Switzerland, 16.12.2006.

addition, generic data available from ecoinvent data v2.2+ (KBOB et al. 2014), Frischknecht et al. (2015a) and Jungbluth et al. (2012) were used.

The bill of materials is shown per square meter of module and relative to the total mass of the input materials of the unframed laminate. It is based on the weight of the materials used in manufacturing PV modules as listed in the life cycle inventories (LCI) of the different PV technologies. The losses (due to breakage, cutting) are included but not explicitly listed in the LCIs. The materials used in the mounting system and in the electric installation as well as working material inputs are not included in the bill of materials.

The rated power per square meter of module is reported in Frischknecht and Itten (2014). Continuous progress is being made in increasing the module conversion efficiency. The rated power of current PV modules is therefore likely to be higher than indicated in Tab. 3.3.

Tab. 3.3 Bill of materials of different types of photovoltaic modules (laminate/unframed and panel/framed) based on the input materials excluding working materials, given in relative terms. The total mass of the input materials of the unframed module (laminate) corresponds to 100 %. Sources: KBOB (2014), Frischknecht et al. (2015a), Jungbluth et al. (2012), de Wild-Scholten (2014), Flury et al. (2012), First Solar, Itten & Frischknecht (2014)

Material				Photovoltaic module (laminate / unframed and panel / framed)				
				Mono-Si	Multi-Si	Micro-Si	CdTe	CI(G)S
Source				Frischknecht et al. 2015	Frischknecht et al. 2015	Flury et al. 2012	Frischknecht et al. 2015	Frischknecht et al. 2015
Laminate / unframed	Subtotal wafer / semiconductor			10.2%	6.2%	0.2%	0.2%	0.1%
	Wafer / semiconductor	silicon, production mix, photovoltaics, at plant	silicon for photovoltaics	10.2%	6.2%	0.0%	0.0%	0.0%
		silane, at plant	silane	0.0%	0.0%	0.2%	0.0%	0.0%
		indium, at regional storage	indium	0.0%	0.0%	0.0%	0.0%	0.0%
		cadmium telluride, semiconductor-grade, at plant	cadmium telluride	0.0%	0.0%	0.0%	0.1%	0.0%
		cadmium sulphide, semiconductor-grade, at plant	cadmium sulphide	0.0%	0.0%	0.0%	0.0%	0.0%
		gallium, semiconductor-grade, at regional storage	gallium	0.0%	0.0%	0.0%	0.0%	0.0%
		selenium, at plant	selenium	0.0%	0.0%	0.0%	0.0%	0.0%
		Further semiconductor materials (to be specified)	nn	0.0%	0.0%	0.0%	0.0%	0.0%
	Subtotal metals			1.5%	1.5%	0.1%	0.1%	0.5%
	Metals	aluminium, primary, at plant	aluminium	0.4%	0.4%	0.0%	0.0%	0.3%
		copper, at regional storage	copper	0.9%	0.9%	0.1%	0.1%	0.1%
		lead, at regional storage	lead	0.0%	0.0%	0.0%	0.0%	0.0%
		molybdenum, at regional storage	molybdenum	0.0%	0.0%	0.0%	0.0%	0.0%
		silver, at regional storage	silver	0.1%	0.1%	0.0%	0.0%	0.0%
		tin, at regional storage	tin	0.1%	0.1%	0.0%	0.0%	0.1%
		zinc oxide, at plant	zinc oxide	0.0%	0.0%	0.0%	0.0%	0.1%
		further metals (to be specified)	nn	0.0%	0.0%	0.0%	0.0%	0.0%
	Subtotal plastics			12.7%	13.2%	3.4%	3.4%	12.2%
	Plastics	ethylvinylacetate, foil, at plant	ethylvinylacetate	7.5%	7.8%	3.2%	2.8%	5.0%
		polyvinylfluoride film, at plant	polyvinylfluoride film	1.0%	1.0%	0.0%	0.0%	0.0%
		polyvinylbutyral foil, at plant	polyvinylbutyral foil	0.0%	0.0%	0.0%	0.0%	1.3%
		polyphenylene sulfide, at plant	polyphenylene sulfide	0.0%	0.0%	0.0%	0.0%	0.6%
		polyethylene terephthalate, granulate, amorphous, at plant	polyethylene terephthalate, PET	3.0%	3.1%	0.0%	0.0%	2.3%
		polyethylene, HDPE, granulate, at plant	polyethylene, HDPE	0.2%	0.2%	0.1%	0.0%	0.3%
		glass fibre reinforced plastic, polyamide, injection moulding, at pla	glass fibre reinforced plastic, polyamide	0.0%	0.0%	0.0%	0.6%	0.0%
		silicone product, at plant	silicone product	1.0%	1.1%	0.1%	0.0%	2.7%
		Further plastics (to be specified)	nn	0.0%	0.0%	0.0%	0.0%	0.0%
	Subtotal solar glass			75.6%	79.0%	96.3%	96.3%	87.2%
	Solar glass	flat glass, uncoated, at plant	flat glass	0.0%	0.0%	0.0%	47.6%	35.4%
		solar glass, low-iron, at regional storage	solar glass	75.6%	79.0%	96.3%	48.7%	51.8%
	Further materials (to be specified)			0.0%	0.0%	0.0%	0.0%	0.0%
Panel / frame	Subtotal metals panel			18.2%	19.0%	19.2%	n.a.	14.8%
	Metals	aluminium alloy, AlMg3, at plant	aluminium alloy	18.2%	19.0%	19.2%	n.a.	14.8%
		further metals (to be specified)	nn	0.0%	0.0%	0.0%	0.0%	0.0%
Total laminate/unframed				100.0%	100.0%	100.0%	100.0%	100.0%
Total panel/framed				118.2%	119.0%	119.2%	n.a.	114.8%
Total weight in kg per square meter of unframed module				11.7	11.2	13.9	17.1	14.9
Rated power in Wp per square meter of module				151	147	100	140	108

The bill of materials of the PV module shall be based on company-specific data that cover a time period of at least one year (12 months) and presented in the PEF report according to the list of materials shown in Tab.

3.3. The working materials required in the production of the module shall not be included in the bill of materials. The material losses during module manufacturing shall be taken into account and may be included in the bill of materials. It shall be specified whether or not the bill of materials displayed in the PEF report includes or excludes the material losses during module manufacturing. It shall be specified whether the module is framed or unframed.

3.3 Functional unit and reference flow

The FU is 1 kWh (kilowatt hour) of DC electricity generated by a photovoltaic module. Tab. 3.4 defines the key aspects used to define the FU.

Tab. 3.4 Key aspects of the FU

What?	DC electrical energy measured in kWh (provided power times unit of time) at the outlet of the DC connector attached to the junction box of the PV module
How much?	1 kWh of DC electrical energy[11]
How well?	DC electrical energy at the photovoltaic module at a given voltage level
How long?	amount of DC electrical energy produced with the photovoltaic module of a given maximum power output during the service life of 30 years

The reference flow is the amount of product (i.e., photovoltaic module) needed to fulfil the defined function and shall be expressed in the maximum power output measured in kWp (kilowatt peak) under standard conditions. All quantitative input and output data collected in the study shall be calculated in relation to this reference flow.

The reference flow (kWp) is linked to the functional unit (kWh) by the inverse of the lifetime electricity production per kWp, as shown in the following equation:

$$\frac{1}{E} = \frac{1}{P_{peak} \cdot Y \cdot LT} \qquad \text{[Equation 1]}$$

where E is the PV electricity generated in kWh, P_{peak} is the maximum power output in kWp, Y is the annual yield in kWh/(kWp·a) and LT is the lifetime in a. An installed capacity of 1 kWp of photovoltaic modules yields on average 975 kWh electricity per year (average European irradiation for optimal orientation including a default linear degradation rate of 0.7 % per year; see subchapter 6.4). The total electricity production during the lifetime of 30 years (see subchapter 6.4) is 29’250 kWh/kWp. Per kWh electricity produced, photovoltaic modules with a maximum power output of 1/29’250 kWp ($3.42 \cdot 10^{-5}$ kWp) are required.

[11] Intermittency of electricity generation is not addressed since the overall amount of electricity produced over the lifetime of a PV system is considered.

3.4 System boundary

The product system of the electricity production with a photovoltaic module consists of five life cycle stages: raw material acquisition and pre-processing, distribution and storage, production of the main product, use and end of life (see Fig. 3.1). The blue boxes in the system diagram indicate processes for which company-specific data are required.

The manufacturing of PV modules shall cover raw material extraction to wafer, cell and module production in case of crystalline silicon modules, the supply chain of semiconductors (micromorphous silicon, cadmium sulphide, cadmium telluride, gallium and other materials used in thin film technologies) in case of thin film PV modules and the supply chain of carrier and connection materials (such as glass, silver, junction box and frame in case of PV panels). A more detailed depiction of the supply chain of mono-Si, multi-Si, micro-Si, CdTe and CIS / CIGS PV modules is shown in Fig. 3.2.

The product system shall also include the mounting system required to fix the PV modules on a slanted roof because its demand depends on the conversion efficiency of the module. The electric installation shall also be taken into account. The inverter and the AC cabling shall not be part of the product system. The transport of the PV modules, the mounting system and the electric installation to the place of installation of the PV system shall be included in a separate life cycle stage. The production of the main product shall comprise the assembly of the PV system. The use phase shall include electricity production and the maintenance efforts (cleaning). The end of life shall cover the transport of the PV modules to a recycling facility or to a landfill, the dismantling of the modules and the recycling / landfilling process itself.

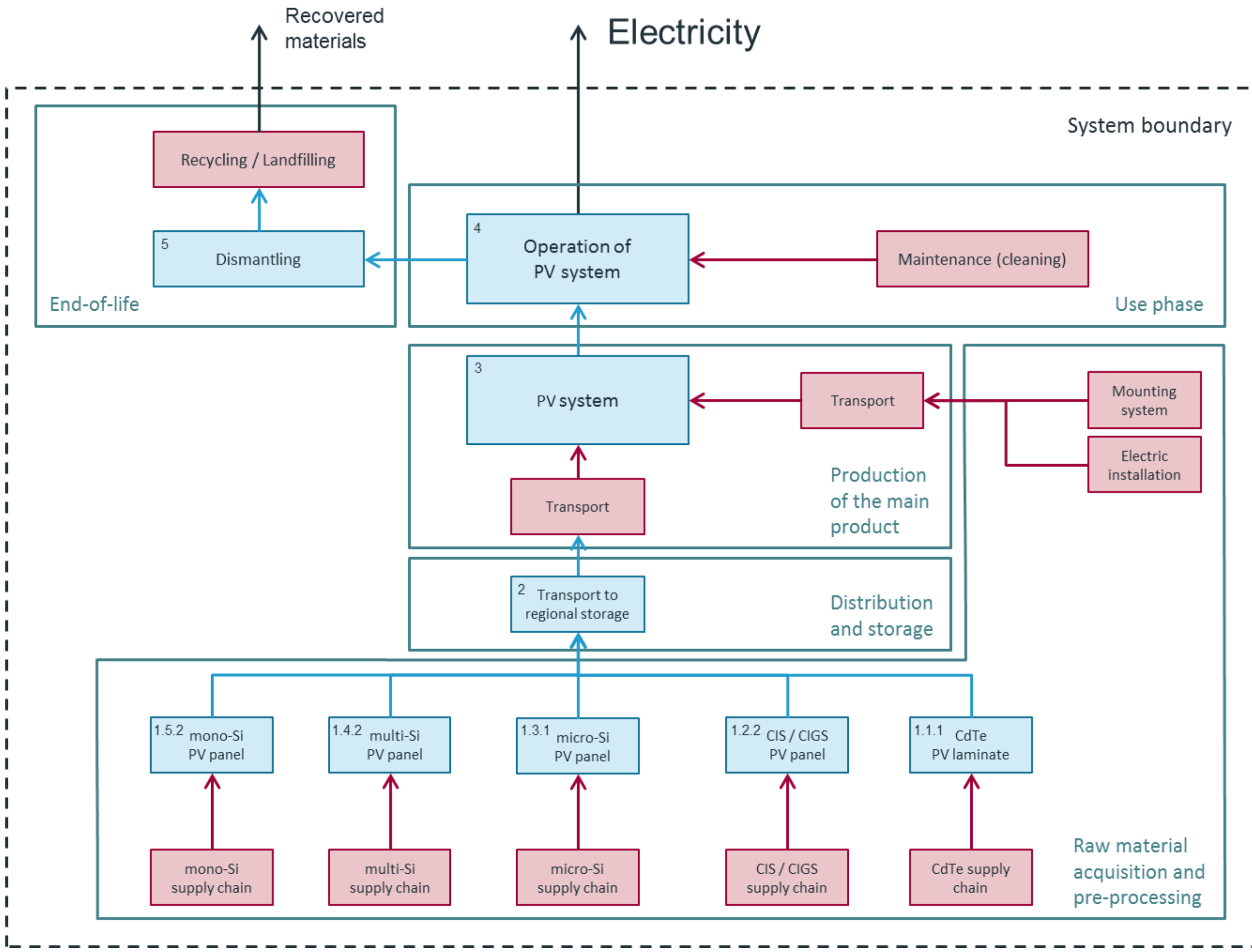

Fig. 3.1 **System Diagram: Product system of electricity produced with a photovoltaic module using mono-Si, multi-Si, micro-Si, CdTe and CIS / CIGS technology. The numbers refer to the definition of life cycle stages in Tab. 3.5 and are used in the lists of mandatory company-specific data and of processes expected to be run by the company (subchapters 5.1 and 5.2, respectively). The supply chain of the individual PV technologies is shown in more detail in Fig. 3.2. Processes to be modelled using company-specific data are shown in blue.**

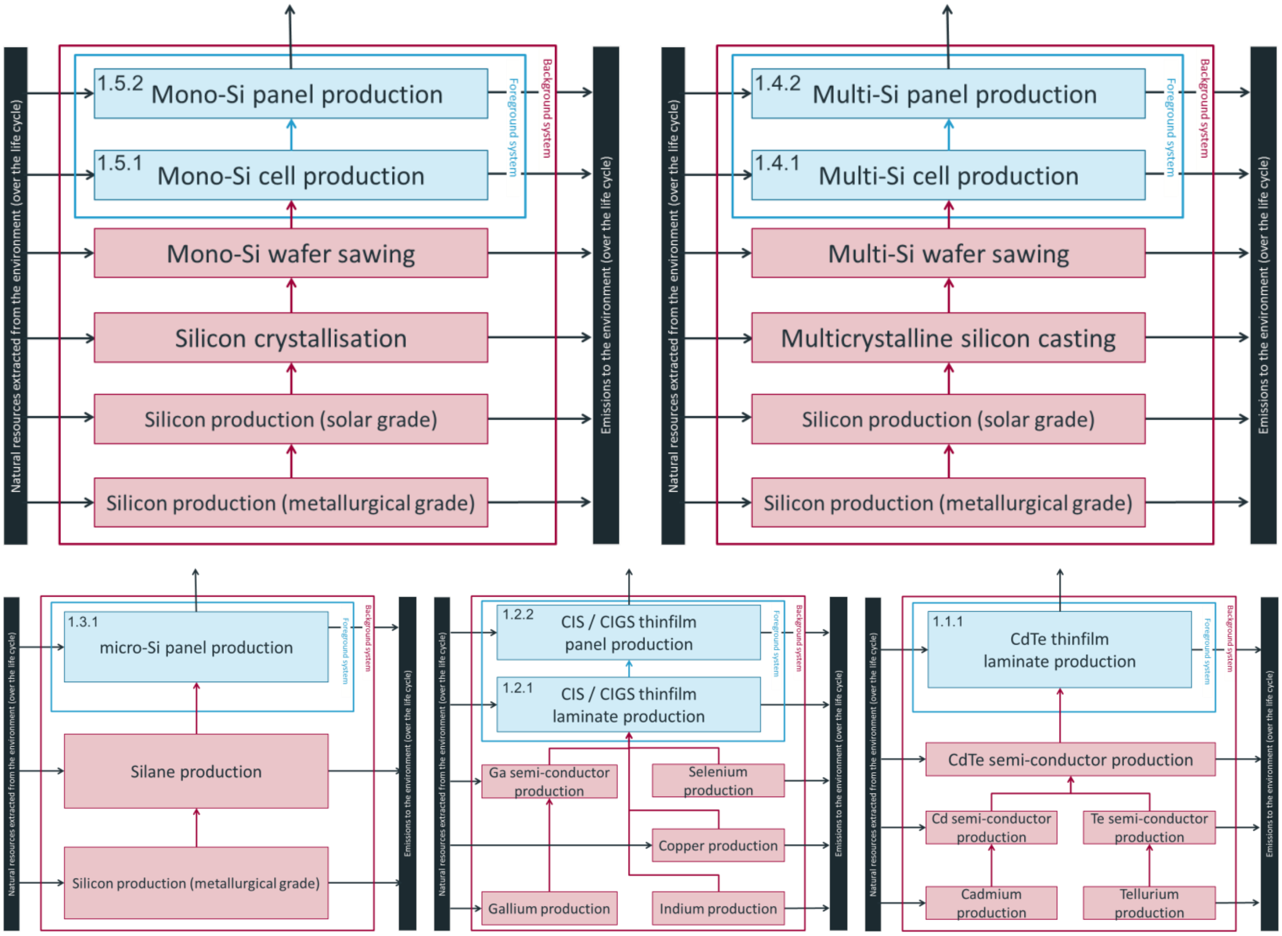

Fig. 3.2 **Excerpt of the mono-Si, multi-Si, micro-Si, CdTe and CIS / CIGS supply chain. Processes to be modelled using primary data are shown in blue. The numbers are used in the lists of mandatory company-specific data and of processes expected to be run by the company (subchapters 5.1 and 5.2, respectively).**

The life cycle stages and processes that shall be included in the system boundary are listed in Tab. 3.5.

Tab. 3.5 Life cycle stages

Life cycle stage	Short description of the processes included
1 raw material acquisition and pre-processing	Production of PV modules, mounting system and electric installation
2 product distribution and storage	Transport of PV modules, mounting system and electric installation to the place of installation of the PV system
3 production of the main product	Assembly of the PV system
4 use stage	Maintenance (cleaning) of the PV system Electricity production
5 end of life stage	Disposal / recycling of PV modules Recycling of mounting system and electric installation

According to this PEFCR, no cut-off is applicable.

Each PEF study done in accordance with this PEFCR shall provide in the PEF study a diagram indicating the organizational boundary, to highlight those activities under the control of the organization and those falling into Situation 1, 2 or 3 of the data needs matrix.

3.5 EF impact assessment

Each PEF study carried out in compliance with this PEFCR shall calculate the PEF-profile including all PEF impact categories listed in Tab. 3.6 below.

Tab. 3.6 List of the impact categories to be used to calculate the PEF profile

Impact category	Indicator	Unit	Recommended default LCIA method
Climate change[12]	Radiative forcing as Global Warming Potential (GWP100)	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)
~~- Climate change-biogenic~~			
~~- Climate change – land use and land transformation~~			
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 $_{eq}$	Steady-state ODPs 1999 as in WMO assessment
Human toxicity, cancer*	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox model (Rosenbaum et al. 2008)
Human toxicity, non- cancer*	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox model (Rosenbaum et al. 2008)
Particulate matter	Impact on human health	disease incidence	UNEP recommended model (Fantke et al. 2016)
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al. 2000)
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg $_{NMVOC\ eq}$	LOTOS-EUROS model (Van Zelm et al. 2008) as implemented in ReCiPe
Acidification	Accumulated Exceedance (AE)	mol $H+_{eq}$	Accumulated Exceedance (Seppälä et al. 2006, Posch et al. 2008)
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N_{eq}	Accumulated Exceedance (Seppälä et al. 2006, Posch et al. 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P_{eq}	EUTREND model (Struijs et al. 2009b) as implemented in ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N_{eq}	EUTREND model (Struijs et al. 2009b) as implemented in ReCiPe
Ecotoxicity, freshwater*	Comparative Toxic Unit for ecosystems (CTU_e)	CTUe	USEtox model (Rosenbaum et al. 2008)
Land use	• Soil quality index[13] • Biotic production • Erosion resistance • Mechanical filtration • Groundwater replenishment	• Dimensionless (pt) • kg biotic production[14] • kg soil • m^3 water • m^3 groundwater	• Soil quality index based on LANCA (EC-JRC)[15] • LANCA (Beck et al. 2010) • LANCA (Beck et al. 2010) • LANCA (Beck et al. 2010) • LANCA (Beck et al. 2010)
Water use**	User deprivation potential (deprivation-weighted water consumption)	m^3 world $_{eq}$	Available WAter REmaining (AWARE) (Boulay et al. 2016)
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb_{eq}	CML 2002 (Guinée et al. 2002) and (van Oers et al. 2002)

Impact category	Indicator	Unit	Recommended default LCIA method
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinée et al. 2002) and (van Oers et al. 2002)

* Long-term emissions (occurring beyond 100 years) shall be excluded from the toxicity-related impact categories. Toxicity emissions to this sub-compartment have a characterisation factor set to 0 in the EF LCIA (to ensure consistency). If included by the applicant in the LCI modelling, the sub-compartment 'unspecified (long-term)' shall be used.

** The results for water use might be overestimated and shall therefore be interpreted with caution. Some of the EF datasets tendered during the pilot phase and used in this PEFCR/OEFSR include inconsistencies in the regionalization and elementary flow implementations. This problem has nothing to do with the impact assessment method or the implementability of EF methods, but occurred during the technical development of some of the datasets. The PEFCR/OEFSR remains valid and usable. The affected EF datasets will be corrected by mid-2019. At that time it will be possible to review this PEFCR/OEFSR accordingly, if seen necessary.

The full list of normalization factors and weighting factors are available in ANNEX 1 – List of EF normalisation and weighting factors.

The full list of characterization factors (EC-JRC 2017a) is available at this link http://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.

The default impact categories shall be complemented with the additional environmental indicator listed in Tab. 3.7. The indicator nuclear waste as well as potential impacts on biodiversity are described in more detail in section 7.4.

Tab. 3.7 Additional environmental indicator to be used to complement the PEF profile

Additional environmental indicator	Indicator	Unit	LCIA method
Nuclear waste	Radiotoxicity index, RTI	m^3 HLW-eq	Frischknecht & Büsser Knöpfel 2013, 2014

3.6 Limitations

The scope of this PEFCR is limited to DC current and to one particular power plant technology, namely photovoltaics. The results of an LCA of PV DC electricity quantified based on this PEFCR allow for comparisons among different PV modules. However, they do not allow for comparisons of real installations (PV module A installed vertically on a façade versus PV module B installed optimally tilt on a rooftop), nor for comparisons

[12] The contribution of the sub-categories "Climate change – biogenic" and "Climate change – land use and land transformation" to the total climate change impacts is lower than 5 %. The environmental impacts shall therefore only be calculated for the category "Climate change" but not for the sub-categories "Climate change – biogenic" and "Climate change – land use and land transformation" (see also subchapter 5.10).

[13] This index is the result of the aggregation, performed by JRC, of the 4 indicators provided by LANCA model as indicators for land use

[14] This refers to occupation. In case of transformation the LANCA indicators are without the year (a)

[15] Forthcoming document on the update of the recommended Impact Assessment methods and factors for the EF

of a module installed in country A versus the same module installed in country B, nor for comparisons of PV electricity with electricity from wind power or the electricity mix from the current supplier. Additional calculations are necessary for these purposes and the results obtained through application of this PEFCR for a specific module technology can be considered indicative and should mainly be used for an initial assessment of a specific technology (or the assessment of development alternatives) in relation to the representative product.

The main assumptions and value judgments are related to the annual yield, the service life of the PV system and the degradation of the module.

The annual yield of the photovoltaic system depends on the location, the orientation, the degradation as well as the mounting. This dependence is very similar for all PV technologies. The scenario relevant for the PEF of PV electricity is the average yield of an optimally oriented PV module installed in Europe. This assumption determines the absolute environmental impacts per kWh of PV electricity but not the values relative to a reference PV technology.

Default values for the degradation rate should be used, because differences in published degradation rates are low and are based on historical modules (Jordan & Kurtz 2012). The application of a degradation rate differing from the default value shall be proven by independently verified tests as described in subchapter 6.4. Long-term degradation of PV modules shall be modelled as a linear function as found by Jordan and Kurtz (2012). Default values for the expected lifetime shall be used (see subchapter 6.4), because an agreed definition of the service life of modules does not exist.

Another value judgment is involved in the treatment of multi-functionality. Multi-functionality occurs for the residential scale PV system, if integrated in a slanted rooftop. However, the reference PV system is mounted on a slanted rooftop. Hence, the PV modules do not fulfil the function of roof tiles (weather protection), but only of a power plant.

The modelling of the end of life of PV modules based on current practice means that the modules shall be assumed to be disposed of in an inert material landfill as long as audited individual compliance scheme statistics, national statistics or EU statistics on the recycling of PV modules are not available (see subchapter 6.5). However, the waste electrical and electronic equipment (WEEE) directive (EU Parliament 2012) prohibits the incineration or landfilling of spent PV modules. Lab scale testing and recycling of production scrap has shown that the WEEE requirements will be met once processes are implemented on industrial scale.

The current version of the impact assessment method to be used for PEF studies shows high uncertainties in the toxicity related impact categories (human toxicity, cancer and non-cancer effects, and freshwater ecotoxicity). These impact categories are therefore temporarily excluded from the procedure to identify the most relevant impact categories, life cycle stages and processes and their results are not included in the benchmark values. A PEF study carried out in compliance with this PEFCR shall still calculate and include the characterised results for the three toxicity impact categories in the PEF report, but these results shall not be used for other communication purposes.

4 Summary of most relevant impact categories, life cycle stages and processes

4.1 Procedure and overview

The most relevant impact categories, life cycle stages and processes were identified based on the remodelled life cycle inventories of the PV product system (see chapter 6) and according to the procedure described in subchapter 7.4 of the PEFCR Guidance (European Commission 2017). For the identification of the most relevant impact categories, the normalised and weighted results per impact category (excluding toxicity related impact categories) were sorted in descending order according to their contribution. The most relevant impact categories cumulatively contribute at least 80 % to the total normalised and weighted impacts.

A similar procedure was followed to identify the most relevant life cycle stages and processes. The contributions of the different life cycle stages / processes to the characterised results of each most relevant impact category were sorted from the highest to the lowest contributing life cycle stage / process. By definition, the most relevant life cycle stages / processes cumulatively contribute at least 80 % to the characterised results in each most relevant impact category (European Commission 2017).

In the following subchapters, the most relevant impact categories, life cycle stages and processes are listed for the representative product and for each sub-category in scope of this PEFCR.

4.2 Representative product

The most relevant impact categories for the representative product (technology mix of CdTe, CIS, micro-Si, multi-Si and mono-Si PV modules) are the following:

- Particulate matter
- Climate change (sum of the sub-indicators 'Climate change - fossil', 'Climate change - biogenic' and 'Climate change - land use and land transformation')
- Resource use, fossil fuels
- Resource use, minerals and metals

The most relevant life cycle stages for the representative product are the following:

- Raw material acquisition and pre-processing
- End of life

The most relevant processes for the representative product are compiled in Tab. 4.1.

Tab. 4.1 List of the most relevant processes for the representative product (technology mix of CdTe, CIS, micro-Si, multi-Si and mono-Si PV modules)

Impact category	**Processes**
Particulate matter	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - CN (from life cycle stage raw material acquisition and pre-processing)
Climate change	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - CN (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - KR (from life cycle stage raw material acquisition and pre-processing)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity from fossil unspecified, production mix, at plant, AC, technology mix, 1kV - 60kV - DE (from life cycle stage raw material acquisition and pre-processing)
	Thermal energy from natural gas, production mix, at heat plant, technology mix regarding firing and flue gas cleaning - CN (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV , consumption mix, at consumer, AC, technology mix, 1kV - 60kV - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Steel hot dip galvanised, single route, at plant, steel sheet hot dip galvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV , consumption mix, to consumer, AC, technology mix, 1kV - 60kV - US (from life cycle stage raw material acquisition and pre-processing)
	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going - GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)

Impact category	Processes
	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA (from life cycle stage end of life)
	Aluminium extrusion, single route, at plant, primary production, aluminium extrusion, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
Resource use, fossil fuels	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - CN (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV - KR (from life cycle stage raw material acquisition and pre-processing)
	Thermal energy from natural gas, production mix, at heat plant, technology mix regarding firing and flue gas cleaning - CN (from life cycle stage raw material acquisition and pre-processing)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV , consumption mix, at consumer, AC, technology mix, 1kV - 60kV - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity from fossil unspecified, production mix, at plant, AC, technology mix, 1kV - 60kV - DE (from life cycle stage raw material acquisition and pre-processing)
	Packaging film, High barrier PE/EVOH/PE, single route, at plant, raw material production, extrusion, blowing, flattening, grammage 0.066 kg/m2 outer, 0.042 kg/m2 inner thickness 135 µm (outer film 90 µm, inner film 45 µm) - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)

Impact category	Processes
	Electricity grid mix 1kV-60kV , consumption mix, to consumer, AC, technology mix, 1kV - 60kV - US (from life cycle stage raw material acquisition and pre-processing)
	HDPE granulates, production mix, at plant, Polymerisation of ethylene, 0.91-0.96 g/cm3, 28 g/mol per repeating unit - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Thermal energy from natural gas, production mix, at heat plant, technology mix regarding firing and flue gas cleaning, MJ, 100% efficiency - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium extrusion, single route, at plant, primary production, aluminium extrusion, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going - GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)
	Steel hot dip galvanised, single route, at plant, steel sheet hot dip galvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
Resource use, minerals and metals	Copper Concentrate (Mining, mix technologies), single route, at plant, copper ore mining and processing, Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt) – GLO (from life cycle stages raw material acquisition and pre-processing and end of life)
	Metallization paste, front side, production mix, at plant, components mixing, 83% silver, 12% isopropanol, 5% lead - World (from life cycle stage raw material acquisition and pre-processing)

4.3 Sub-category cadmium-telluride PV modules

The most relevant impact categories for the sub-category cadmium-telluride PV modules in scope of this PEFCR are the following:

- Climate change (sum of the sub-indicators 'Climate change - fossil', 'Climate change - biogenic' and 'Climate change - land use and land transformation')
- Resource use, minerals and metals
- Resource use, fossil fuels
- Particulate matter
- Acidification

The most relevant life cycle stages for the sub-category cadmium-telluride PV modules in scope of this PEFCR are the following:

- Raw material acquisition and pre-processing
- Distribution and storage
- End of life

The most relevant processes for the sub-category cadmium-telluride PV modules in scope of this PEFCR are compiled in Tab. 4.2.

Tab. 4.2 List of the most relevant processes for the sub-category cadmium-telluride PV modules

Impact category	**Processes**
Climate change	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – MY (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Flat glass, uncoated, at plant, production mix, per kg flat glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going – GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)
	Steel hot dip galvanised, single route, at plant, steel sheet hot dip galvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA (from life cycle stage end of life)
Resource use, minerals and metals	Copper Concentrate (Mining, mix technologies), single route, at plant, copper ore mining and processing, Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt) – GLO (from life cycle stages raw material acquisition and pre-processing and end of life)
Resource use, fossil fuels	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – MY (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Flat glass, uncoated, at plant, production mix, per kg flat glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)

Impact category	Processes
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going – GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)
	HDPE granulates, production mix, at plant, Polymerisation of ethylene, 0.91-0.96 g/cm3, 28 g/mol per repeating unit - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Packaging film, High barrier PE/EVOH/PE, single route, at plant, raw material production, extrusion, blowing, flattening, grammage: 0.066 kg/m2 outer, 0.042 kg/m2 inner; thickness: 135 µm (outer film: 90 µm, inner film: 45 µm) - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
Particulate matter	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going – GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Flat glass, uncoated, at plant, production mix, per kg flat glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – MY (from life cycle stage raw material acquisition and pre-processing)
	Copper Concentrate (Mining, mix technologies), single route, at plant, copper ore mining and processing, Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt) – GLO (from life cycle stages raw material acquisition and pre-processing and end of life)
Acidification	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going – GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)

Impact category	Processes
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – MY (from life cycle stage raw material acquisition and pre-processing)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Flat glass, uncoated, at plant, production mix, per kg flat glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)

4.4 Sub-category copper-indium-gallium-selenide PV modules

The most relevant impact categories for the sub-category copper-indium-gallium-selenide PV modules in scope of this PEFCR are the following:

- Climate change (sum of the sub-indicators 'Climate change - fossil', 'Climate change - biogenic' and 'Climate change - land use and land transformation')
- Resource use, fossil fuels
- Resource use, minerals and metals
- Particulate matter

The most relevant life cycle stages for the sub-category copper-indium-gallium-selenide PV modules in scope of this PEFCR are the following:

- Raw material acquisition and pre-processing
- End of life

The most relevant processes for the sub-category copper-indium-gallium-selenide PV modules in scope of this PEFCR are compiled in Tab. 4.3.

Tab. 4.3 List of the most relevant processes for the sub-category copper-indium-gallium-selenide PV modules

Impact category	Processes
Climate change	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – DE (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Flat glass, uncoated, at plant, production mix, per kg flat glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Steel hot dip galvanised, single route, at plant, steel sheet hot dip galvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Nitrogen liquid production, production mix, at plant, technology mix, 100% active substance – RER (from life cycle stage raw material acquisition and pre-processing)
	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going – GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)
	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA (from life cycle stage end of life)
Resource use, fossil fuels	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – DE (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)

Impact category	Processes
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Flat glass, uncoated, at plant, production mix, per kg flat glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Nitrogen liquid production, production mix, at plant, technology mix, 100% active substance – RER (from life cycle stage raw material acquisition and pre-processing)
	Packaging film, High barrier PE/EVOH/PE, single route, at plant, raw material production, extrusion, blowing, flattening, grammage: 0.066 kg/m2 outer, 0.042 kg/m2 inner; thickness: 135 µm (outer film: 90 µm, inner film: 45 µm) - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going – GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)
	HDPE granulates, production mix, at plant, Polymerisation of ethylene, 0.91-0.96 g/cm3, 28 g/mol per repeating unit - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
Resource use, minerals and metals	Copper Concentrate (Mining, mix technologies), single route, at plant, copper ore mining and processing, Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt) – GLO (from life cycle stages raw material acquisition and pre-processing and end of life)
	Steel hot dip galvanised, single route, at plant, steel sheet hot dip galvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
Particulate matter	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going – GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)

Impact category	Processes
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Flat glass, uncoated, at plant, production mix, per kg flat glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Copper Concentrate (Mining, mix technologies), single route, at plant, copper ore mining and processing, Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt) – GLO (from life cycle stages raw material acquisition and pre-processing and end of life)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – DE (from life cycle stage raw material acquisition and pre-processing)
	Steel hot dip galvanised, single route, at plant, steel sheet hot dip galvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Pallet, wood (80x120), single route, at plant, sawing, piling, nailing, 25 kg/piece, nominal loading capacity of 1000kg - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)

4.5 Sub-category micromorphous silicon PV modules

The most relevant impact categories for the sub-category micromorphous silicon PV modules in scope of this PEFCR are the following:

- Particulate matter
- Climate change (sum of the sub-indicators 'Climate change - fossil', 'Climate change - biogenic' and 'Climate change - land use and land transformation')
- Resource use, fossil fuels
- Resource use, minerals and metals

The most relevant life cycle stages for the sub-category micromorphous silicon PV modules in scope of this PEFCR are the following:

- Raw material acquisition and pre-processing
- End of life

The most relevant processes for the sub-category micromorphous silicon PV modules in scope of this PEFCR are compiled in Tab. 4.4.

Tab. 4.4 List of the most relevant processes for the sub-category micromorphous silicon PV modules

Impact category	Processes
Particulate matter	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – CN (from life cycle stage raw material acquisition and pre-processing)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
Climate change	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – CN (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going – GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)
Resource use, fossil fuels	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – CN (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)

Impact category	Processes
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going – GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)
Resource use, minerals and metals	Copper Concentrate (Mining, mix technologies), single route, at plant, copper ore mining and processing, Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt) – GLO (from life cycle stages raw material acquisition and pre-processing and end of life)

4.6 Sub-category multicrystalline silicon PV modules

The most relevant impact categories for the sub-category multicrystalline silicon PV modules in scope of this PEFCR are the following:

- Particulate matter
- Climate change (sum of the sub-indicators 'Climate change - fossil', 'Climate change - biogenic' and 'Climate change - land use and land transformation')
- Resource use, minerals and metals
- Resource use, fossil fuels

The most relevant life cycle stages for the sub-category multicrystalline silicon PV modules in scope of this PEFCR are the following:

- Raw material acquisition and pre-processing
- End of life

The most relevant processes for the sub-category multicrystalline silicon PV modules in scope of this PEFCR are compiled in Tab. 4.5.

Tab. 4.5 List of the most relevant processes for the sub-category multicrystalline silicon PV modules

Impact category	Processes
Particulate matter	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – CN (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
Climate change	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – CN (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – KR (from life cycle stage raw material acquisition and pre-processing)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity from fossil unspecified, production mix, at plant, AC, technology mix, 1kV - 60kV – DE (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV , consumption mix, at consumer, AC, technology mix, 1kV - 60kV - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Steel hot dip galvanised, single route, at plant, steel sheet hot dip galvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Thermal energy from natural gas, production mix, at heat plant, technology mix regarding firing and flue gas cleaning - CN (from life cycle stage raw material acquisition and pre-processing)
	silicon carbide production, production mix, at plant, technology mix, 100% active substance - RER (from life cycle stage raw material acquisition and pre-processing)

Impact category	Processes
	Steel cold rolled coil, single route, at plant, blast furnace route, carbon steel - EU-28+EFTA (from life cycle stage end of life)
	Electricity grid mix 1kV-60kV , consumption mix, to consumer, AC, technology mix, 1kV - 60kV - US (from life cycle stage raw material acquisition and pre-processing)
	Aluminium extrusion, single route, at plant, primary production, aluminium extrusion, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Transoceanic ship, containers, consumption mix, to consumer, heavy fuel oil driven, cargo, 27.500 dwt payload capacity, ocean going - GLO (from life cycle stages raw material acquisition and pre-processing and distribution and storage)
Resource use, minerals and metals	Copper Concentrate (Mining, mix technologies), single route, at plant, copper ore mining and processing, Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt) – GLO (from life cycle stages raw material acquisition and pre-processing and end of life)
	Metallization paste, front side, production mix, at plant, components mixing, 83% silver, 12% isopropanol, 5% lead - World (from life cycle stage raw material acquisition and pre-processing)
Resource use, fossil fuels	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – CN (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – KR (from life cycle stage raw material acquisition and pre-processing)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)

Impact category	Processes
	Electricity grid mix 1kV-60kV , consumption mix, at consumer, AC, technology mix, 1kV - 60kV - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Packaging film, High barrier PE/EVOH/PE, single route, at plant, raw material production, extrusion, blowing, flattening, grammage: 0.066 kg/m2 outer, 0.042 kg/m2 inner; thickness: 135 µm (outer film: 90 µm, inner film: 45 µm) - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Electricity from fossil unspecified, production mix, at plant, AC, technology mix, 1kV - 60kV – DE (from life cycle stage raw material acquisition and pre-processing)
	Thermal energy from natural gas, production mix, at heat plant, technology mix regarding firing and flue gas cleaning – CN (from life cycle stage raw material acquisition and pre-processing)
	HDPE granulates, production mix, at plant, Polymerisation of ethylene, 0.91-0.96 g/cm3, 28 g/mol per repeating unit - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV , consumption mix, to consumer, AC, technology mix, 1kV - 60kV – US (from life cycle stage raw material acquisition and pre-processing)
	silicon carbide production, production mix, at plant, technology mix, 100% active substance - RER (from life cycle stage raw material acquisition and pre-processing)
	Aluminium extrusion, single route, at plant, primary production, aluminium extrusion, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Steel hot dip galvanised, single route, at plant, steel sheet hot dip galvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Metallization paste, front side, production mix, at plant, components mixing, 83% silver, 12% isopropanol, 5% lead - World (from life cycle stage raw material acquisition and pre-processing)

4.7 Sub-category monocrystalline silicon PV modules

The most relevant impact categories for the sub-category monocrystalline silicon PV modules in scope of this PEFCR are the following:

- Particulate matter
- Climate change (sum of the sub-indicators 'Climate change - fossil', 'Climate change - biogenic' and 'Climate change - land use and land transformation')
- Resource use, fossil fuels
- Resource use, minerals and metals

The most relevant life cycle stages for the sub-category monocrystalline silicon PV modules in scope of this PEFCR are the following:

- Raw material acquisition and pre-processing
- End of life

The most relevant processes for the sub-category monocrystalline silicon PV modules in scope of this PEFCR are compiled in Tab. 4.6.

Tab. 4.6 List of the most relevant processes for the sub-category monocrystalline silicon PV modules

Impact category	Processes
Particulate matter	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – CN (from life cycle stage raw material acquisition and pre-processing)
Climate change	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – CN (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – KR (from life cycle stage raw material acquisition and pre-processing)
	Thermal energy from natural gas, production mix, at heat plant, technology mix regarding firing and flue gas cleaning – CN (from life cycle stage raw material acquisition and pre-processing)
	Electricity from fossil unspecified, production mix, at plant, AC, technology mix, 1kV - 60kV – DE (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV , consumption mix, at consumer, AC, technology mix, 1kV - 60kV - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV , consumption mix, to consumer, AC, technology mix, 1kV - 60kV – US (from life cycle stage raw material acquisition and pre-processing)
	Steel hot dip galvanised, single route, at plant, steel sheet hot dip galvanization, 1.5 mm sheet thickness, 0.02 mm zinc thickness - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
Resource use, fossil fuels	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – CN (from life cycle stage raw material acquisition and pre-processing)

Impact category	**Processes**
	Aluminium ingot mix (high purity), single route, at plant, primary production, aluminium casting, 2.7 g/cm3, >99% Al - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot (silicon and magnesium main solutes), single route, at plant, primary production, aluminium casting and alloying, 2.7 g/cm3 - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Aluminium ingot mix, consumption mix, to consumer, primary production, aluminium ingot product, primary production - EU-28+EFTA (from life cycle stage end of life)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – KR (from life cycle stage raw material acquisition and pre-processing)
	Thermal energy from natural gas, production mix, at heat plant, technology mix regarding firing and flue gas cleaning – CN (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV , consumption mix, at consumer, AC, technology mix, 1kV - 60kV - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity from fossil unspecified, production mix, at plant, AC, technology mix, 1kV - 60kV – DE (from life cycle stage raw material acquisition and pre-processing)
	Solar glas, at plant, production mix, per kg solar glass - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV , consumption mix, to consumer, AC, technology mix, 1kV - 60kV – US (from life cycle stage raw material acquisition and pre-processing)
	Packaging film, High barrier PE/EVOH/PE, single route, at plant, raw material production, extrusion, blowing, flattening, grammage: 0.066 kg/m2 outer, 0.042 kg/m2 inner; thickness: 135 µm (outer film: 90 µm, inner film: 45 µm) - EU-28+EFTA (from life cycle stage raw material acquisition and pre-processing)
	Thermal energy from natural gas, production mix, at heat plant, technology mix regarding firing and flue gas cleaning, MJ, 100% efficiency - EU-28+3 (from life cycle stage raw material acquisition and pre-processing)
	Electricity grid mix 1kV-60kV, consumption mix, to consumer, AC, technology mix, 1kV - 60kV – JP (from life cycle stage raw material acquisition and pre-processing)

Impact category	Processes
Resource use, minerals and metals	Copper Concentrate (Mining, mix technologies), single route, at plant, copper ore mining and processing, Copper - gold - silver - concentrate (28% Cu; 22.3 Au gpt; 37.3 Ag gpt) – GLO (from life cycle stages raw material acquisition and pre-processing and end of life)

5 Life cycle inventory

All newly created processes shall be EF-compliant.

Sampling is allowed and shall be conducted as specified in subchapter 5.1 of this PEFCR. However, sampling is not mandatory and any applicant of this PEFCR may decide to collect data from all the plants, without performing any sampling. The data collected from different production sites shall be weighted based on the production volume of each facility, measured in m^2 of PV cells or modules on a yearly basis.

5.1 List of mandatory company-specific data

Company-specific data are required in particular for the manufacturing of PV modules (see Fig. 3.1) and may also be used to model (part of) the semiconductor material supply chain. For monocrystalline and multicrystalline silicon PV modules, company-specific data are required for cell production (see Fig. 3.2). Several companies producing crystalline silicon cells or modules are vertically integrated and have control over wafer production, silicon crystallization and partly also solar grade silicon production. Only in such cases, company-specific data shall be used for these process steps to the extent they rely on their own supply chain.

The properties of the analysed PV module, particularly the maximum power output under standard conditions and the specific weight per m^2 or Wp, usually have a significant influence on the environmental impacts of 1 kWh electricity generated by a rooftop PV system. These properties shall be taken into account by using company-specific data for the life cycle stages “distribution and storage”, “production of the main product”, “use” and “end of life”. The list of processes, for which the use of company-specific data is mandatory, is therefore more comprehensive than the list of processes expected to be run by the company applying this PEFCR (see subchapter 5.2). The mandatory company-specific data for processes that are not run by the company applying this PEFCR are limited to a few properties of the PV modules with a strong influence on the results. This means, for instance, that primary data are required to calculate the amount of mounting system needed and the mass of PV module to be disposed of. However, the production of the mounting system and the end of life treatment of PV modules do not need to be modelled with company-specific data.

At a minimum, the following processes shall be modelled with company-specific data[16]:

- Cadmium-Telluride PV modules

  1.1.1 Photovoltaic laminate, CdTe, at plant
  2 Photovoltaic laminate, CdTe, at regional storage
  3 3kWp slanted-roof installation, CdTe, laminate, mounted, on roof
  4 electricity, PV, at 3kWp slanted-roof, CdTe, laminate, mounted
  5 end of life of CdTe PV module

- Copper-Indium-Gallium-Selenide PV modules

[16] The process names in the system diagram shown in Fig. 3.1 and Fig. 3.2 are abbreviated. The numbers ensure an unambiguous assignment of the processes to be modelled with company-specific data to the process names used in the system diagram.

1.2.1 Photovoltaic laminate, CIS, at plant
1.2.2 Photovoltaic panel, CIS, at plant
2 Photovoltaic panel, CIS, at regional storage
3 3kWp slanted-roof installation, CIS, panel, mounted, on roof
4 electricity, PV, at 3kWp slanted-roof, CIS, panel, mounted
5 end of life of CIS PV module

- Micromorphous Silicon PV modules

1.3.1 Photovoltaic panel, micro-Si, at plant
2 Photovoltaic panel, micro-Si, at regional storage
3 3kWp slanted-roof installation, micro-Si, panel, mounted, on roof
4 electricity, PV, at 3kWp slanted-roof, micro-Si, panel, mounted
5 end of life of micro-Si PV module

- Multicrystalline Silicon PV modules

1.4.1 Photovoltaic cell, multi-Si, at plant
1.4.2 Photovoltaic panel, multi-Si, at plant
2 Photovoltaic panel, multi-Si, at regional storage
3 3kWp slanted-roof installation, multi-Si, panel, mounted, on roof
4 electricity, PV, at 3kWp slanted-roof, multi-Si, panel, mounted
5 end of life of multi-Si PV module

- Monocrystalline Silicon PV modules

1.5.1 Photovoltaic cell, mono-Si, at plant
1.5.2 Photovoltaic panel, mono-Si, at plant
2 Photovoltaic panel, mono-Si, at regional storage
3 3kWp slanted-roof installation, mono-Si, panel, mounted, on roof
4 electricity, PV, at 3kWp slanted-roof, mono-Si, panel, mounted
5 end of life of mono-Si PV module

The activity data to be collected and the default datasets to be used for each process are listed in the excel file named “PEFCR_PV_electricity_v1.0 - Life cycle inventory.xlsx”, sheet “company-specific data”. An example of a process that shall be modelled with company-specific data is shown in Tab. 5.1.

Tab. 5.1 List of the mandatory company-specific data to be collected for the process "3 kWp slanted-roof installation, multi-Si, panel, mounted, on roof" (example). This process represents the construction of the rooftop PV system and includes the multi-Si PV panels required for a maximum power output of 3 kWp (rejected and replaced defective PV panels over the lifetime shall be included), the slanted-roof construction and the electric installation. The electricity demand required to install the PV system and the transport of all components to the construction site shall also be considered.

Process	Requirements for data collection purposes			Requirements for modelling purposes									Most relevant process
	Activity data to be collected	Specific requirements (e.g. frequency, measurement standard, etc)	Unit of measure	Default dataset to be used	Dataset source (i.e. node)	UUID	Default Data quality parameters					Remarks	
							TiR	TeR	GR	P	DQR		
3kWp slanted-roof installation, multi-Si, panel, mounted, on roof	Inputs												
	Photovoltaic panel, multi-Si, at regional storage	Calculate the panel area required for a 3kWp PV system Use the maximum power output (kWp) under standard conditions Include a default failure rate of 3% (1% rejects, 2% replacements) if specific data are not available	m2									Use the life cycle inventory modelled with company-specific data	
	Slanted roof construction	Calculate the panel area required for a 3kWp PV system Use the maximum power output of PV panels (kWp) under standard conditions	m2	RAW MAT & PRE-PROC: slanted-roof construction, mounted, on roof	http://eplca.jrc.ec.europa.eu/EF-SDP/	d60802ed-380e-31bc-bd67-08fde7f5445c	2.0	2.0	1.0	2.0	1.8		
	Lorry transport	Calculation (mass x distance) Transport of PV panels, slanted roof construction and electric installation from the regional storage to the installation site Use a default transport distance of 100 km if specific data are not available Calculate the mass of PV panels, slanted roof construction and electric installation required Mass of slanted roof construction: 4.35 kg/m2 Mass of electric installation: 32.6 kg/p	kgkm	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3		
	Outputs												
	3kWp slanted-roof installation, multi-Si, panel, mounted, on roof		p										

Company-specific data shall cover a time period of at least one year (12 months).

In case sampling is needed to collect data from different production sites, different sub-populations shall be identified by considering the geographical distribution, the technologies applied and the production capacity of all facilities. The number of sub-populations (*Nsp*) may be identified as:

$$\mathrm{Nsp} = \mathrm{g} \cdot \mathrm{t} \cdot \mathrm{c} \qquad \text{[Equation 2]}$$

where *g* is the number of countries in which the plants are located, *t* is the number of technologies and *c* is the number of classes of plant capacity.

Once the sub-populations have been identified, for each sub-population the size of sample shall be calculated (the sub-sample size) based on the total production of the sub-population. The total production shall represent the product under analysis (e.g. total amount of multi-Si PV cells or modules produced, measured in m^2). The percentage of production to be covered by each sub-population shall not be lower than 75 %. The data collected from different production sites shall be weighted based on the production volume of each facility.

The company applying this PEFCR shall describe the sub-populations and report the percentage of the total production that is covered by the collected samples.

5.2 List of processes expected to be run by the company

The following processes are expected to be run by the company applying the PEFCR[17]:

- Cadmium-Telluride PV modules
  - 1.1.1 Photovoltaic laminate, CdTe, at plant
- Copper-Indium-Gallium-Selenide PV modules
  - 1.2.1 Photovoltaic laminate, CIS, at plant
  - 1.2.2 Photovoltaic panel, CIS, at plant
- Micromorphous Silicon PV modules
  - 1.3.1 Photovoltaic panel, micro-Si, at plant
- Multicrystalline Silicon PV modules
  - 1.4.1 Photovoltaic cell, multi-Si, at plant
  - 1.4.2 Photovoltaic panel, multi-Si, at plant
- Monocrystalline Silicon PV modules
  - 1.5.1 Photovoltaic cell, mono-Si, at plant
  - 1.5.2 Photovoltaic panel, mono-Si, at plant

[17] The process names in the system diagram shown in Fig. 3.1 and Fig. 3.2 are abbreviated. The numbers ensure an unambiguous assignment of the processes expected to be run by the company to the process names used in the system diagram.

All processes expected to be run by the company are mandatory company-specific processes (see subchapter 5.1). The processes that are expected to be run by the company applying the PEFCR are listed in the excel file named "PEFCR_PV_electricity_v1.1 - Life cycle inventory.xlsx", sheet "processes in situation 1".

5.3 Data gaps

The excel file named "PEFCR_PV_electricity_v1.1 - Life cycle inventory.xlsx", sheet "data gaps – proxies", contains a list of data gaps in the default datasets that were found in the remodelling. Some data gaps were filled by using proxy default datasets, which are listed in the same excel file.

5.4 Data quality requirements

The data quality of each dataset and the total EF study shall be calculated and reported. The calculation of the DQR shall be based on the following formula with 4 criteria:

$$\mathrm{DQR} = \frac{\overline{\mathrm{Te}_{\mathrm{R}}} + \overline{\mathrm{G}_{\mathrm{R}}} + \overline{\mathrm{Ti}_{\mathrm{R}}} + \overline{\mathrm{P}}}{4} \qquad \text{[Equation 3]}$$

where TeR is the Technological-Representativeness, GR is the Geographical-Representativeness, TiR is the Time-Representativeness, and P is the Precision/uncertainty. The representativeness (technological, geographical and time-related) characterises to what degree the processes and products selected are depicting the system analysed, while the precision indicates the way the data is derived and related level of uncertainty.

The next chapters provide tables with the criteria to be used for the semi-quantitative assessment of each criterion. If a dataset is constructed with company-specific activity data, company-specific emission data and secondary sub-processes, the DQR of each shall be assessed separately.

5.4.1 Company-specific datasets

The score of criterion P cannot be higher than 3 while the score for TiR, TeR, and GR cannot be higher than 2 (the DQR score shall be ≤1.6). The DQR shall be calculated at the level-1 disaggregation, before any aggregation of sub-processes or elementary flows is performed. The DQR of company-specific datasets shall be calculated as following:

1) Select the most relevant sub-processes and direct elementary flows that account for at least 80% of the total environmental impact of the company-specific dataset, listing them from the most contributing to the least contributing one.

2) Calculate the DQR criteria TeR, TiR, GR and P for each most relevant process and each most relevant direct elementary flow. The values of each criterion shall be assigned based on Tab. 5.2.

> 2.a) Each most relevant elementary flow consists of the amount and elementary flow naming (e.g. 40 g carbon dioxide). For each most relevant elementary flow, evaluate the 4 DQR criteria named Te_{R-EF}, Ti_{R-EF}, G_{R-EF}, P_{EF} in Tab. 5.2. It shall be evaluated for example, the timing of the flow measured, for which technology the flow was measured and in which geographical area.

2.b) Each most relevant process is a combination of activity data and the secondary dataset used. For each most relevant process, the DQR is calculated by the applicant of the PEFCR as a combination of the 4 DQR criteria for activity data and the secondary dataset: (i) Ti_R and P shall be evaluated at the level of the activity data (named Ti_{R-AD}, P_{AD} in Tab. 5.2) and (ii) Te_R, Ti_R and G_R shall be evaluated at the level of the secondary dataset used (named Te_{R-SD} , Ti_{R-SD} and G_{R-SD} in Tab. 5.2). As Ti_R is evaluated twice, the mathematical average of Ti_{R-AD} and Ti_{R-SD} represents the Ti_R of the most relevant process.

3) Calculate the environmental contribution of each most relevant process and elementary flow to the total environmental impact of all most-relevant processes and elementary flows, in % (weighted using 13 EF impact categories, with the exclusion of the 3 toxicity-related ones). For example, the newly developed dataset has only two most relevant processes, contributing in total to 80% of the total environmental impact of the dataset:

- Process 1 carries 30% of the total dataset environmental impact. The contribution of this process to the total of 80% is 37.5% (the latter is the weight to be used).
- Process 2 carries 50% of the total dataset environmental impact. The contribution of this process to the total of 80% is 62.5% (the latter is the weight to be used).

4) Calculate the Te_R, Ti_R, G_R and P criteria of the newly developed dataset as the weighted average of each criterion of the most relevant processes and direct elementary flows. The weight is the relative contribution (in %) of each most relevant process and direct elementary flow calculated in step 3.

5) The applicant of the PEFCR shall calculate the total DQR of the newly developed dataset using the equation 4, where $\overline{Te_R}, \overline{G_R}, \overline{Ti_R}, \overline{P}$ are the weighted average calculated as specified in point 4).

$$DQR = \frac{\overline{Te_R}+\overline{G_R}+\overline{Ti_R}+\overline{P}}{4} \quad \text{[Equation 4]}$$

NOTE: in case the newly developed dataset has most relevant processes filled in by non-EF compliant datasets (and thus without DQR), then these datasets cannot be included in step 4 and 5 of the DQR calculation. (1) The weight of step 3 shall be recalculated for the EF-compliant datasets only. Calculate the environmental contribution of each most-relevant EF compliant process and elementary flow to the total environmental impact of all most-relevant EF compliant processes and elementary flows, in %. Continue with step 4 and 5. (2) The weight of the non-EF compliant dataset (calculated in step 3) shall be used to increase the DQR criteria and total DQR accordingly. For example:

- Process 1 carries 30% of the total dataset environmental impact and is ILCD entry level compliant. The contribution of this process to the total of 80% is 37.5% (the latter is the weight to be used).
- Process 2 carries 50% of the total dataset environmental impact and is EF compliant. The contribution of this process to all most-relevant EF compliant processes is 100%. The latter is the weight to be used in step 4.
- After step 5, the parameters $\overline{Te_R}, \overline{G_R}, \overline{Ti_R}, \overline{P}$ and the total DQR shall be multiplied with 1.375.

Tab. 5.2 How to assess the value of the DQR criteria for datasets with company-specific information

	P_{EF} and P_{AD}	TiR_{-EF} and TiR_{-AD}	TiR_{-SD}	TeR_{-EF} and TeR_{-SD}	GR_{-EF} and GR_{-SD}
1	Measured / calculated and externally verified	The data refers to the most recent annual administration period with respect to the EF report publication date	The EF report publication date happens within the time validity of the dataset	The elementary flows and the secondary dataset reflect exactly the technology of the newly developed dataset	The data(set) reflects the exact geography where the process modelled in the newly created dataset takes place
2	Measured / calculated and internally verified, plausibility checked by reviewer	The data refers to maximum 2 annual administration periods with respect to the EF report publication date	The EF report publication date happens not later than 2 years beyond the time validity of the dataset	The elementary flows and the secondary dataset is a proxy of the technology of the newly developed dataset	The data(set) partly reflects the geography where the process modelled in the newly created dataset takes place
3	Measured / calculated / literature and plausibility not checked by reviewer OR Qualified estimate based on calculations plausibility checked by reviewer	The data refers to maximum three annual administration periods with respect to the EF report publication date	Not applicable	Not applicable	Not applicable
4-5	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable

5.5 Data needs matrix (DNM)

All processes required to model the product and outside the list of mandatory company-specific (listed in section 5.1) shall be evaluated using the Data Needs Matrix (see Tab. 5.3). The DNM shall be used by the PEFCR applicant to evaluate which data is needed and shall be used within the modelling of its PEF, depending on the level of influence the applicant (company) has on the specific process. The following three cases are found in the DNM and are explained below:

1. **Situation 1**: the process is run by the company applying the PEFCR
2. **Situation 2**: the process is not run by the company applying the PEFCR but the company has access to (company-)specific information.

3. **Situation 3**: the process is not run by the company applying the PEFCR and this company does not have access to (company-)specific information.

Tab. 5.3 Data Needs Matrix (DNM)[18]

<table>
<tr><th></th><th></th><th>Most relevant process</th><th>Other process</th></tr>
<tr><td rowspan="2">Situation 1: process run by the company applying the PEFCR</td><td>Option 1</td><td colspan="2">Provide company-specific data (as requested in the PEFCR) and create a company specific dataset partially disaggregated at least at level 1 (DQR ≤1.6).
Calculate the DQR values (for each criteria + total)</td></tr>
<tr><td>Option 2</td><td></td><td>Use default secondary dataset in PEFCR, in aggregated form (DQR ≤3.0).
Use the default DQR values</td></tr>
<tr><td rowspan="3">Situation 2: process <u>not</u> run by the company applying the PEFCR but with access to (company-)specific information</td><td>Option 1</td><td colspan="2">Provide company-specific data (as requested in the PEFCR) and create a company specific dataset partially disaggregated at least at level 1 (DQR ≤1.6).
Calculate the DQR values (for each criteria + total)</td></tr>
<tr><td>Option 2</td><td>Use company-specific activity data for transport (distance), and substitute the sub-processes used for electricity mix and transport with supply-chain specific PEF compliant datasets (DQR ≤3.0).*
Re-evaluate the DQR criteria within the product specific context</td><td></td></tr>
<tr><td>Option 3</td><td></td><td>Use company-specific activity data for transport (distance), and substitute the sub-processes used for electricity mix and transport with supply-chain specific PEF compliant datasets (DQR ≤4.0).
Use the default DQR values</td></tr>
<tr><td rowspan="2">Situation 3: process <u>not</u> run by the company applying the PEFCR and <u>without</u> access to (company)-specific information</td><td>Option 1</td><td>Use default secondary dataset, in aggregated form (DQR ≤3.0).
Re-evaluate the DQR criteria within the product specific context</td><td></td></tr>
<tr><td>Option 2</td><td></td><td>Use default secondary dataset in PEFCR, in aggregated form (DQR ≤4.0)
Use the default DQR values</td></tr>
</table>

*Disaggregated datasets shall be used.

[18] The options described in the DNM are not listed in order of preference.

5.5.1 Processes in situation 1

For each process in situation 1 there are two possible options:

- The process is in the list of most relevant processes as specified in the PEFCR or is not in the list of most relevant process, but still the company wants to provide company specific data (option 1);
- The process is not in the list of most relevant processes and the company prefers to use a secondary dataset (option 2).

Situation 1/Option 1

For all processes run by the company and where the company applying the PEFCR uses company-specific data, the DQR of the newly developed dataset shall be evaluated as described in section 5.4.1.

Situation 1/Option 2

For the non-most relevant processes only, if the applicant decides to model the process without collecting company-specific data, then the applicant shall use the secondary dataset listed in the PEFCR together with its default DQR values listed here.

If the default dataset to be used for the process is not listed in the PEFCR, the applicant of the PEFCR shall take the DQR values from the metadata of the original dataset.

5.5.2 Processes in situation 2

When a process is not run by the company applying the PEFCR, but there is access to company-specific data, then there are two possible options:

- The company applying the PEFCR has access to extensive supplier-specific information and wants to create a new EF-compliant dataset[19] (Option 1);
- The company has some supplier-specific information and wants to make some minimum changes (Option 2).
- The process is not in the list of most relevant processes and the company prefers to use a secondary dataset (Option 3).

Situation 2/Option 1

For all processes run by the company and where the company applying the PEFCR uses company-specific data, the DQR of the newly developed dataset shall be evaluated as described in section 5.4.1.

[19] The review of the newly created dataset is optional.

Situation 2/Option 2

Company-specific activity data for transport are used and the sub-processes used for electricity mix and transport with supply-chain specific PEF compliant datasets are substituted starting from the default secondary dataset provided in the PEFCR.

Please note that the PEFCR lists all dataset names together with the UUID of their aggregated dataset. For this situation, the disaggregated version of the dataset is required.

The applicant of the PEFCR shall make the DQR values of the dataset used context-specific by re-evaluating Te_R and Ti_R using the table(s) provided. The criteria G_R shall be lowered by 30%[20] and the criteria P shall keep the original value.

Situation 2/Option 3

For the non-most relevant processes, the applicant may use the corresponding secondary dataset listed in the PEFCR together with its DQR values.

If the default dataset to be used for the process is not listed in the PEFCR, the applicant of the PEFCR shall take the DQR values from the original dataset.

[20] In situation 2, option 2 it is proposed to lower the parameter G_R by 30% in order to incentivize the use of company-specific information and reward the efforts of the company in increasing the geographic representativeness of a secondary dataset through the substitution of the electricity mixes and of the distance and means of transportation.

Tab. 5.4 How to assess the value of the DQR criteria when secondary datasets are used

	TiR	TeR	G_R
1	The EF report publication date happens within the time validity of the dataset	The technology used in the EF study is exactly the same as the one in scope of the dataset	The process modelled in the EF study takes place in the country the dataset is valid for
2	The EF report publication date happens not later than 2 years beyond the time validity of the dataset	The technologies used in the EF study is included in the mix of technologies in scope of the dataset	The process modelled in the EF study takes place in the geographical region (e.g. Europe) the dataset is valid for
3	The EF report publication date happens not later than 4 years beyond the time validity of the dataset	The technologies used in the EF study are only partly included in the scope of the dataset	The process modelled in the EF study takes place in one of the geographical regions the dataset is valid for
4	The EF report publication date happens not later than 6 years beyond the time validity of the dataset	The technologies used in the EF study are similar to those included in the scope of the dataset	The process modelled in the EF study takes place in a country that is not included in the geographical region(s) the dataset is valid for, but sufficient similarities are estimated based on expert judgement
5	The EF report publication date happens later than 6 after the time validity of the dataset	The technologies used in the EF study are different from those included in the scope of the dataset	The process modelled in the EF study takes place in a different country than the one the dataset is valid for

5.5.3 Processes in situation 3

When a process is not run by the company applying the PEFCR and the company does not have access to company-specific data, there are two possible options:

- It is in the list of most relevant processes (situation 3, option 1)
- It is not in the list of most relevant processes (situation 3, option 2)

Situation 3/Option 1

In this case, the applicant of the PEFCR shall make the DQR values of the dataset used context-specific by re-evaluating Te_R, Ti_R and G_R, using the table(s) provided. The criteria P shall keep the original value.

Situation 3/Option 2

For the non-most relevant processes, the applicant shall use the corresponding secondary dataset listed in the PEFCR together with its DQR values listed.

If the default dataset to be used for the process is not listed in the PEFCR, the applicant of the PEFCR shall take the DQR values from the original dataset.

5.6 Which datasets to use?

The secondary datasets to be used by the applicant are those listed in this PEFCR. Whenever a dataset needed to calculate the PEF-profile is not among those listed in this PEFCR, then the applicant shall choose between the following options (in hierarchical order):

- Use an EF-compliant dataset available on one of the following nodes:
    - http://lcdn.thinkstep.com/Node
    - http://eplca.jrc.ec.europa.eu/EF-node/
    - http://lcdn.blonkconsultants.nl/Node/
    - http://ecoinvent.lca-data.com
    - http://lcdn-cepe.org
    - https://lcdn.quantis-software.com/PEF/
- Use an EF-compliant dataset available in a free or commercial source;
- Use another EF-compliant dataset considered to be a good proxy. In such case this information shall be included in the "limitation" section of the PEF report.
- Use an ILCD-entry level-compliant dataset. In such case this information shall be included in the "data gap" section of the PEF report.

5.7 How to calculate the average DQR of the study

In order to calculate the average DQR of the EF study, the applicant shall calculate separately the TeR, TiR, GR and P for the EF study as the weighted average of all most relevant processes, based on their relative environmental contribution to the total single score (excluding the 3 toxicity-related ones). The calculation rules explained in chapter 5.4 shall be used.

5.8 Allocation rules

There is one instance in the crystalline silicon PV supply chain, where a multiproduct process occurs. Cuttings (circular segments) from monocrystalline wafer production are fed into multicrystalline silicon casting. The cradle to gate efforts and environmental impacts of the supply of solar grade silicon used in Czochralski monocrystalline production shall be fully allocated to the monocrystalline silicon wafers. This allocation complies with internal book-keeping standards. According to these standards the costs for the feedstock (polysilicon), which is turned to cutting waste (and used in multicrystalline silicon PV modules), is attributed to the monocrystalline silicon wafers. The (internal) recycling efforts and environmental impacts required to prepare the cuttings for an input into the multicrystalline casting process shall fully be allocated to the multicrystalline silicon wafers.

Tab. 5.5 Allocation rules

Process	Allocation rule	Modelling instructions
single-Si wafer, photovoltaics, at plans	Allocation according to internal book-keeping standards.	The cuttings are considered as waste and the supply chain impacts related to these cuttings shall be fully allocated to the production of monocrystalline silicon wafers.
silicon, multi-Si, casted, at plant	Allocation according to internal book-keeping standards.	The cuttings from monocrystalline wafer production are burden-free. The recycling efforts to prepare the cuttings for use in the multicrystalline silicon casting process shall be fully allocated to the multicrystalline silicon wafers.

5.9 Electricity modelling

The guidelines in this section shall only be used for the processes where company-specific information is collected (situation 1 / Option 1 & 2 / Option 1 of the DNM).

The following electricity mix shall be used in hierarchical order:

(i) Supplier-specific electricity product shall be used if:
 (a) available, and
 (b) the set of minimum criteria to ensure the contractual instruments are reliable is met.

(ii) The supplier-specific total electricity mix shall be used if:
 (a) available, and
 (b) the set of minimum criteria to ensure the contractual instruments are reliable is met.

(iii) As a last option the 'country-specific residual grid mix, consumption mix' shall be used (available at http://lcdn.thinkstep.com/Node/). Country-specific means the country in which the life cycle stage occurs. This may be an EU country or non-EU country. The residual grid mix characterizes the unclaimed, untracked or publicly shared electricity. This prevents double counting with the use of supplier-specific electricity mixes in (i) and (ii).

Note: if for a country, there is a 100% tracking system in place, case (i) shall be applied.

Note: for the use stage, the consumption grid mix shall be used.

The environmental integrity of the use of supplier-specific electricity mix depends on ensuring that contractual instruments (for tracking) **reliably and uniquely convey claims to consumers**. Without this, the PEF lacks the accuracy and consistency necessary to drive product/corporate electricity procurement decisions and accurate consumer (buyer of electricity) claims. Therefore, a set of minimum criteria that relate to the integrity of the contractual instruments as reliable conveyers of environmental footprint information has been identified. They represent the minimum features necessary to use supplier-specific mix within PEF studies.

Set of minimal criteria to ensure contractual instruments from suppliers:

A supplier-specific electricity product/mix may only be used when the applicant ensures that any contractual instrument meets the criteria specified below. If contractual instruments do not meet the criteria, then 'country-specific residual grid mix, consumption mix' shall be used in the modelling.

A contractual instrument used for electricity modelling shall:

1. Convey attributes:
    - Convey the energy type mix associated with the unit of electricity produced.
    - The energy type mix shall be calculated based on delivered electricity, incorporating certificates sourced and retired on behalf of its customers. Electricity from facilities for which the attributes have been sold off (via contracts or certificates) shall be characterized as having the environmental attributes of the country residual consumption mix where the facility is located.
2. Be a unique claim:
    - Be the only instruments that carry the environmental attribute claim associated with that quantity of electricity generated.
    - Be tracked and redeemed, retired, or cancelled by or on behalf of the company (e.g. by an audit of contracts, third-party certification, or may be handled automatically through other disclosure registries, systems, or mechanisms).
3. Be as close as possible to the period to which the contractual instrument is applied.

Modelling 'country-specific residual grid mix, consumption mix':

Datasets for residual grid mix, per energy type, per country and per voltage have been purchased by the European Commission and are available in the dedicated node (http://lcdn.thinkstep.com/Node/). In case the necessary dataset is not available, an alternative dataset shall be chosen according to the procedure described in section 5.6. If no dataset is available, the following approach may be used:

Determine the country consumption mix (e.g. X% of MWh produced with hydro energy, Y% of MWh produced with coal power plant) and combine them with LCI datasets per energy type and country/region (e.g. LCI dataset for the production of 1MWh hydro energy in Switzerland):

- Activity data related to non-EU country consumption mix per detailed energy type shall be determined based on:
    - Domestic production mix per production technologies
    - Import quantity and from which neighbouring countries
    - Transmission losses
    - Distribution losses
    - Type of fuel supply (share of resources used, by import and / or domestic supply)

  These data may be found in the publications of the International Energy Agency (IEA).

- Available LCI datasets per fuel technologies in the node. The LCI datasets available are generally specific to a country or a region in terms of:
    - Fuel supply (share of resources used, by import and / or domestic supply),
    - Energy carrier properties (e.g. element and energy contents)
    - Technology standards of power plants regarding efficiency, firing technology, flue-gas desulphurisation, NOx removal and de-dusting.

Allocation rules:

Wherever possible, allocation should be avoided by subdivision of the process system. This means for instance, that the electricity demand of a production plant producing several products should be measured separately for each process or product. If this is not possible, the allocation rules for electricity described in Tab. 5.6 shall be followed. The allocation used shall be documented in the PEF report.

Tab. 5.6 Allocation rules for electricity

Process	Physical relationship	Modelling instructions
PV cell production	Area (m^2 of PV cells)	The allocation of the electricity consumption of a specific production plant shall be based on the total amount of PV cells produced at this site, measured in m^2 on a yearly basis.
PV module production	Area (m^2 of PV modules)	The allocation of the electricity consumption of a specific production plant shall be based on the total amount of PV modules produced at this site, measured in m^2 on a yearly basis.
PV cell and module production in the same plant	Area (m^2 of PV cells and modules), weighted by the default specific electricity consumption per m^2	The allocation of the electricity consumption of a specific production plant shall be based on the total amount of PV cells and modules produced at this site, measured in m^2 on a yearly basis. The areas of PV cells and modules produced shall be weighted based on the specific electricity consumption per m^2 (outer dimensions including production losses) according to the default datasets created in the remodelling (cells: 51.8 MJ/m^2; modules: 13.4 MJ/m^2). The following formulae shall be used to calculate the allocation factors (AF): $AF_{cells}=\frac{Production_{cells}[m^2]\cdot 51.8\frac{MJ}{m^2}}{Production_{cells}[m^2]\cdot 51.8\frac{MJ}{m^2}+Production_{modules}[m^2]\cdot 13.4\frac{MJ}{m^2}}$ $AF_{modules}=\frac{Production_{modules}[m^2]\cdot 13.4\frac{MJ}{m^2}}{Production_{cells}[m^2]\cdot 51.8\frac{MJ}{m^2}+Production_{modules}[m^2]\cdot 13.4\frac{MJ}{m^2}}$
PV modules at regional storage	Not applicable	The actual European supply mix of PV modules shall be used if several production plants exist. The share of each plant shall be determined based on the amount of PV modules supplied to Europe, measured in m^2 on a yearly basis.

If the consumed electricity comes from more than one electricity mix, each mix source shall be used in terms of its proportion in the total kWh consumed. For example, if a fraction of this total kWh consumed is coming from a specific supplier a supplier-specific electricity mix shall be used for this part. See below for on-site electricity use.

A specific electricity type may be allocated to one specific product in the following conditions:

a. The production (and related electricity consumption) of a product occurs in a separate site (building), the energy type physical related to this separated site may be used.
b. The production (and related electricity consumption) of a product occurs in a shared space with specific energy metering or purchase records or electricity bills, the product specific information (measure, record, bill) may be used.
c. All the products produced in the specific plant are supplied with a public available PEF study. The company who wants to make the claim shall make all PEF studies available. The allocation rule applied shall be described in the PEF study, consistently applied in all PEF studies connected to the site and verified. An example is the 100% allocation of a greener electricity mix to a specific product.

On-site electricity generation:

If on-site electricity production is equal to the site own consumption, two situations apply:

- No contractual instruments have been sold to a third party: the own electricity mix (combined with LCI datasets) shall be modelled.
- Contractual instruments have been sold to a third party: the 'country-specific residual grid mix, consumption mix' (combined with LCI datasets) shall be used.

If electricity is produced in excess of the amount consumed on-site within the defined system boundary and is sold to, for example, the electricity grid, this system can be seen as a multifunctional situation. The system will provide two functions (e.g. product + electricity) and the following rules shall be followed:

- If possible, apply subdivision.
- Subdivision applies both to separate electricity productions or to a common electricity production where you can allocate based on electricity amounts the upstream and direct emissions to your own consumption and to the share you sell out of your company (e.g. if a company has a wind mill on its production site and export 30% of the produced electricity, emissions related to 70% of produced electricity should be accounted in the PEF study).
- If not possible, direct substitution shall be used. The country-specific residual consumption electricity mix shall be used as substitution[21].
- Subdivision is considered as not possible when upstream impacts or direct emissions are closely related to the product itself.

[21] For some countries, this option is a best case rather than a worst case.

5.10 Climate change modelling

The impact category 'climate change' shall be modelled considering three sub-categories:

1. Climate change – fossil: This sub-category includes emissions from peat and calcination/carbonation of limestone. The emission flows ending with '(fossil)' (e.g., 'carbon dioxide (fossil)' and 'methane (fossil)') shall be used if available.
2. Climate change – biogenic: This sub-category covers carbon emissions to air (CO_2, CO and CH_4) originating from the oxidation and/or reduction of biomass by means of its transformation or degradation (e.g. combustion, digestion, composting, landfilling) and CO_2 uptake from the atmosphere through photosynthesis during biomass growth – i.e. corresponding to the carbon content of products, biofuels or aboveground plant residues such as litter and dead wood. Carbon exchanges from native forests[22] shall be modelled under sub-category 3 (incl. connected soil emissions, derived products, residues). The emission flows ending with '(biogenic)' shall be used.

   A simplified modelling approach shall be used when modelling the foreground emissions. Only the emission 'methane (biogenic)' is modelled, while no further biogenic emissions and uptakes from atmosphere are included. When methane emissions can be both fossil or biogenic, the release of biogenic methane shall be modelled first and then the remaining fossil methane.

   Credits from biogenic carbon storage shall not be modelled since the product life cycle or part of the life cycle does not have a lifetime beyond 100 years.
3. Climate change – land use and land transformation: This sub-category accounts for carbon uptakes and emissions (CO_2, CO and CH_4) originating from carbon stock changes caused by land use change and land use. This sub-category includes biogenic carbon exchanges from deforestation, road construction or other soil activities (incl. soil carbon emissions). For native forests, all related CO_2 emissions are included and modelled under this sub-category (including connected soil emissions, products derived from native forest[23] and residues), while their CO_2 uptake is excluded. The emission flows ending with '(land use change)' shall be used.

   For land use change, all carbon emissions and removals shall be modelled following the modelling guidelines of PAS 2050:2011 (BSI 2011) and the supplementary document PAS2050-1:2012 (BSI 2012) for horticultural products. PAS 2050:2011 (BSI 2011): Large emissions of GHGs can result as a consequence of land use change. Removals as a direct result of land use change (and not as a result of long-term management practices) do not usually occur, although it is recognized that this could happen in specific circumstances. Examples of direct land use change are the conversion of land used for growing crops to industrial use or conversion from forestland to cropland. All forms of land use change that result in emissions or removals are to be included. Indirect land use change refers to such conversions of land use as a consequence of changes in

[22] Native forests – represents native or long-term, non-degraded forests. Definition adapted from table 8 in Annex V C(2010)3751 to Directive 2009/28/EC.

[23] Following the instantaneous oxidation approach in IPCC 2013 (Chapter 2).

land use elsewhere. While GHG emissions also arise from indirect land use change, the methods and data requirements for calculating these emissions are not fully developed. Therefore, the assessment of emissions arising from indirect land use change is not included.

The GHG emissions and removals arising from direct land use change shall be assessed for any input to the life cycle of a product originating from that land and shall be included in the assessment of GHG emissions. The emissions arising from the product shall be assessed on the basis of the default land use change values provided in PAS 2050:2011 Annex C, unless better data is available. For countries and land use changes not included in this annex, the emissions arising from the product shall be assessed using the included GHG emissions and removals occurring as a result of direct land use change in accordance with the relevant sections of the IPCC (2006). The assessment of the impact of land use change shall include all direct land use change occurring not more than 20 years, or a single harvest period, prior to undertaking the assessment (whichever is the longer). The total GHG emissions and removals arising from direct land use change over the period shall be included in the quantification of GHG emissions of products arising from this land on the basis of equal allocation to each year of the period.

1) Where it can be demonstrated that the land use change occurred more than 20 years prior to the assessment being carried out, no emissions from land use change should be included in the assessment.

2) Where the timing of land use change cannot be demonstrated to be more than 20 years, or a single harvest period, prior to making the assessment (whichever is the longer), it shall be assumed that the land use change occurred on 1 January of either:

- the earliest year in which it can be demonstrated that the land use change had occurred; or
- on 1 January of the year in which the assessment of GHG emissions and removals is being carried out.

The following hierarchy shall apply when determining the GHG emissions and removals arising from land use change occurring not more than 20 years or a single harvest period, prior to making the assessment (whichever is the longer):

1. where the country of production is known and the previous land use is known, the GHG emissions and removals arising from land use change shall be those resulting from the change in land use from the previous land use to the current land use in that country (additional guidelines on the calculations can be found in PAS 2050-1:2012);
2. where the country of production is known, but the former land use is not known, the GHG emissions arising from land use change shall be the estimate of average emissions from the land use change for that crop in that country (additional guidelines on the calculations can be found in PAS 2050-1:2012);
3. where neither the country of production nor the former land use is known, the GHG emissions arising from land use change shall be the weighted average of the average land use change emissions of that commodity in the countries in which it is grown.

Knowledge of the prior land use can be demonstrated using a number of sources of information, such as satellite imagery and land survey data. Where records are not available, local knowledge of prior land use can be used. Countries in which a crop is grown can be determined from import statistics, and a cut-off threshold of not less than 90% of the weight of imports may be applied. Data sources, location and timing of land use change associated with inputs to products shall be reported.

Soil carbon storage shall not be modelled, calculated and reported as additional environmental information.

The sum of the three sub-categories shall be reported.

5.11 Modelling wastes and recycled content

The waste of products used during the manufacturing, distribution, retail, the use stage or after use shall be included in the overall modelling of the life cycle of the organisation. Overall, this should be modelled and reported at the life cycle stage where the waste occurs. This section gives guidelines on how to model the end of life of products as well as the recycled content.

The Circular Footprint Formula is used to model the end of life of products as well as the recycled content and is a combination of "material + energy + disposal", i.e.:

Material: $(1-R_1)E_V + R_1 \times \left(AE_{recycled} + (1-A)E_V \times \frac{Q_{Sin}}{Q_p}\right) + (1-A)R_2 \times \left(E_{recyclingEoL} - E_V^* \times \frac{Q_{Sout}}{Q_P}\right)$

Energy: $(1-B)R_3 \times (E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec})$

Disposal: $(1-R_2-R_3) \times E_D$

With the following parameters:

A: allocation factor of burdens and credits between supplier and user of recycled materials.

B: allocation factor of energy recovery processes: it applies both to burdens and credits. It shall be set to zero for all PEF studies.

Qs_{in}: quality of the ingoing secondary material, i.e. the quality of the recycled material at the point of substitution.

Qs_{out}: quality of the outgoing secondary material, i.e. the quality of the recyclable material at the point of substitution.

Q_p: quality of the primary material, i.e. quality of the virgin material.

R_1: it is the proportion of material in the input to the production that has been recycled from a previous system.

R_2: it is the proportion of the material in the product that will be recycled (or reused) in a subsequent system. R_2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R_2 shall be measured at the output of the recycling plant.

R_3: it is the proportion of the material in the product that is used for energy recovery at EoL.

$E_{recycled}$ (E_{rec}): specific emissions and resources consumed (per functional unit) arising from the recycling process of the recycled (reused) material, including collection, sorting and transportation process.

$E_{recyclingEoL}$ (E_{recEoL}): specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting and transportation process.

E_v: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.

E^*_v: specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.

EER: specific emissions and resources consumed (per functional unit) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, …).

$E_{SE,heat}$ and $E_{SE,elec}$: specific emissions and resources consumed (per functional unit) that would have arisen from the specific substituted energy source, heat and electricity respectively.

ED: specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the EoL of the analysed product, without energy recovery.

$X_{ER,heat}$ and $X_{ER,elec}$: the efficiency of the energy recovery process for both heat and electricity.

LHV: Lower Heating Value of the material in the product that is used for energy recovery.

The default parameter values for A, R_1 and R_2 are listed in Annex C of the PEFCR Guidance (European Commission 2017). The parameters used in the remodelling are compiled in Tab. 6.10.

6 Life cycle stages

6.1 Raw material acquisition and pre-processing

The life cycle stage raw material acquisition and pre-processing shall include the manufacturing of the photovoltaic modules, the mounting system and the electric installation. The supply chain of the modules shall include the production of the modules, the cells and wafers (if applicable) and the supply chain of the materials required in the module and in manufacturing (such as working materials and process gases), including raw material extraction and refining. The supply chain of the frame (if applicable), the mounting system and the electric installation shall similarly include raw material extraction and refining.

The processes taking place in the life cycle stage raw material acquisition and pre-processing, the inputs and outputs as well as the default datasets used in the remodelling[24] are listed in the excel file named "PEFCR_PV_electricity_v1.0 - Life cycle inventory.xlsx", sheet "Raw-Materials&Pre-Processing". Processes that are expected to be run by the company applying the PEFCR are written in capital letters (see column A in the excel sheet). The applicant shall report the DQR values (for each criterion and total) for all the datasets used (see columns I-M).[25] The most relevant processes are indicated with an "X" in column O in the excel sheet. The production of CdTe PV laminates is shown in Tab. 6.1 as an example of a process included in the life cycle stage raw material acquisition and pre-processing.

[24] The remodelling aimed to link the life cycle inventories of the PV product system compiled in the original PEF screening study (Stolz et al. 2016) to the PEF compliant datasets tendered by the European Commission. The remodelled datasets were then used to calculate the benchmark values (see chapter 4) and identify the most relevant impact categories, life cycle stages and processes (see subchapter 7.1). The benchmark aggregated datasets created in the remodelling can be accessed on the JRC node http://eplca.jrc.ec.europa.eu/EF-SDP .

[25] DQR values are not available for data gaps and are therefore not included in the average DQR value of the company-specific dataset (see section 5.4.1). All data gaps shall be listed in a separate section of the PEF report (see ANNEX 2 – Check-list for the PEF study).

Tab. 6.1 **Raw material acquisition and pre-processing using the process “photovoltaic laminate, CdTe, at plant” as an example. This process represents the production of a CdTe PV laminate in Malaysia (MY) and includes all the raw materials, chemicals and process gases as well as electricity consumption and transport of the materials to the production plant. The capital letters in the process name (first column) indicate that this process is expected to be run by the company applying the PEFCR.**

Process	Process: Name	Process: Unit of measure	Default dataset: R1	Amount	Dataset	Dataset source (i.e. node)	UUID	Data quality parameters: TiR	TeR	GR	P	DQR	Remarks	Most relevant process
PHOTOVOLTAIC LAMINATE, CdTe, AT PLANT (MY)	**Inputs**													
	Electricity (MY)	MJ	0	*company-specific*	Electricity grid mix 1kV-60kV AC, technology mix consumption mix, to consumer 1kV - 60kV	http://lcdn.thinkstep.com/Node/	2d582839-51d8-4b79-ba69-00def3f999d8	1.0	1.0	1.0	2.0	1.3	Default amount: 1.09E+02	X
	Solar glass	kg	0	*company-specific*	Solar glas production mix at plant per kg solar glass	https://lcdn.quantis-software.com/PEF/	958e1761-0da6-4343-b625-c1809d054464	2.3	2.1	2.1	2.1	2.1	Default amount: 8.38E+00	X
	Flat glass tempering	kg	0	*company-specific*	Flat glas, tempering production mix at plant per kg tempered glass	https://lcdn.quantis-software.com/PEF/	392b3e79-c2cf-495e-8393-c5547733101b	2.3	2.1	2.1	2.1	2.1	Default amount: 8.38E+00	
	Flat glass (uncoated)	kg	0	*company-specific*	Flat glass, uncoated production mix at plant per kg flat glass	https://lcdn.quantis-software.com/PEF/	db079380-36a6-490b-9c2f-fe0517dd12f5	2.3	2.1	2.1	2.1	2.1	Default amount: 8.13E+00	X
	Copper	kg	0.44	*company-specific*	CFF Copper	http://eplca.jrc.ec.europa.eu/EF-SDP/	0bfe8b02-b4f0-448a-a5cb-9f8e054920f2	1.0	1.0	1.0	1.0	1.0	Default amount: 1.16E-02	
	Cadmium sulphide	kg	0	*company-specific*	Cadmium sulphide production technology mix production mix, at plant 100% active substance	http://ecoinvent.lca-data.com/	757ed4a4-1674-422d-bbee-5a4dea699f0b	1.0	2.0	2.0	2.0	1.8	Default amount: 3.52E-03	
	Cadmium telluride	kg	0	*company-specific*	Cadmium telluride production technology mix production mix, at plant 100% active substance	http://ecoinvent.lca-data.com/	8738fb3a-05a0-4df9-b4b0-b4a84b355c84	1.0	2.0	2.0	2.0	1.8	Default amount: 2.34E-02	
	Ethylene vinyl acetate (EVA)	kg	0	*company-specific*	Packaging film, High barrier PE/EVOH/PE raw material production, extrusion, blowing, flattening single route, at plant grammage: 0.066 kg/m2 outer, 0.042 kg/m2 inner; thickness: 135 µm (outer film: 90 µm, inner film: 45 µm)	http://lcdn.thinkstep.com/Node/	3bc4d696-e1ed-4ac8-b275-0630500e976c	2.0	2.0	2.0	2.0	2.0	Default amount: 4.86E-01 Packaging film PE/EVOH/PE is used as a proxy for EVA	X
	Glass fibre reinforced plastic	kg	0	*company-specific*	Glass fibres production mix at plant per kg glass fibres	https://lcdn.quantis-software.com/PEF/	20350b04-54e6-4298-9d61-c7722faa11f3	2.3	2.1	2.1	2.1	2.1	Default amount: 1.08E-01 Glass fibres are used as a proxy for glass fibre reinforced plastic	
	Silicone	kg	0	*company-specific*	Silicone, high viscosity hydrolysis and methanolysis of dimethyldichloro silane production mix, at plant >30 000 centi Poise	http://lcdn.thinkstep.com/Node/	a70cefdb-690a-42b3-ac18-6d1ebce0a997	3.0	3.0	3.0	2.0	2.8	Default amount: 3.07E-03	
	Silica sand	kg	0	*company-specific*	silica sand production technology mix production mix, at plant 100% active substance	http://ecoinvent.lca-data.com/	573168e4-8f9e-46a3-a684-6187deeea33d	1.0	2.0	2.0	2.0	1.8	Default amount: 4.68E-02	
	Tap water	kg	0	*company-specific*	Tap water technology mix at user per kg water	https://lcdn.quantis-software.com/PEF/	212b8494-a769-4c2e-8d82-9a6ef61baad7	2.4	2.0	2.0	2.0	2.1	Default amount: 2.11E+02	
	Nitrogen	kg	0	*company-specific*	Nitrogen liquid production technology mix production mix, at plant 100% active substance	http://ecoinvent.lca-data.com/	085a93bb-b5b7-4137-a8de-637b4d85a93d	1.0	1.0	1.0	2.0	1.3	Default amount: 7.32E-02	
	Helium	kg	0	3.64E-02	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Data gap	
	Nitric acid	kg	0	*company-specific*	Nitric acid production technology mix production mix, at plant 100% active substance	http://ecoinvent.lca-data.com/	153d694d-6e48-47c4-9797-ff4bb6678612	1.0	2.0	2.0	2.0	1.8	Default amount: 5.72E-02	
	Sulphuric acid	kg	0	*company-specific*	Sulphuric acid production technology mix production mix, at plant 100% active substance	http://ecoinvent.lca-data.com/	eb6abe54-7e5d-4ee4-b3f1-08c1e220ef94	5.0	1.0	1.0	2.0	2.3	Default amount: 3.93E-02	

Tab. 6.1 **Raw material acquisition and pre-processing using the process "photovoltaic laminate, CdTe, at plant" as an example. This process represents the production of a CdTe PV laminate in Malaysia (MY) and includes all the raw materials, chemicals and process gases as well as electricity consumption and transport of the materials to the production plant. The capital letters in the process name (first column) indicate that this process is expected to be run by the company applying the PEFCR. (continued)**

Process	Process: Name	Process: Unit of measure	Default dataset: R1	Amount	Dataset	Dataset source (i.e. node)	UUID	Data quality parameters: TiR	TeR	GR	P	DQR	Remarks	Most relevant process
PHOTOVOLTAIC LAMINATE, CdTe, AT PLANT (MY)	Hydrogen peroxide	kg	0	*company-specific*	Hydrogen peroxide, 50% production technology mix production mix, at plant 100% active substance	http://ecoinvent.lca-data.com/	c222168e-3bf0-4adc-800b-172f3b36a662	1.0	2.0	2.0	2.0	1.8	Default amount: 1.67E-02	
	Sodium hydroxide	kg	0	*company-specific*	Sodium hydroxide production technology mix production mix, at plant 100% active substance	http://ecoinvent.lca-data.com/	2ba49ead-4683-4671-bded-d52b80215e9e	1.0	2.0	1.0	2.0	1.5	Default amount: 4.93E-02	
	Sodium chloride	kg	0	*company-specific*	Sodium chloride powder production technology mix production mix, at plant 100% active substance	http://ecoinvent.lca-data.com/	bd92e590-afa8-430c-8089-6491c32163fb	1.0	2.0	2.0	2.0	1.8	Default amount: 4.53E-02	
	Isopropanol	kg	0	*company-specific*	isopropanol production technology mix production mix, at plant 100% active substance	http://ecoinvent.lca-data.com/	2e127b35-0c42-485e-9611-bddcdb0cab4a	1.0	2.0	2.0	2.0	1.8	Default amount: 2.08E-03	
	Chemicals organic	kg	0	9.74E-03	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Data gap	
	Chemicals inorganic	kg	0	3.76E-02	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Data gap	
	Corrugated board	kg	0	*company-specific*	Corrugated board, uncoated Kraft Pulping Process, pulp pressing and drying production mix, at plant flute thickness 0.8- 2.8 mm, R1=88%	http://lcdn.thinkstep.com/Node/	574bdb1e-2ed3-46f1-bd14-bb76f739bb71	1.0	1.0	1.0	2.0	1.3	Default amount: 5.22E-01	
	Freight train transport	kgkm	0	*company-specific*	Freight train, average (without fuel) technology mix, electricity and diesel driven, cargo consumption mix, to consumer average train, gross tonne weight 1000t / 726t payload capacity	http://lcdn.thinkstep.com/Node/	02e87631-6d70-48ce-affd-1975dc36f5be	1.0	1.0	1.0	2.0	1.3	Default amount: 5.35E+03	
	Lorry transport	kgkm	0	*company-specific*	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Default amount: 4.13E+02	
	Ship transport	kgkm	0	*company-specific*	Transoceanic ship, containers heavy fuel oil driven, cargo consumption mix, to consumer 27.500 dwt payload capacity, ocean going	http://lcdn.thinkstep.com/Node/	6ca61112-1d5b-473c-abfa-4accc66a8a63	1.0	2.0	2.0	2.0	1.8	Default amount: 2.31E+05	X
	Airplane transport	kgkm	0	*company-specific*	Cargo plane technology mix, kerosene driven, cargo consumption mix, to consumer 65 t payload	http://lcdn.thinkstep.com/Node/	1cc5d465-a12a-43da-aa86-a9c6383c78ac	2.0	2.0	1.0	2.0	1.8	Default amount: 0.00E+00	
	Photovoltaic panel factory	p	0	4.00E-06	RAW MAT & PRE-PROC: photovoltaic panel factory CdTe/p/US/I	http://eplca.jrc.ec.europa.eu/EF-SDP/	9d93c9b9-3d8e-3877-984e-ed754986c54d	2.0	3.0	1.0	3.0	2.3		
	Outputs													
	Photovoltaic laminate, CdTe, at plant (MY)	m2	0	1.00E+00										
	Plastic waste (incineration)	kg	0	*company-specific*	Waste incineration of plastics (unspecified) waste-to-energy plant with dry flue gas treatment, including transport and pre-treatment production mix, at consumer unspecified plastic waste	http://lcdn.thinkstep.com/Node/	8137b889-a1d8-4109-8aa7-e2aaee38fa5f	1.0	2.0	1.0	2.0	1.5	Default amount: 7.08E-01	
	Municipal solid waste (incineration)	kg	0	*company-specific*	Waste incineration of municipal solid waste waste-to-energy plant with dry flue gas treatment, including transport and pre-treatment production mix, at consumer municipal solid waste	http://lcdn.thinkstep.com/Node/	2f07be1f-d11a-46ac-b4f0-49c5f28b5b93	1.0	2.0	1.0	2.0	1.5	Default amount: 3.00E-02	

Transport of raw materials and intermediate products

Transport of raw materials and intermediate products to the production site shall be included.

Tab. 6.2 shows the default transport distances by train and lorry (lorry >32 t, EURO 4) for some frequently used raw materials and intermediate products. These default values may also be used to estimate default transport distances for similar products required in the supply chain of PV modules. The transport scenario of European suppliers fits best with the scenarios shown in Tab. 6.2. That is why this PEFCR deviates in this respect from the default scenario described in the PEFCR Guidance (European Commission 2017). The default transport distances shown in Tab. 6.2 shall be used in case company-specific information is not available. For transports by lorry, a default utilization ratio of 64 % shall be used if specific data are not available. This utilization ratio includes empty return trips (European Commission 2017).

For suppliers located outside Europe, the default transport scenario according to the Product Environmental Footprint Guidance should be used. This scenario includes the transport of raw materials or intermediate products between the harbour or airport and the factories in and outside Europe, which is estimated to 1’000 km by lorry (>32 t, EURO 4). The intercontinental transport to Europe occurs either by transoceanic container ship (18’000 km) or by cargo airplane (10’000 km) (European Commission 2016). If the location of the supplier is known, specific data may be used to calculate the transport distances to the production site.[26]

Air cargo shipping semi-finished products such as wafers and cells is usually very rare and shall be included according to its share in supply logistics in a three years period.

[26] The distances for transports by container ship and by airplane should be calculated using https://www.searates.com/reference/portdistance/ (accessed on 12.06.2018).

Tab. 6.2 **Means of transport and corresponding default transport distances in km for logistics (table adapted from Frischknecht et al. (2007), Tab. 4.2, p. 13).**

	Density	consumption in Europe	
	kg/m³	km train	km lorry 32t
mineral products:			
gravel / sand	2'000	-	50
cement	3'150	100	100
concrete (w/o reinforcing steel)	2'200	-	50
float glass	2'500	600	100
metals:			
steel/ cast iron	7'900	200	100
copper	8'900	200	100
aluminium	2'700	200	100
plastics:			
PVC	1'400	200	100
PE	950	200	100
PP	900	200	100
wood (from Swiss forests):			
sawn timber (softwood)	450 [1]	100	50
structural timber (softwood)	450 [1]	-	100
particle board	680 [1]	200	50
basic chemicals, inorganic (carrier substance to be considered additionally):			
caustic soda	1'045	600	100
soda (sodium carbonate)	2'532	600	100
hydrochloric acid	909	200	100
sulphuric acid	1'840	600	100
nitric acid	1'383	600	100
phosphoric acid	1'685	600	100
hydrofluoric acid	993	600	100
basic chemicals, organic:			
ethylene		600	100
naphtha		600	100
refrigerants		600	100
organ. solvents		600	100
pesticides		600	100
gases (if not produced on the spot)			
if bought in cylinders: doubling of transport distances (due to tare weight)			
oxygen		100	50
nitrogen		100	50
hydrogen		100	50
helium		100	50

Tab. 6.3 Default scenarios for the transport of raw materials and intermediate products to the production site. It is distinguished between suppliers located within Europe and suppliers located outside Europe.

Process	Process: Name	Process: Unit of measure	Default dataset: Utilization ratio	Amount	Dataset	Dataset source (i.e. node)	UUID	Data quality parameters: TiR	TeR	GR	P	DQR	Remarks	Most relevant process
Suppliers located in Europe	Lorry transport*	km	0.64	50-100 (depending on the material)	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Empty return trips are included in the default utilization ratio See also Tab. 6.2 "Means of transport and corresponding default transport distances in km for logistics"	
	Freight train transport	km	not applicable	100-600 (depending on the material)	Freight train, average (without fuel) technology mix, electricity and diesel driven, cargo consumption mix, to consumer average train, gross tonne weight 1000t / 726t payload capacity	http://lcdn.thinkstep.com/Node/	02e87631-6d70-48ce-affd-1975dc36f5be	1.0	1.0	1.0	2.0	1.3	See also Tab. 6.2 "Means of transport and corresponding default transport distances in km for logistics"	
Suppliers located outside Europe	Lorry transport*	km	0.64	1'000	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Empty return trips are included in the default utilization ratio The default distance includes the transport of raw materials or intermediate products between the harbor and the factories in and outside Europe	
	Ship transport	km	not applicable	18'000	Transoceanic ship, containers heavy fuel oil driven, cargo consumption mix, to consumer 27.500 dwt payload capacity, ocean going	http://lcdn.thinkstep.com/Node/	6ca61112-1d5b-473c-abfa-4accc66a8a63	1.0	2.0	2.0	2.0	1.8		X

* The applicant of this PEFCR shall always check the utilisation ratio applied in the default dataset and adapt it accordingly.

Packaging materials

The use and disposal of packaging materials shall be considered for the entire product system and modelled as part of the raw material acquisition stage. The raw material consumption of reusable packaging shall be calculated by dividing the actual weight of the packaging by the reuse rate. The reuse rate affects the quantity of transport that is needed per FU. The transport impact shall be calculated by dividing the one-way trip impact by the number of times this packaging is reused.

For reusable packaging pools that are owned by the company applying this PEFCR, the reuse rate should be calculated using supply-chain-specific data. Depending on the data available within the company, two different approaches may be used to calculate the reuse rate, which are described in detail in section 7.16.2 of the PEFCR Guidance (European Commission 2017). For reusable packaging from third party operated pools, the default reuse rates provided in the PEFCR Guidance shall be used, unless data of better quality are available (European Commission 2017):

- Plastic pallets: 50 trips (Nederlands Instituut voor Bouwbiologie en Ecologie 2014)[27]
- Wooden pallets: 25 trips (Nederlands Instituut voor Bouwbiologie en Ecologie 2014)[28]

Modelling the recycled content

The following formula is used to model the recycled content:

$$(1 - R_1)E_V + R_1 \times \left(AE_{recycled} + (1 - A)E_V \times \frac{Q_{Sin}}{Q_p} \right)$$

The R_1 values applied shall be supply-chain specific or default as provided in the table above, in relation with the DNM. Material-specific values based on supply market statistics are not accepted as a proxy. The applied R_1 values shall be subject to PEF study verification.

When using supply-chain specific R_1 values other than 0, traceability throughout the supply chain is necessary. The following general guidelines shall be followed when using supply-chain specific R_1 values:

- The supplier information (through e.g., statement of conformity or delivery note) shall be maintained during all stages of production and delivery at the converter.
- Once the material is delivered to the converter for production of the end products, the converter shall handle information through their regular administrative procedures.
- The converter for production of the end products claiming recycled content shall demonstrate through his management system the [%] of recycled input material into the respective end product(s).
- The latter demonstration shall be transferred upon request to the user of the end product. In case a PEF profile is calculated and reported, this shall be stated as additional technical information of the PEF profile.

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[27] The less conservative number is used.

[28] Half of plastic pallets is used as approximation.

- Company-owned traceability systems can be applied as long as they cover the general guidelines outlined above.

The default parameter values for A, R_1 and R_2 are listed in Annex C of the PEFCR Guidance (European Commission 2017). These parameters shall be used by a company applying this PEFCR if company-specific parameter values are not available. Tab. 6.10 in subchapter 6.5 shows the parameters used in the remodelling.

6.2 Distribution and storage

The transport of the photovoltaic modules from factory to a regional storage located in Europe shall be modelled within this life cycle stage. The transport from regional storage to the photovoltaic power system where the photovoltaic modules are installed shall be modelled within the life cycle stage production of the main product. If photovoltaic modules are produced in several production sites, the share of each facility in the European supply mix shall be accounted for in the life cycle stage distribution and storage.

The waste of products during the distribution and storage shall be included in the life cycle stage production of the main product. If company-specific data on the share of broken PV modules are not available, a default failure rate of 3 % shall be used. This default failure rate includes the share of rejected and defective PV modules (see subchapter 6.3 and footnote 30).

The default transport distances and means of transport shown in Tab. 6.4 should be used if specific data are not available. These transport scenarios were estimated for the crystalline silicon photovoltaics supply chain by Itten and Frischknecht (2014). Four world regions and thus four default transport routes from those regions to Europe are distinguished. Air cargo shipping of PV modules is usually very rare and shall be included according to its share in supply logistics in a three years period. In case supply-chain specific information is available for one or several transport parameters, they may be applied following the Data Needs Matrix.

The processes taking place in the life cycle stage distribution and storage, the inputs and outputs as well as the default datasets used in the remodelling are listed in the excel file named “PEFCR_PV_electricity_v1.0 - Life cycle inventory.xlsx”, sheet “Distribution&Storage”. Processes that are expected to be run by the company applying the PEFCR are written in capital letters (see column A in the excel sheet). The applicant shall report the DQR values (for each criterion and total) for all the datasets used (see columns I-M). The most relevant processes are indicated with an “X” in column O in the excel sheet. The distribution and storage of mono-Si PV panels is shown in Tab. 6.5 as an example of a process included in this life cycle stage.

Tab. 6.4 Default scenarios for the transport of photovoltaic modules from the production site to a regional storage in Europe. It is distinguished between production sites located in Europe, China, Asia & Pacific and America.

Process	Process		Default dataset					Data quality parameters						Most relevant process
	Name	Unit of measure	Utilization ratio	Amount	Dataset	Dataset source (i.e. node)	UUID	TiR	TeR	GR	P	DQR	Remarks	
Production in Europe	Lorry transport*	km	0.64	940	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Empty return trips are included in the default utilization ratio	
Production in China	Lorry transport*	km	0.64	940	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Empty return trips are included in the default utilization ratio The default distance represents the transport of raw materials or intermediate products between the harbor and the factories in and outside Europe	
	Ship transport	km	not applicable	20'000	Transoceanic ship, containers heavy fuel oil driven, cargo consumption mix, to consumer 27.500 dwt payload capacity, ocean going	http://lcdn.thinkstep.com/Node/	6ca61112-1d5b-473c-abfa-4accc66a8a63	1.0	2.0	2.0	2.0	1.8		X
Production in Asia & Pacific	Lorry transport*	km	0.64	940	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Empty return trips are included in the default utilization ratio The default distance represents the transport of raw materials or intermediate products between the harbor and the factories in and outside Europe	
	Ship transport	km	not applicable	15'550	Transoceanic ship, containers heavy fuel oil driven, cargo consumption mix, to consumer 27.500 dwt payload capacity, ocean going	http://lcdn.thinkstep.com/Node/	6ca61112-1d5b-473c-abfa-4accc66a8a63	1.0	2.0	2.0	2.0	1.8		X
Production in America	Lorry transport*	km	0.64	940	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Empty return trips are included in the default utilization ratio The default distance represents the transport of raw materials or intermediate products between the harbor and the factories in and outside Europe	
	Ship transport	km	not applicable	6'500	Transoceanic ship, containers heavy fuel oil driven, cargo consumption mix, to consumer 27.500 dwt payload capacity, ocean going	http://lcdn.thinkstep.com/Node/	6ca61112-1d5b-473c-abfa-4accc66a8a63	1.0	2.0	2.0	2.0	1.8		X

* The applicant of this PEFCR shall always check the utilisation ratio applied in the default dataset and adapt it accordingly.

Tab. 6.5 Distribution and storage using the process "photovoltaic panel, mono-Si, at regional storage" as an example. This process represents the shares of mono-Si PV modules from the production regions Europe (EU), China (CN) and Asia & Pacific (APAC) in the European supply mix and the transport to a regional storage located in Europe. The capital letters in the process name (first column) indicate that this process is expected to be run by the company applying the PEFCR.

Process	Process		Default dataset											Most relevant process
	Name	Unit of measure	R1	Amount	Dataset	Dataset source (i.e. node)	UUID	Data quality parameters					Remarks	
								TiR	TeR	GR	P	DQR		
Photovoltaic panel, mono-Si, at regional storage	**Inputs**													
	Photovoltaic panel, mono-Si, at plant (EU)	m2	0	*company-specific*									Default amount: 1.45E-01	
	Photovoltaic panel, mono-Si, at plant (CN)	m2	0	*company-specific*									Default amount: 7.96E-01	
	Photovoltaic panel, mono-Si, at plant (APAC)	m2	0	*company-specific*									Default amount: 5.88E-02	
	Freight train transport	kgkm	0	*company-specific*	Freight train, average (without fuel) technology mix, electricity and diesel driven, cargo consumption mix, to consumer average train, gross tonne weight 1000t / 726t payload capacity	http://lcdn.thinkstep.com/Node/	02e87631-6d70-48ce-affd-1975dc36f5be	1.0	1.0	1.0	2.0	1.3	Default amount: 0.00E+00	
	Lorry transport	kgkm	0	*company-specific*	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Default amount: 1.07E+04	
	Ship transport	kgkm	0	*company-specific*	Transoceanic ship, containers heavy fuel oil driven, cargo consumption mix, to consumer 27.500 dwt payload capacity, ocean going	http://lcdn.thinkstep.com/Node/	6ca61112-1d5b-473c-abfa-4accc66a8a63	1.0	2.0	2.0	2.0	1.8	Default amount: 1.91E+05	
	Airplane transport	kgkm	0	*company-specific*	Cargo plane technology mix, kerosene driven, cargo consumption mix, to consumer 65 t payload	http://lcdn.thinkstep.com/Node/	1cc5d465-a12a-43da-aa86-a9c6383c78ac	2.0	2.0	1.0	2.0	1.8	Default amount: 0.00E+00	
	Outputs													
	Photovoltaic panel, mono-Si, at regional storage	m2	0	1.00E+00										

6.3 Production of the main product

The life cycle stage production of the main product shall comprise the construction of the photovoltaic power system, which is composed of the photovoltaic modules, the mounting system and the electric installation. The transport from regional storage to the photovoltaic power system where the photovoltaic modules are installed shall also be modelled within this life cycle stage.

A PV system mounted on a slanted roof is defined as the reference system, which shall be used for a comparison of different PV modules.[29] The area of modules required for a PV system with a maximum power output of 3 kWp shall be calculated using the maximum power output measured in kilowatt peak (kWp) under standard conditions. The waste of products used during the manufacturing shall be included in the modelling by accounting for a representative share of rejected modules (delivered but not installed) and defective modules (to be replaced during the 30 years of operation).[30] The transport and mounting (if applicable) of rejected and defective modules shall also be included in the production of the main product. The disposal of the rejected and defective PV modules shall be included in the life cycle stage end of life.

The transport of the PV modules, the slanted-roof construction and the electric installation from the regional storage to the installation site shall be included using a lorry (>32 t, EURO 4) and a 100 km default distance unless specific data of sufficient quality are available (see Tab. 6.6). The amount of PV modules transported by lorries is usually limited by the sensitivity of the product. Hence, the loading area of the lorry is completely covered with flat pallets but the height of the pile of PV modules does not fill the available volume and the payload capacity of the lorry is only partly utilized. The payload for the transport of crystalline silicon (multi-Si, mono-Si) and thin-film (CdTe, CIS, micro-Si) PV modules by lorry is 16.0 t and 20.3 t, respectively.[31] Assuming that 21 % of the total distance travelled by lorries are driven with empty load (European Commission 2017) results in an average payload of 12.6 t for crystalline silicon and of 16.0 t for thin-film PV modules. With a payload capacity of 24.7 t, this corresponds to a utilization ratio of 51 % and 65 %. In case supply-chain specific information is available for one or several transport parameters, they may be applied following the Data Needs Matrix.

The processes taking place in the life cycle stage production of the main product, the inputs and outputs as well as the default datasets used in the remodelling are listed in the excel file named "PEFCR_PV_electricity_v1.0 - Life cycle inventory.xlsx", sheet "Main-Product". Processes that are expected to be run by the company applying the PEFCR are written in capital letters (see column A in the excel sheet). The applicant shall report the DQR values (for each criterion and total) for all the datasets used (see columns I-M). The most relevant processes are indicated with an "X" in column O in the excel sheet.

The construction of a 3 kWp PV system mounted on a slanted roof with CIS PV modules is shown in Tab. 6.7 as an example of a process included in the life cycle stage production of the main product.

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[29] The present PEFCR may also be applied to other PV installations such as open ground and roof-integrated PV systems.
[30] A failure rate of 3 % during the lifetime of the photovoltaic power system was applied in the PEF screening study. This failure rate represents the sum of rejected (1 %) and defective (2 %) PV modules and shall be used if company-specific data are not available.
[31] Personal communication with two large manufacturers of PV modules, 13.12.2016 and 19.12.2016.

Tab. 6.6 Default scenario for the transport of photovoltaic modules, slanted-roof construction and installation from a regional storage to the construction site.

Process	Process: Name	Unit of measure	Utilization ratio	Default dataset: Amount	Dataset	Dataset source (i.e. node)	UUID	Data quality parameters: TiR	TeR	GR	P	DQR	Remarks	Most relevant process
Crystalline silicon PV modules (mono-Si, multi-Si)	Lorry transport*	km	0.51	100	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Empty return trips are included in the default utilization ratio	
Thin-film PV modules (CdTe, CIS, micro-Si)	Lorry transport*	km	0.65	100	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Empty return trips are included in the default utilization ratio	
Mounting structure Electric installation	Lorry transport*	km	0.64	100	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Empty return trips are included in the default utilization ratio	

* The applicant of this PEFCR shall always check the utilisation ratio applied in the default dataset and adapt it accordingly.

Tab. 6.7 Production of the main product using the process "3 kWp slanted-roof installation, CIS, panel, mounted, on roof" as an example. This process represents the construction of the PV system and includes the CIS PV modules, the slanted-roof construction and the electric installation. The transport of components to the installation site and the electricity consumption are also included in this process.

Process	Process: Name	Unit of measure	R1	Default dataset: Amount	Dataset	Dataset source (i.e. node)	UUID	Data quality parameters: TiR	TeR	GR	P	DQR	Remarks	Most relevant process
3kWp slanted-roof installation, CIS, panel, mounted, on roof	**Inputs**													
	Photovoltaic panel, CIS, at regional storage	m2	0	*company-specific*									Default amount: 2.86E+01	
	Slanted roof construction	m2	0	*company-specific*	RAW MAT & PRE-PROC: slanted-roof construction, mounted, on roof	http://eplca.jrc.ec.europa.eu/EF-SDP/	d60802ed-380e-31bc-bd67-08fde7f5445c	2.0	2.0	1.0	2.0	1.8	Default amount: 2.78E+01	
	Electric installation	p	0	1.00E+00	RAW MAT & PRE-PROC: electric installation, photovoltaic plant, at plant/p/CH/I	http://eplca.jrc.ec.europa.eu/EF-SDP/	e2f75729-69b9-3a2a-b989-3e10bf2ccdf5	2.0	3.0	1.0	2.0	2.0		
	Electricity (EU)	MJ	0	1.44E-01	Residual grid mix AC, technology mix consumption mix, to consumer 1kV - 60kV	http://lcdn.thinkstep.com/Node/	8fb75312-431d-42f6-9a4f-22fa886f7fe3	1.0	1.0	1.0	2.0	1.3		
	Lorry transport	kgkm	0	*company-specific*	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Default amount: 6.11E+04	
	Outputs													
	3kWp slanted-roof installation, CIS, panel, mounted, on roof	p	0	1.00E+00										

6.4 Use stage

The use stage shall include the electricity generated with the photovoltaic power system and the water used to clean the photovoltaic modules. For reasons of comparability the three parameters annual yield, degradation rate and lifetime shall be assumed as described below. The use phase shall be modelled based on an optimally oriented module mounted on a slanted roof in Europe.

The annual yield depends on the location of installation, the mounting and orientation of the modules (façade versus rooftop, inclination and orientation), the degradation and the performance ratio of the module. Tab. 6.8 shows the cumulative installed photovoltaic power in Europe according to IEA-PVPS (2013) and the country-specific average yield at optimal angle in urban areas according to EPIA (2012). The annual average yield of optimally oriented modules in Europe weighted according to the cumulative installed photovoltaic power corresponds to 1’090 kWh/kWp (excluding degradation effects) with an average solar irradiation of 1’331 kWh/m^2. The average European yield shall be used.

Tab. 6.8 Cumulative installed photovoltaic power in Europe in 2012 according to IEA-PVPS (2013) and country specific average annual yield in kWh/kWp at optimal angle in urban areas according to EPIA (2012), and average solar irradiation at optimal angle based on data retrieved from PVGIS[32]; degradation of photovoltaic modules is not included.

Country	Cumulative installed power (MW)	Share	average yield at optimal angle in urban areas (kWh/kWp)	average solar irradiation at optimal angle (kWh/m^2)
Austria	363	0.6%	1'027	1'314
Belgium	2'698	4.2%	930	1'100
Germany	32'462	51.1%	936	1'147
Denmark	332	0.5%	945	1'130
Spain	4'706	7.4%	1'471	1'812
France	4'033	6.3%	1'117	1'386
United Kingdom	1'901	3.0%	920	1'111
Italy	16'450	25.9%	1'326	1'611
Netherlands	345	0.5%	933	1'112
Portugal	210	0.3%	1'494	1'840
Sweden	24	0.0%	826	1'101
Europe (PVPS members)	**63'524**	**100.0%**	**1'090**	**1'331**

In line with the IEA PVPS methodology guidelines (Frischknecht et al. 2015b) and the ADEME methodology guidelines (Payet et al. 2013), the lifetime of the photovoltaic power plants shall be assumed to be 30 years. A default linear degradation rate of 0.7 % per year shall be applied unless long-term scientific evidence and independently verified test results prove a different value. If a different degradation rate is applied,

[32] http://re.jrc.ec.europa.eu/pvgis/ (accessed on 29.04.2014)

supporting scientific evidence and test results shall be provided in the PEF report. The testing methods and independent verification of the results shall be done according to state-of-the-art continuous outdoor I-V and performance ratio methods (e.g. according the PVUSA and PR methods depicted in IEC Standard 61724 (IEC 1998)) or equivalent indoor measurements taken over a period of at least 10 years. Independent verification shall be done through ISO/IEC 17025 accredited testing laboratories (ISO/IEC 2005).

The initial nameplate capacity of the PV module – as printed in the data sheet – shall be used as the starting point of the degradation curve. Since measurement uncertainties on performance measurements are factored in the performance tolerance provided on the data sheet, e.g. +2.5 % / -0 %, the lower value of the nameplate capacity shall be used.

A degradation of 0.7 % per year leads to a loss in yield of 21 % during the last year of operation. Hence, the default weighted average yield of a PV module installed in Europe and operated during 30 years is 10.5 % below the average yield shown in Tab. 6.8[33]. The average annual yield of optimally oriented modules in Europe is 975 kWh per kWp when degradation is taken into account.

Annual yield as well as degradation rate of a particular PV module may differ from the values used in the screening LCA. According to Jordan & Kurtz (2012) degradation rates are higher for thin-film PV modules (1.0 % median; 1.5 % average) than for crystalline silicon modules (0.5 % median, 0.7 % average). Product specific annual yield data (at optimal angle in an urban area with 1'331 kWh/m^2 annual solar irradiation) and degradation rate may be used if based on evidence (certificates, measurements).

The use stage of PV modules includes the supply of water used for cleaning and the subsequent treatment of wastewater. A constant amount of water is used per unit area of PV modules. The area of modules needed to provide a given maximum power output depends on the module conversion efficiency. Hence, the supply and treatment of water for the cleaning of PV modules are product dependent processes.[34] The main function approach shall be applied as described in the PEFCR Guidance (European Commission 2017), i.e. the total amount of water used for cleaning the PV modules shall be included. A water use of 20 L/m^2 of PV modules shall be assumed.

The PV modules replaced during the use stage shall be included in the life cycle stage production of the main product. The disposal of the rejected and defective PV modules shall be taken into account in the end of life stage.

The processes taking place in the use stage, the inputs and outputs as well as the default datasets used in the remodelling are listed in the excel file named "PEFCR_PV_electricity_v1.0 - Life cycle inventory.xlsx", sheet "Use". Processes that are expected to be run by the company applying the PEFCR are written in capital letters (see column A in the excel sheet). The applicant shall report the DQR values (for each criterion and

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[33] 0.7 % loss per year times 30 years equals 21 % loss in the last year. A loss of 0 % in the first year and 21 % in year 30 results in an average loss of 21 % / 2 = 10.5 %.

[34] These processes were not identified as most relevant in the remodeling. The use stage contributes below 0.1 % to the total impacts in the most relevant impact categories of each sub-category. Hence, the processes of water supply and wastewater treatment have a negligible share in the total impacts.

total) for all the datasets used (see columns I-M). The most relevant processes are indicated with an “X” in column O in the excel sheet.

The electricity generation with a 3 kWp PV system mounted on a slanted roof with micro-Si PV modules is shown in Tab. 6.9 as an example of a process included in the use stage.

Tab. 6.9 Use stage using the process “electricity, PV, at 3 kWp slanted-roof, micro-Si, panel, mounted” as an example. This process represents the electricity generated by the PV system and includes the water used to clean the PV modules, the wastewater treatment and the solar energy that is converted to electricity.

Process	Process: Name	Process: Unit of measure	Default dataset: R1	Amount	Dataset	Dataset source (i.e. node)	UUID	Data quality parameters: TiR	TeR	GR	P	DQR	Remarks	Most relevant process
electricity, PV, at 3kWp slanted-roof, micro-Si, panel, mounted	**Inputs**													
	3kWp slanted-roof installation, micro-Si, panel, mounted, on roof	p	0	*company-specific*									Default amount: 1.14E-05	
	Tap water	kg	0	*company-specific*	Tap water technology mix at user per kg water	https://lcdn.quantis-software.com/PEF/	212b8494-a769-4c2e-8d82-9a6ef61baad7	2.4	2.0	2.0	2.0	2.1	Default amount: 6.84E-03	
	Solar energy	MJ	0	3.60E+00	Energy, solar, converted	All nodes	1c80d3da-b8c4-4275-a552-c96a709a11dd	n.a.	n.a.	n.a.	n.a.	n.a.	Elementary flow	
	Outputs													
	electricity, PV, at 3kWp slanted-roof, micro-Si, panel, mounted	kWh	0	1.00E+00										
	Wastewater (wastewater treatment plant)	kg	0	*company-specific*	Treatment of residential wastewater, small plant waste water treatment including sludge treatment production mix, at plant 1m3 of waste water treated	http://lcdn.thinkstep.com/Node/	8126980a-29e9-416c-991d-2aa5fdad9062	2.0	2.0	2.0	2.0	2.0	Default amount: 6.84E-03	

6.5 End of life

The end of life stage is a life cycle stage that in general includes the waste of the product in scope, such as the primary packaging or the product left at its end of use. The end of life stage shall include the dismantling of the photovoltaic module, the mounting system and the electric installation including the transport to a recycling plant. According to the waste electrical and electronic equipment (WEEE) directive (EU Parliament 2012), spent PV modules shall be treated and recycled (neither incinerated nor directly landfilled). With an expected lifetime of 30 years and installation of photovoltaic modules in significant amounts only starting a decade ago, there have been no significant volumes of end of life PV modules. Hence practical, verifiable experience on industrial scale recycling processes is missing for the majority of the technologies. However, lab scale testing and recycling of production scrap has shown that the WEEE requirements will be met once processes are implemented on industrial scale.

The end of life of PV modules shall be modelled based on current practice. Recycling of PV modules shall only be accounted for to the extent to which PV module recycling is taking place today (based on EU statistics, national statistics or individually audited statistics[35]). Otherwise the PV modules shall be assumed to be disposed of in an inert material landfill. Since statistical data on the recycling of PV modules were not available in 2017, the end of life of PV modules was modelled by the disposal on an inert material landfill in the remodelling. As there is significant uncertainty around the regulation of reuse of electricity generating equipment (especially in view of product and consumer safety), reuse of PV modules shall not be considered.

The mounting system and the electric installation are usually separated from the modules during the dismantling of PV systems. These components are then treated in a recycling plant, which allows the recovery of steel, aluminium and copper.

For reusable packaging (e.g. wooden pallets, see also subchapter 6.1), the reuse rate determines the quantity of packaging material (per product sold) to be treated at end of life. The amount of packaging treated at end of life shall be calculated by dividing the actual weight of the packaging by the number of times this packaging was reused.

The end of life shall be modelled using the formula and guidance provided in subchapter 5.11 'Modelling wastes and recycled content' of this PEFCR together with the default parameters listed in Tab. 6.10.

Before selecting the appropriate R_2 value, an evaluation for recyclability of the material shall be done and the PEF study shall include a statement on the recyclability of the materials/products. The statement on the recyclability shall be provided together with an evaluation for recyclability that includes evidence for the following three criteria (as described by ISO 14021:1999, section 7.7.4 'Evaluation methodology'):

1. The collection, sorting and delivery systems to transfer the materials from the source to the recycling facility are conveniently available to a reasonable proportion of the purchasers, potential purchasers and users of the product;

[35] Statistical data on the recycling of PV modules are not available yet. The implementation of the WEEE directive is expected to generate statistical data in the future.

2. The recycling facilities are available to accommodate the collected materials;
3. Evidence is available that the product for which recyclability is claimed is being collected and recycled.

Point 1 and 3 can be proven by recycling statistics (country specific) derived from industry associations or national bodies. Approximation to evidence at point 3 can be provided by applying for example the design for recyclability evaluation outlined in EN 13430 Material recycling (Annexes A and B) or other sector-specific recyclability guidelines if available.[36]

Following the evaluation for recyclability, the appropriate R_2 values (supply-chain specific or default) shall be used. If one criterion is not fulfilled or the sector-specific recyclability guidelines indicate a limited recyclability an R_2 value of 0% shall be applied.

Company-specific R_2 values (measured at the output of the recycling plant) shall be used when available. If no company-specific values are available and the criteria for evaluation of recyclability are fulfilled (see below), application-specific R_2 values shall be used as listed in the table below,

- If an R_2 value is not available for a specific country, then the European average shall be used.
- If an R_2 value is not available for a specific application, the R_2 values of the material shall be used (e.g. materials average).
- In case no R_2 values are available, R_2 shall be set equal to 0 or new statistics may be generated in order to assign an R_2 value in the specific situation.

The applied R_2 values shall be subject to the PEF study verification.

For secondary materials substituting primary materials, the point of substitution at level 2 shall be used (European Commission 2017).[37] Pre-consumer scrap shall be modelled according to Option 1 of the PEFCR Guidance. This means that pre-consumer scrap shall be allocated to the product system, which generated the scrap. The treatment of scrap shall be modelled in a separate process (European Commission 2017).

Tab. 6.10 shows the parameters values of the Circular Footprint Formula used in the remodelling. For steel, aluminium and copper it is distinguished between the application in the PV module and the application in the mounting system or electric installation.

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[36] E.g. the EPBP design guidelines (http://www.epbp.org/design-guidelines), or Recyclability by design (http://www.recoup.org/)

[37] Personal communication Michele Galatola, Environmental Footprint Team, European Commission, 20.12.2016.

Tab. 6.10 Parameters of the Circular Footprint Formula to be used by a company applying this PEFCR. These parameters are based on Annex C of the PEFCR Guidance (European Commission 2017). The application specific parameter values of metals used in the mounting system and the electric installation (written in italics) were amended based on the remodelling.[38]

Category	Material	Application	Parameters						
			A	B	R_1	R_2	R_3	$Q_{s,in} / Q_p$	$Q_{s,out} / Q_p$
Metals	Steel	photovoltaic panel	0.20	0	0.37	0	0	1.00	n.a.
		mounting structure	*0.20*	*0*	*0.37*	*0.95*	*0*	*1.00*	*1.00*
		electric installation	*0.20*	*0*	*0.37*	*0.95*	*0*	*1.00*	*1.00*
	Aluminum	photovoltaic panel	0.20	0	0.32	0	0	1.00	n.a.
		mounting structure	*0.20*	*0*	*0.32*	*0.95*	*0*	*1.00*	*1.00*
	Aluminum alloys	AlMg3 - photovoltaic panel	0.20	0	0.77	0	0	1.00	n.a.
	Copper	photovoltaic panel	0.20	0	0.44	0	0	1.00	n.a.
		electric installation	*0.20*	*0*	*0.44*	*0.95*	*0*	*1.00*	*1.00*
	Copper telluride	photovoltaic panel	0.20	0	0	0	0	n.a.	n.a.
	Cadmium	photovoltaic panel	0.20	0	0	0	0	n.a.	n.a.
Glass	Glass	photovoltaic panel	0.20	0	0	0	0	n.a.	n.a.

At the end of life, transports from the installation site (customer) to the end of life treatment facility shall be included. In the screening study, the transport distance of the PV modules to the inert material landfill was estimated at 200 km. If no specific information on the transport distances is available, standard distances based on expert judgments as reported in the screening LCA shall be used.

The processes taking place in the end of life stage, the inputs and outputs as well as the default datasets used in the remodelling are listed in the excel file named "PEFCR_PV_electricity_v1.0 - Life cycle inventory.xlsx", sheet "End-of-Life". Processes that are expected to be run by the company applying the PEFCR are written in capital letters (see column A in the excel sheet). The applicant shall report the DQR values (for each criterion and total) for all the datasets used (see columns I-M). The most relevant processes are indicated with an "X" in column O in the excel sheet.

The dismantling and treatment of a 3 kWp PV system mounted on a slanted roof with multi-Si PV modules is shown in Tab. 6.11 as an example of a process included in the end of life stage.

[38] Personal communication An de Schryver, Environmental Footprint Team, European Commission, 28.02.2018.

Tab. 6.11 End of life stage using the process “3 kWp slanted-roof installation, multi-Si, panel, mounted, at EoL” as an example. This process represents the dismantling of the PV system per kWh electricity produced and the electricity generation during the use stage. The recycling of aluminium, copper and steel contained in the mounting system and in the electric installation and the transport and disposal of the multi-Si PV modules on an inert material landfill are also accounted for.

Process	Process		Default dataset											Most relevant process
	Name	Unit of measure	R1	Amount	Dataset	Dataset source (i.e. node)	UUID	Data quality parameters					Remarks	
								TiR	TeR	GR	P	DQR		
end of life of multi-Si PV module	**Inputs**													
	electricity, PV, at 3kWp slanted-roof, multi-Si, panel, mounted	kWh	0	1.00E+00										
	Aluminium EoL	kg	0	*company-specific*	END-OF-LIFE: CFF Aluminum Recycling at EoL (R2)	http://eplca.jrc.ec.europa.eu/EF-SDP/	2b001f10-f4b2-47a6-8196-b00d06bd658c	2.0	1.0	1.0	2.0	1.5	Default amount: 6.60E-04	
	Copper EoL	kg	0	*company-specific*	END-OF-LIFE: CFF Copper Recycling at EoL (R2)	http://eplca.jrc.ec.europa.eu/EF-SDP/	6457cc71-4aab-4e2c-bb42-43a637d90b75	2.0	1.0	1.0	2.0	1.5	Default amount: 1.67E-04	
	Steel EoL	kg	0	*company-specific*	END-OF-LIFE: CFF Steel Recycling at EoL (R2)	http://eplca.jrc.ec.europa.eu/EF-SDP/	7587c948-dee2-4748-afed-aee051e4ea25	2.0	1.0	1.0	2.0	1.5	Default amount: 3.59E-04	
	Lorry transport	kgkm	0	*company-specific*	Articulated lorry transport, Euro 4, Total weight >32 t (without fuel) diesel driven, Euro 4, cargo consumption mix, to consumer more than 32t gross weight / 24,7t payload capacity	http://lcdn.thinkstep.com/Node/	938d5ba6-17e4-4f0d-bef0-481608681f57	1.0	1.0	1.0	2.0	1.3	Default amount: 5.37E-01	
	Outputs													
	3kWp slanted-roof installation, multi-Si, panel, mounted, at EoL	kWh	0	1.00E+00										
	Disposal of PV module (inert material landfill)	kg	0	*company-specific*	Landfill of inert material (other materials) landfill including leachate treatment and with transport without collection and pre-treatment production mix (region specific sites), at landfill site The carbon and water content are respectively of 0%C and and 0% Water (in weight %)	http://lcdn.thinkstep.com/Node/	448ab0f1-4dd6-4d85-b654-35736bb772f4	2.0	2.0	2.0	2.0	2.0	Default amount: 2.68E-03	

7 PEF results

7.1 Benchmark values

The benchmark values for the representative product (see definition in subchapter 3.2) and the individual PV technologies in scope of this PEFCR (CdTe, CIS, micro-Si, multi-Si, mono-Si) are presented in the following sections per kWh DC electricity produced by the PV system. The results of the use stage[39] are shown separately from the impacts caused in the other life cycle stages (raw material acquisition and pre-processing, distribution and storage, production of the main product, end of life).

The applicant of this PEFCR shall use the benchmark values of the sub-category (i.e. PV technology) that his product belongs to. In addition, comparisons may be made to the representative product.

7.1.1 Representative product

The characterised, normalised and weighted benchmark values for the representative product are shown in Tab. 7.1, Tab. 7.2 and Tab. 7.3, respectively.

[39] The negative values for the use stage in some impact categories arise from the treatment of water used for the cleaning of PV modules. The PEF compliant dataset "Treatment of residential wastewater, small plant; waste water treatment including sludge treatment; production mix, at plant; 1m3 of waste water treated" includes credits for the use of wet sludge as a fertilizer in agricultural applications. The negative impacts in the use stage may be overestimated by using this dataset since the amount of nutrients (N, P_2O_5, K_2O) contained in the waste water from the cleaning of PV modules is usually very small.

Tab. 7.1 **Characterised benchmark values for the representative product (technology mix of CdTe, CIS, micro-Si, multi-Si and mono-Si PV modules) per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, Technology mix, panel, mounted".**

Impact category	Unit	Life cycle excl. use stage	Use stage
Representative Product (virtual)			
Climate change	kg $CO_{2\ eq}$	5.93E-02	1.05E-05
Ozone depletion	kg CFC-11 $_{eq}$	3.47E-10	1.97E-14
Particulate matter	disease incidence	1.57E-08	-5.81E-13
Ionising radiation, human health	kBq $U^{235}{}_{eq}$	4.66E-03	5.53E-07
Photochemical ozone formation, human health	kg NMVOC $_{eq}$	1.61E-04	1.00E-08
Acidification	mol H+ $_{eq}$	2.88E-04	5.13E-09
Eutrophication, terrestrial	mol N $_{eq}$	5.90E-04	-2.19E-08
Eutrophication, freshwater	kg P $_{eq}$	4.33E-07	6.34E-09
Eutrophication, marine	kg N $_{eq}$	5.70E-05	3.45E-08
Land use	Dimensionless (pt)	3.54E-01	-5.03E-04
Water use	m^3 world $_{eq}$	2.28E-02	1.58E-04
Resource use, minerals and metals	kg Sb $_{eq}$	5.44E-07	5.24E-12
Resource use, fossils	MJ	7.36E-01	4.48E-05

Tab. 7.2 **Normalised benchmark values for the representative product (technology mix of CdTe, CIS, micro-Si, multi-Si and mono-Si PV modules) per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, Technology mix, panel, mounted".**

Impact category	Unit	Life cycle excl. use stage	Use stage
Representative Product (virtual)			
Climate change	1/(Person·Year)	7.65E-06	1.35E-09
Ozone depletion	1/(Person·Year)	1.48E-08	8.43E-13
Particulate matter	1/(Person·Year)	2.46E-05	-9.11E-10
Ionising radiation, human health	1/(Person·Year)	1.10E-06	1.31E-10
Photochemical ozone formation, human health	1/(Person·Year)	3.97E-06	2.47E-10
Acidification	1/(Person·Year)	5.19E-06	9.25E-11
Eutrophication, terrestrial	1/(Person·Year)	3.33E-06	-1.24E-10
Eutrophication, freshwater	1/(Person·Year)	1.70E-07	2.49E-09
Eutrophication, marine	1/(Person·Year)	2.01E-06	1.22E-09
Land use	1/(Person·Year)	2.66E-07	-3.78E-10
Water use	1/(Person·Year)	1.98E-06	1.37E-08
Resource use, minerals and metals	1/(Person·Year)	9.39E-06	9.05E-11
Resource use, fossils	1/(Person·Year)	1.13E-05	6.85E-10

Tab. 7.3 Weighted benchmark values for the representative product (technology mix of CdTe, CIS, micro-Si, multi-Si and mono-Si PV modules) per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, Technology mix, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Representative Product (virtual)			
Climate change	Pt.	1.70E-06	2.99E-10
Ozone depletion	Pt.	1.00E-09	5.69E-14
Particulate matter	Pt.	2.35E-06	-8.70E-11
Ionising radiation, human health	Pt.	5.93E-08	7.04E-12
Photochemical ozone formation, human health	Pt.	2.02E-07	1.26E-11
Acidification	Pt.	3.44E-07	6.14E-12
Eutrophication, terrestrial	Pt.	1.30E-07	-4.84E-12
Eutrophication, freshwater	Pt.	5.01E-09	7.34E-11
Eutrophication, marine	Pt.	6.28E-08	3.81E-11
Land use	Pt.	2.24E-08	-3.18E-11
Water use	Pt.	1.79E-07	1.24E-09
Resource use, minerals and metals	Pt.	7.59E-07	7.32E-12
Resource use, fossils	Pt.	1.01E-06	6.11E-11
Total	*Pt.*	*6.82E-06*	*1.62E-09*

7.1.2 Sub-category cadmium-telluride PV modules

The characterised, normalised and weighted benchmark values for the sub-category cadmium-telluride PV modules in scope of this PEFCR are shown in Tab. 7.4, Tab. 7.5 and Tab. 7.6, respectively.

Tab. 7.4 Characterised benchmark values for the sub-category CdTe PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, CdTe, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Cadmium-Telluride (CdTe) PV modules			
Climate change	kg $CO_{2\ eq}$	1.99E-02	1.07E-05
Ozone depletion	kg CFC-11 $_{eq}$	1.19E-11	2.02E-14
Particulate matter	disease incidence	1.50E-09	-5.94E-13
Ionising radiation, human health	kBq $U^{235}{}_{eq}$	1.82E-03	5.65E-07
Photochemical ozone formation, human health	kg NMVOC $_{eq}$	9.39E-05	1.02E-08
Acidification	mol H+ $_{eq}$	1.47E-04	5.25E-09
Eutrophication, terrestrial	mol N $_{eq}$	3.73E-04	-2.24E-08
Eutrophication, freshwater	kg P $_{eq}$	3.68E-07	6.49E-09
Eutrophication, marine	kg N $_{eq}$	3.44E-05	3.53E-08
Land use	Dimensionless (pt)	1.90E-01	-5.15E-04
Water use	m^3 world $_{eq}$	4.30E-03	1.61E-04
Resource use, minerals and metals	kg Sb $_{eq}$	2.71E-07	5.36E-12
Resource use, fossils	MJ	2.66E-01	4.58E-05

Tab. 7.5 Normalised benchmark values for the sub-category CdTe PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, CdTe, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Cadmium-Telluride (CdTe) PV modules			
Climate change	1/(Person·Year)	2.56E-06	1.38E-09
Ozone depletion	1/(Person·Year)	5.09E-10	8.62E-13
Particulate matter	1/(Person·Year)	2.35E-06	-9.33E-10
Ionising radiation, human health	1/(Person·Year)	4.32E-07	1.34E-10
Photochemical ozone formation, human health	1/(Person·Year)	2.31E-06	2.52E-10
Acidification	1/(Person·Year)	2.65E-06	9.45E-11
Eutrophication, terrestrial	1/(Person·Year)	2.11E-06	-1.27E-10
Eutrophication, freshwater	1/(Person·Year)	1.44E-07	2.54E-09
Eutrophication, marine	1/(Person·Year)	1.21E-06	1.25E-09
Land use	1/(Person·Year)	1.43E-07	-3.87E-10
Water use	1/(Person·Year)	3.74E-07	1.40E-08
Resource use, minerals and metals	1/(Person·Year)	4.67E-06	9.26E-11
Resource use, fossils	1/(Person·Year)	4.07E-06	7.01E-10

Tab. 7.6 **Weighted benchmark values for the sub-category CdTe PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, CdTe, panel, mounted".**

Impact category	Unit	Life cycle excl. use stage	Use stage
Cadmium-Telluride (CdTe) PV modules			
Climate change	Pt.	5.69E-07	3.06E-10
Ozone depletion	Pt.	3.43E-11	5.82E-14
Particulate matter	Pt.	2.24E-07	-8.90E-11
Ionising radiation, human health	Pt.	2.32E-08	7.20E-12
Photochemical ozone formation, human health	Pt.	1.18E-07	1.29E-11
Acidification	Pt.	1.76E-07	6.28E-12
Eutrophication, terrestrial	Pt.	8.23E-08	-4.95E-12
Eutrophication, freshwater	Pt.	4.26E-09	7.51E-11
Eutrophication, marine	Pt.	3.79E-08	3.90E-11
Land use	Pt.	1.21E-08	-3.26E-11
Water use	Pt.	3.38E-08	1.27E-09
Resource use, minerals and metals	Pt.	3.78E-07	7.48E-12
Resource use, fossils	Pt.	3.63E-07	6.25E-11
Total	*Pt.*	*2.02E-06*	*1.66E-09*

7.1.3 Sub-category copper-indium-gallium-selenide PV modules

The characterised, normalised and weighted benchmark values for the sub-category copper-indium-gallium-selenide PV modules in scope of this PEFCR are shown in Tab. 7.7, Tab. 7.8 and Tab. 7.9, respectively.

Tab. 7.7 Characterised benchmark values for the sub-category CIS PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, CIS, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Copper-Indium-Gallium-Selenide (CIS) PV modules			
Climate change	kg $CO_{2\ eq}$	3.59E-02	1.39E-05
Ozone depletion	kg CFC-11 $_{eq}$	2.64E-11	2.62E-14
Particulate matter	disease incidence	1.92E-09	-7.70E-13
Ionising radiation, human health	kBq $U^{235}{}_{eq}$	5.70E-03	7.34E-07
Photochemical ozone formation, human health	kg NMVOC $_{eq}$	1.02E-04	1.33E-08
Acidification	mol H+ $_{eq}$	1.69E-04	6.81E-09
Eutrophication, terrestrial	mol N $_{eq}$	3.97E-04	-2.90E-08
Eutrophication, freshwater	kg P $_{eq}$	3.63E-07	8.41E-09
Eutrophication, marine	kg N $_{eq}$	3.69E-05	4.58E-08
Land use	Dimensionless (pt)	3.10E-01	-6.67E-04
Water use	m^3 world $_{eq}$	6.27E-03	2.09E-04
Resource use, minerals and metals	kg Sb $_{eq}$	4.80E-07	6.95E-12
Resource use, fossils	MJ	5.16E-01	5.94E-05

Tab. 7.8 Normalised benchmark values for the sub-category CIS PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, CIS, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Copper-Indium-Gallium-Selenide (CIS) PV modules			
Climate change	1/(Person·Year)	4.63E-06	1.79E-09
Ozone depletion	1/(Person·Year)	1.13E-09	1.12E-12
Particulate matter	1/(Person·Year)	3.01E-06	-1.21E-09
Ionising radiation, human health	1/(Person·Year)	1.35E-06	1.74E-10
Photochemical ozone formation, human health	1/(Person·Year)	2.52E-06	3.27E-10
Acidification	1/(Person·Year)	3.04E-06	1.23E-10
Eutrophication, terrestrial	1/(Person·Year)	2.24E-06	-1.64E-10
Eutrophication, freshwater	1/(Person·Year)	1.42E-07	3.30E-09
Eutrophication, marine	1/(Person·Year)	1.31E-06	1.62E-09
Land use	1/(Person·Year)	2.33E-07	-5.02E-10
Water use	1/(Person·Year)	5.46E-07	1.82E-08
Resource use, minerals and metals	1/(Person·Year)	8.28E-06	1.20E-10
Resource use, fossils	1/(Person·Year)	7.91E-06	9.09E-10

Tab. 7.9 Weighted benchmark values for the sub-category CIS PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, CIS, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Copper-Indium-Gallium-Selenide (CIS) PV modules			
Climate change	Pt.	1.03E-06	3.97E-10
Ozone depletion	Pt.	7.61E-11	7.54E-14
Particulate matter	Pt.	2.87E-07	-1.15E-10
Ionising radiation, human health	Pt.	7.26E-08	9.33E-12
Photochemical ozone formation, human health	Pt.	1.28E-07	1.67E-11
Acidification	Pt.	2.02E-07	8.15E-12
Eutrophication, terrestrial	Pt.	8.78E-08	-6.41E-12
Eutrophication, freshwater	Pt.	4.20E-09	9.73E-11
Eutrophication, marine	Pt.	4.07E-08	5.05E-11
Land use	Pt.	1.96E-08	-4.22E-11
Water use	Pt.	4.93E-08	1.64E-09
Resource use, minerals and metals	Pt.	6.69E-07	9.70E-12
Resource use, fossils	Pt.	7.05E-07	8.11E-11
Total	*Pt.*	*3.29E-06*	*2.15E-09*

7.1.4 Sub-category micromorphous silicon PV modules

The characterised, normalised and weighted benchmark values for the sub-category micromorphous silicon PV modules in scope of this PEFCR are shown in Tab. 7.10, Tab. 7.11 and Tab. 7.12, respectively.

Tab. 7.10 Characterised benchmark values for the sub-category micro-Si PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, micro-Si, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Micromorphous silicon (micro-Si) PV modules			
Climate change	kg $CO_{2\ eq}$	4.30E-02	1.50E-05
Ozone depletion	kg CFC-11 $_{eq}$	1.48E-11	2.82E-14
Particulate matter	disease incidence	9.65E-09	-8.32E-13
Ionising radiation, human health	kBq $U^{235}{}_{eq}$	5.15E-03	7.92E-07
Photochemical ozone formation, human health	kg NMVOC $_{eq}$	1.47E-04	1.43E-08
Acidification	mol H+ $_{eq}$	2.57E-04	7.35E-09
Eutrophication, terrestrial	mol N $_{eq}$	5.76E-04	-3.14E-08
Eutrophication, freshwater	kg P $_{eq}$	3.64E-07	9.09E-09
Eutrophication, marine	kg N $_{eq}$	5.27E-05	4.95E-08
Land use	Dimensionless (pt)	1.92E-01	-7.20E-04
Water use	m^3 world $_{eq}$	1.12E-02	2.26E-04
Resource use, minerals and metals	kg Sb $_{eq}$	3.20E-07	7.51E-12
Resource use, fossils	MJ	5.60E-01	6.41E-05

Tab. 7.11 Normalised benchmark values for the sub-category micro-Si PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, micro-Si, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Micromorphous silicon (micro-Si) PV modules			
Climate change	1/(Person·Year)	5.54E-06	1.93E-09
Ozone depletion	1/(Person·Year)	6.34E-10	1.21E-12
Particulate matter	1/(Person·Year)	1.52E-05	-1.31E-09
Ionising radiation, human health	1/(Person·Year)	1.22E-06	1.88E-10
Photochemical ozone formation, human health	1/(Person·Year)	3.62E-06	3.53E-10
Acidification	1/(Person·Year)	4.64E-06	1.32E-10
Eutrophication, terrestrial	1/(Person·Year)	3.25E-06	-1.77E-10
Eutrophication, freshwater	1/(Person·Year)	1.43E-07	3.56E-09
Eutrophication, marine	1/(Person·Year)	1.86E-06	1.75E-09
Land use	1/(Person·Year)	1.44E-07	-5.42E-10
Water use	1/(Person·Year)	9.71E-07	1.96E-08
Resource use, minerals and metals	1/(Person·Year)	5.53E-06	1.30E-10
Resource use, fossils	1/(Person·Year)	8.57E-06	9.82E-10

Tab. 7.12 Weighted benchmark values for the sub-category micro-Si PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, micro-Si, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Micromorphous silicon (micro-Si) PV modules			
Climate change	Pt.	1.23E-06	4.29E-10
Ozone depletion	Pt.	4.28E-11	8.15E-14
Particulate matter	Pt.	1.45E-06	-1.25E-10
Ionising radiation, human health	Pt.	6.55E-08	1.01E-11
Photochemical ozone formation, human health	Pt.	1.84E-07	1.80E-11
Acidification	Pt.	3.08E-07	8.80E-12
Eutrophication, terrestrial	Pt.	1.27E-07	-6.93E-12
Eutrophication, freshwater	Pt.	4.21E-09	1.05E-10
Eutrophication, marine	Pt.	5.81E-08	5.45E-11
Land use	Pt.	1.22E-08	-4.56E-11
Water use	Pt.	8.77E-08	1.77E-09
Resource use, minerals and metals	Pt.	4.47E-07	1.05E-11
Resource use, fossils	Pt.	7.65E-07	8.76E-11
Total	*Pt.*	*4.73E-06*	*2.32E-09*

7.1.5 Sub-category multicrystalline silicon PV modules

The characterised, normalised and weighted benchmark values for the sub-category multicrystalline silicon PV modules in scope of this PEFCR are shown in Tab. 7.13, Tab. 7.14 and Tab. 7.15, respectively.

Tab. 7.13 Characterised benchmark values for the sub-category multi-Si PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, multi-Si, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Multicrystalline silicon (multi-Si) PV modules			
Climate change	kg $CO_{2\ eq}$	4.88E-02	1.02E-05
Ozone depletion	kg CFC-11 $_{eq}$	3.04E-10	1.92E-14
Particulate matter	disease incidence	1.17E-08	-5.66E-13
Ionising radiation, human health	kBq $U^{235}{}_{eq}$	4.38E-03	5.39E-07
Photochemical ozone formation, human health	kg NMVOC $_{eq}$	1.29E-04	9.75E-09
Acidification	mol H+ $_{eq}$	2.41E-04	5.00E-09
Eutrophication, terrestrial	mol N $_{eq}$	4.73E-04	-2.13E-08
Eutrophication, freshwater	kg P $_{eq}$	4.56E-07	6.18E-09
Eutrophication, marine	kg N $_{eq}$	4.33E-05	3.36E-08
Land use	Dimensionless (pt)	3.49E-01	-4.90E-04
Water use	m^3 world $_{eq}$	1.96E-02	1.54E-04
Resource use, minerals and metals	kg Sb $_{eq}$	6.07E-07	5.11E-12
Resource use, fossils	MJ	6.16E-01	4.36E-05

Tab. 7.14 Normalised benchmark values for the sub-category multi-Si PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, multi-Si, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Multicrystalline silicon (multi-Si) PV modules			
Climate change	1/(Person·Year)	6.29E-06	1.31E-09
Ozone depletion	1/(Person·Year)	1.30E-08	8.21E-13
Particulate matter	1/(Person·Year)	1.84E-05	-8.88E-10
Ionising radiation, human health	1/(Person·Year)	1.04E-06	1.28E-10
Photochemical ozone formation, human health	1/(Person·Year)	3.18E-06	2.40E-10
Acidification	1/(Person·Year)	4.34E-06	9.01E-11
Eutrophication, terrestrial	1/(Person·Year)	2.67E-06	-1.20E-10
Eutrophication, freshwater	1/(Person·Year)	1.79E-07	2.42E-09
Eutrophication, marine	1/(Person·Year)	1.53E-06	1.19E-09
Land use	1/(Person·Year)	2.62E-07	-3.68E-10
Water use	1/(Person·Year)	1.71E-06	1.34E-08
Resource use, minerals and metals	1/(Person·Year)	1.05E-05	8.82E-11
Resource use, fossils	1/(Person·Year)	9.44E-06	6.68E-10

Tab. 7.15 Weighted benchmark values for the sub-category multi-Si PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, multi-Si, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Multicrystalline silicon (multi-Si) PV modules			
Climate change	Pt.	1.40E-06	2.91E-10
Ozone depletion	Pt.	8.76E-10	5.54E-14
Particulate matter	Pt.	1.75E-06	-8.47E-11
Ionising radiation, human health	Pt.	5.58E-08	6.86E-12
Photochemical ozone formation, human health	Pt.	1.62E-07	1.23E-11
Acidification	Pt.	2.88E-07	5.98E-12
Eutrophication, terrestrial	Pt.	1.04E-07	-4.71E-12
Eutrophication, freshwater	Pt.	5.27E-09	7.15E-11
Eutrophication, marine	Pt.	4.78E-08	3.71E-11
Land use	Pt.	2.21E-08	-3.10E-11
Water use	Pt.	1.54E-07	1.21E-09
Resource use, minerals and metals	Pt.	8.48E-07	7.13E-12
Resource use, fossils	Pt.	8.42E-07	5.96E-11
Total	*Pt.*	*5.68E-06*	*1.58E-09*

7.1.6 Sub-category monocrystalline silicon PV modules

The characterised, normalised and weighted benchmark values for the sub-category monocrystalline silicon PV modules in scope of this PEFCR are shown in Tab. 7.16, Tab. 7.17 and Tab. 7.18, respectively.

Tab. 7.16 Characterised benchmark values for the sub-category mono-Si PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, mono-Si, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Monocrystalline silicon (mono-Si) PV modules			
Climate change	kg $CO_{2\ eq}$	8.04E-02	9.93E-06
Ozone depletion	kg CFC-11 $_{eq}$	5.09E-10	1.87E-14
Particulate matter	disease incidence	2.40E-08	-5.51E-13
Ionising radiation, human health	kBq $U^{235}{}_{eq}$	5.21E-03	5.25E-07
Photochemical ozone formation, human health	kg NMVOC $_{eq}$	2.12E-04	9.50E-09
Acidification	mol H+ $_{eq}$	3.72E-04	4.87E-09
Eutrophication, terrestrial	mol N $_{eq}$	7.65E-04	-2.08E-08
Eutrophication, freshwater	kg P $_{eq}$	4.27E-07	6.02E-09
Eutrophication, marine	kg N $_{eq}$	7.74E-05	3.28E-08
Land use	Dimensionless (pt)	4.04E-01	-4.77E-04
Water use	m^3 world $_{eq}$	3.17E-02	1.50E-04
Resource use, minerals and metals	kg Sb $_{eq}$	5.34E-07	4.98E-12
Resource use, fossils	MJ	9.73E-01	4.25E-05

Tab. 7.17 Normalised benchmark values for the sub-category mono-Si PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, mono-Si, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Monocrystalline silicon (mono-Si) PV modules			
Climate change	1/(Person·Year)	1.04E-05	1.28E-09
Ozone depletion	1/(Person·Year)	2.18E-08	8.00E-13
Particulate matter	1/(Person·Year)	3.77E-05	-8.65E-10
Ionising radiation, human health	1/(Person·Year)	1.23E-06	1.24E-10
Photochemical ozone formation, human health	1/(Person·Year)	5.23E-06	2.34E-10
Acidification	1/(Person·Year)	6.71E-06	8.78E-11
Eutrophication, terrestrial	1/(Person·Year)	4.32E-06	-1.17E-10
Eutrophication, freshwater	1/(Person·Year)	1.67E-07	2.36E-09
Eutrophication, marine	1/(Person·Year)	2.73E-06	1.16E-09
Land use	1/(Person·Year)	3.03E-07	-3.59E-10
Water use	1/(Person·Year)	2.76E-06	1.30E-08
Resource use, minerals and metals	1/(Person·Year)	9.22E-06	8.59E-11
Resource use, fossils	1/(Person·Year)	1.49E-05	6.50E-10

Tab. 7.18 Weighted benchmark values for the sub-category mono-Si PV modules per kWh PV electricity; process name "electricity, PV, at 3kWp slanted-roof, mono-Si, panel, mounted".

Impact category	Unit	Life cycle excl. use stage	Use stage
Monocrystalline silicon (mono-Si) PV modules			
Climate change	Pt.	2.30E-06	2.84E-10
Ozone depletion	Pt.	1.47E-09	5.40E-14
Particulate matter	Pt.	3.60E-06	-8.25E-11
Ionising radiation, human health	Pt.	6.63E-08	6.68E-12
Photochemical ozone formation, human health	Pt.	2.67E-07	1.19E-11
Acidification	Pt.	4.46E-07	5.83E-12
Eutrophication, terrestrial	Pt.	1.69E-07	-4.59E-12
Eutrophication, freshwater	Pt.	4.94E-09	6.96E-11
Eutrophication, marine	Pt.	8.53E-08	3.61E-11
Land use	Pt.	2.55E-08	-3.02E-11
Water use	Pt.	2.49E-07	1.18E-09
Resource use, minerals and metals	Pt.	7.45E-07	6.94E-12
Resource use, fossils	Pt.	1.33E-06	5.80E-11
Total	*Pt.*	*9.28E-06*	*1.54E-09*

7.2 PEF profile

The applicant shall calculate the PEF profile of its product in compliance with all requirements included in this PEFCR. The following information shall be included in the PEF report:

- full life cycle inventory;
- characterised results in absolute values, for all impact categories (including toxicity; as a table);
- normalised and weighted result in absolute values, for all impact categories (including toxicity; as a table);
- the aggregated single score in absolute values.

Together with the PEF report, the applicant shall develop an aggregated EF-compliant dataset of its product in scope. This dataset shall be made available on the EF node (http://eplca.jrc.ec.europa.eu/EF-node). The disaggregated version may stay confidential.

7.3 Additional technical information

The applicant shall include the following technical information in the PEF report:

- maximum power output of the PV module
- module area (incl. frame, if applicable)
- warranty period

If the applicant of this PEFCR uses a degradation rate deviating from the default value of 0.7 % per year (see conditions for using a different degradation rate in subchapter 6.4), the following additional information shall be included in the PEF report:

- degradation rate
- scientific evidence and test results proving the specific degradation rate

7.4 Additional environmental information

The radiotoxicity potential of nuclear waste shall be quantified as an additional indicator to complement the environmental profile. The results for the indicator nuclear waste (see Tab. 3.7) shall be presented separately from the default impact category indicators listed in Tab. 3.6. This indicator shall be used in the life cycle impact assessment prior to normalization only and shall not be used in benchmarking.

The indicator radiotoxicity potential of nuclear waste is described in section 7.4.1. A few explanations of the biodiversity impacts of PV electricity are given in section 7.4.2.

7.4.1 Radiotoxicity potential of nuclear waste

The indicator “ionising radiations – human health effects” covers the releases of radioactive substances from nuclear (and partly other) facilities and mines during their operation. The potential environmental impacts due to radioactive wastes are not covered by this indicator. That is why the amount of nuclear waste[40] is considered mandatory in the IEA-PVPS methodological guidelines and in the EN 15804 (2013). However, the amount (mass or volume) of nuclear wastes does not consider the radiotoxicity of the different types of nuclear waste.

The hazardousness of radioactive wastes depends on their persistence (half-life) and on the type and intensity of their radiation. The radiotoxicity of the individual isotopes contained in the various types of radioactive waste is quantified using the internationally discussed and accepted radiotoxicity index (RTI) of radioactive wastes (see e.g. Miyahara et al. 2001; OECD 2007). It is defined as

$RTI = \Sigma_i A_i \times DF_i/DL$

with:
A_i = activity of the nuclide i in Bq,
DF_i = dose factor for the ingestion of the nuclide i in Sv/Bq,
DL = 0.1 mSv/a, dose limit value for the release from a deep geological repository (NAGRA 2008a).

The specific RTI of the different standard types of nuclear wastes is used as the basis for characterization. The high level wastes are used as the reference substance (see Tab. 7.19). The characterization factor shall be applied to the final repository volume of radioactive wastes, including their encasing. The impact category indicator radiotoxicity index representing the impact category nuclear waste has been developed within the ecological scarcity method 2013 (Frischknecht & Büsser Knöpfel 2013; 2014).

Tab. 7.19 Radiotoxicity index (RTI) per m³ of waste, density and characterization factors. The density of low and medium as well as of high radioactive wastes is based on NAGRA (2008b).

Elementary flow	UUID	RTI	Density	Characterization factor
Low radioactive wastes	f0aeeb00-6d5b-4e9d-8e3b-169d2b2e56d4	4.10E+07 m^{-3}	1.85E+03 kg/m^3	2.43E-08 m^3HLW-eq/kg
Medium radioactive wastes	a60b91d7-798b-4f76-973e-edc4ec8815a6	4.10E+07 m^{-3}	1.85E+03 kg/m^3	2.43E-08 m^3HLW-eq/kg
High radioactive waste	26fd4ed1-a97f-4be3-a9ea-ca9273b48101	9.30E+11 m^{-3}	5.63E+02 kg/m^3	1.78E-03 m^3HLW-eq/kg
Radioactive tailings	8df3d2af-d7ac-4365-9b4a-17e28b9ca482	0.00E+00 m^{-3}	n.a.	0.00E+00 m^3HLW-eq/kg
Volume occupied, final repository for radioactive waste	0fdfa11c-0397-4f46-b1cf-d9266d5a5a13	9.30E+11 m^{-3}	n.a.	7.60E-01 m^3HLW-eq/m^3
Volume occupied, final repository for low-active radioactive waste	1fc2328b-d860-4aa7-ac27-34aa1cce4f9d	4.10E+07 m^{-3}	n.a.	4.50E-05 m^3HLW-eq/m^3

7.4.2 Biodiversity

Biodiversity is not considered as relevant for this PEFCR. Biodiversity is closely related to the type and extent of land use. The land occupation of buildings with roof-mounted PV systems is fully allocated to the building.

[40] The amount of radioactive waste resulting from electricity production is also used in the European fuel mix disclosure (European Commission 2009).

The biodiversity impacts of electricity generated with the reference PV system, which is mounted on a slanted roof, are therefore insignificant.[41]

[41] Biodiversity impacts may be relevant for open ground PV systems and were analyzed by Peschel (). Depending on the selected site, biodiversity impacts of ground-mounted PV systems may be positive (e.g. due to low biodiversity in former brownfield sites or intensively cultivated agricultural land) or negative (e.g. due to high biodiversity in high nature value sites). Several best-practice measures can be taken to mitigate biodiversity impacts of open ground PV systems (). The site used for the open ground PV system shall be described and the measures taken to mitigate biodiversity impacts shall be reported.

8 Verification

The verification of an EF study/report carried out in compliance with this PEFCR shall be done according to all the general requirements included in Section 8 of the PEFCR Guidance version 6.3 and the requirements listed below.

The verifier(s) shall verify that the EF study is conducted in compliance with this PEFCR.

These requirements will remain valid until an EF verification scheme is adopted at European level or alternative verification approaches applicable to EF studies/report are included in existing or new policies.

The verifier(s) shall validate the accuracy and reliability of the quantitative information used in the calculation of the study. As this can be highly resource intensive, the following requirements shall be followed:

- the verifier shall check if the correct version of all impact assessment methods was used. For each of the most relevant impact categories, at least 50% of the characterisation factors shall be verified, while all normalisation and weighting factors of all ICs shall be verified. In particular, the verifier shall check that the characterisation factors correspond to those included in the EF impact assessment method the study declares compliance with[42];
- all the newly created datasets shall be checked on their EF compliancy (for the meaning of EF compliant datasets refer to Annex H of the Guidance). All their underlying data (elementary flows, activity data and sub processes) shall be validated;
- the aggregated EF-compliant dataset of the product in scope (meaning, the EF study) is available on the EF node (http://eplca.jrc.ec.europa.eu/EF-node);
- for at least 70% of the most relevant processes in situation 2 option 2 of the DNM, 70% of the underlying data shall be validated. The 70% data shall include all energy and transport sub processes for those in situation 2 option 2;
- for at least 60% of the most relevant processes in situation 3 of the DNM, 60% of the underlying data shall be validated;
- for at least 50% of the other processes in situation 1, 2 and 3 of the DNM, 50% of the underlying data shall be validated.

In particular, it shall be verified for the selected processes if the DQR of the process satisfies the minimum DQR as specified in the DNM.

The selection of the processes to be verified for each situation shall be done ordering them from the most contributing to the less contributing one and selecting those contributing up to the identified percentage starting from the most contributing ones. In case of non-integer numbers, the rounding shall be made always considering the next upper integer.

These data checks shall include, but should not be limited to, the activity data used, the selection of secondary sub-processes, the selection of the direct elementary flows and the CFF parameters. For example, if there are 5 processes and each one of them includes 5 activity data, 5 secondary datasets and 10 CFF parameters, then the verifier(s) has to check at least 4 out of 5 processes (70%) and, for each process, (s)he

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[42] Available at http://eplca.jrc.ec.europa.eu/LCDN/developer.xhtml

shall check at least 4 activity data (70% of the total amount of activity data), 4 secondary datasets (70% of the total amount of secondary datasets), and 7 CFF parameters (70% of the total amount of CFF parameters), i.e. the 70% of each of data that could be possible subject of check.

The verification of the EF report shall be carried out by randomly checking enough information to provide reasonable assurance that the EF report fulfils all the conditions listed in section 8 of the PEFCR Guidance.

The type of review depends on the intended application of the PEF study as specified in Subchapter 9.2 of the PEF Guide (European Commission 2013):

“Unless otherwise specified in relevant policy instruments, any study intended for external communication shall be critically reviewed by at least one independent and qualified external reviewer (or review team). A PEF study to support a comparative assertion intended to be disclosed to the public shall be based on relevant PEFCRs and critically reviewed by an independent panel of three qualified external reviewers. Any PEF study intended for internal communication claiming to be in line with the PEF Guide shall be critically reviewed by at least one independent and qualified external reviewer (or review team).”

PEF studies used for comparative assertions shall be carried out in compliance with this PEFCR and take the limitations described in subchapter 3.6 into account. An overview of the verification requirements is given in Tab. 8.1.

Tab. 8.1 Overview of the verification requirements depending on the addressees (internal / external) and the use (with / without comparative assertion) of the PEF study

<table>
<tr><th></th><th>Internal communication (with claim to be in line with the PEF Guide and the PEFCR)</th><th>External communication</th></tr>
<tr><td>Without comparative assertion</td><td rowspan="2">Review by <u>at least one</u> independent and qualified external reviewer</td><td>Review by <u>at least one</u> independent and qualified external reviewer</td></tr>
<tr><td>With comparative assertion</td><td>Review by an independent <u>panel of three</u> qualified external reviewers</td></tr>
</table>

9 References

de Wild-Scholten M. J. (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection. SmartGreenScans, Groet, NL, retrieved from: www.smartgreenscans.nl.

EN 15804 (2013) EN 15804:2012+A1:2013 - Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products. European Committee for Standardisation (CEN), Brussels.

EPIA (2012) Connecting the sun - solar photovoltaics on the road to large-scale grid integration. European Photovoltaic Industry Association (EPIA), Brussels - Belgium.

EU Parliament (2012) Directive 2012/19/EU of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE). *In: Official Journal of the European Union*, **2012**(197), pp. 38-71.

European Commission (2009) Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC. European Commission; Commission of the European Communities, Brussels, retrieved from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:211:0055:0093:EN:PDF.

European Commission (2013) Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. Official Journal of the European Union.

European Commission (2016) Product Environmental Footprint Guidance. Version 6.0. European Commission.

European Commission (2017) PEFCR Guidance Document - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3, December 2017. European Commission.

FHI-ISE (2013) Photovoltaics report. Fraunhofer Institute (FHI) for Solar Energy System (ISE), Freiburg, Germany, retrieved from: www.ise.fraunhofer.de.

Flury K., Frischknecht R. and Itten R. (2012) Life cycle assessment of Oerlikon Solar μC-Si solar modules. treeze Ltd., Uster.

Frischknecht R., Jungbluth N., Althaus H.-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M. (2007) Overview and Methodology. ecoinvent report No. 1, v2.0. Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.

Frischknecht R. and Büsser Knöpfel S. (2013) Swiss Eco-Factors 2013 according to the Ecological Scarcity Method. Methodological fundamentals and their application in Switzerland. Environmental studies no. 1330. Federal Office for the Environment, Bern, retrieved from: http://www.bafu.admin.ch/publikationen/publikation/01750/index.html?lang=en.

Frischknecht R. and Itten R. (2014) PEFCR photovoltaic electricity generation; Definition of scope, of the representative product and of the model for the PEF screening study. treeze Ltd. commissioned by Technical Secretariat PEF Pilot "Photovoltaic Electricity Generation", Uster, Switzerland.

Frischknecht R. and Büsser Knöpfel S. (2014) Ecological scarcity 2013—new features and its application in industry and administration—54th LCA forum, Ittigen/Berne, Switzerland, December 5, 2013. *In: Int J LCA*, **19**(6), pp. 1361-1366, 10.1007/s11367-014-0744-z.

Frischknecht R., Itten R., Sinha P., de Wild Scholten M., Zhang J., Fthenakis V., Kim H. C., Raugei M. and Stucki M. (2015a) Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems. International Energy Agency (IEA) PVPS Task 12.

Frischknecht R., Heath G., Raugei M., Sinha P. and de Wild-Scholten M. (2015b) Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 3rd edition, IEA-PVPS T12-03:2015. International Energy Agency, IEA, Paris.

IEA-PVPS (2013) Trends in Photovoltaic Applications - Survey report of selected IEA countries between 1992 and 2012. PVPS T1 - 23 : 2013. International Energy Agency (IEA), retrieved from: www.iea-pvps.org.

IEC (1998) IEC 61724: Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis. International Electrotechnical Commission, Geneva CH.

ISO/IEC (2005) ISO/IEC 17025:2005: General requirements for the competence of testing and calibration laboratories. International Organization for Standardization and International Electrotechnical Commission, Geneva CH.

Itten R. and Frischknecht R. (2014) LCI of the global chrystalline photovoltaics supply chain and Chinese multi-chrystalline supply chain. Swiss Federal Office of Energy, Bern.

Itten R., Wyss F. and Frischknecht R. (2014) LCI of the global crystalline photovoltaics supply chain and of future photovoltaics electricity production. treeze Ltd., Uster, Switzerland.

Jordan D. C. and Kurtz S. R. (2012) Photovoltaic Degradation Rates — An Analytical Review. National Renewable Energy Laboratory, NREL, Golden, Colorado, USA.

Jungbluth N., Stucki M., Frischknecht R. and Buesser S. (2010) Photovoltaics. In: *Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz,* Vol. ecoinvent report No. 6-XII, v2.2+ (Ed. Bauer C. and Dones R.). pp. 233. ESU-services Ltd., Uster, CH retrieved from: www.esu-services.ch.

Jungbluth N., Stucki M., Flury K., Frischknecht R. and Buesser S. (2012) Life Cycle Inventories of Photovoltaics. ESU-services Ltd., Uster, CH, retrieved from: www.esu-services.ch.

KBOB, eco-bau and IPB (2014) ecoinvent Datenbestand v2.2+; Grundlage für die KBOB-Empfehlung 2009/1:2014: Ökobilanzdaten im Baubereich, Stand April 2014. Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren c/o BBL Bundesamt für Bauten und Logistik, retrieved from: www.lc-inventories.ch.

Miyahara K., Makino H., Takasu A., Naito M., Umeke H., Wakasugi K. and Ishiguro K. (2001) Application of non-dose/risk indicators for confidence-building in the H12 safety assessment. *In proceedings from: Issues relating to safety standards on the geological disposal of radioactive waste* International Atomic Energy Agency, IAEA, Vienna.

NAGRA (2008a) Technischer Bericht 08-05 - Begründung der Abfallzuteilung, der Barrierensysteme und der Anforderungen an die Geologie Bericht zur Sicherheit und technischen Machbarkeit. Nationale Gesellschaft für die Lagerung radioaktiver Abfälle, nagra, Wettingen, retrieved from: www.nagra.ch.

NAGRA (2008b) Technischer Bericht 08-06 - Modellhaftes Inventar für radioaktive Materialien - MIRAM 08. Nationale Gesellschaft für die Lagerung radioaktiver Abfälle, nagra, Wettingen, retrieved from: www.nagra.ch.

Nederlands Instituut voor Bouwbiologie en Ecologie (2014) Vergelijkend LCA onderzoek houten en kunststof pallets.

OECD (2007) Consideration of timescales in post-closure safety of geological disposal of radioactive waste. Organisation for Economic Co-operation and Development, Nuclear Energy Agency, Radioactive Waste Management Committee, OECD/NEA/RWMC, Paris.

Payet J., Evon B., Sié M., Blanc I., Belon-Saint-Pierre D., Guermont C., Adra N., Puech C. and Durand Y. (2013) Methodological framework for assessing the environmental impacts of photovoltaic systems using the life cycle assessment method. ADEME.

PCR CPC 171 & 173 (2013) Product Category Rules (PCR) for preparing an Environmental Product Declaration (EPD) for Electricity, Steam, and Hot and Cold Water Generation and Distribution, version 2.02. The International EPD Consortium (IEC), retrieved from: www.environdec.com.

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.

ANNEX 1 – List of EF normalisation and weighting factors

Global normalisation factors are applied within the EF. The normalisation factors as the global impact per person are used in the EF calculations.

Impact category	Unit	Normalisation factor	Normalisation factor per person	Impact assessment robustness	Inventory coverage completeness	Inventory robustness	Comment
Climate change	kg CO_2 eq	5.35E+13	7.76E+03	I	II	I	
Ozone depletion	kg CFC-11 eq	1.61E+08	2.34E-02	I	III	II	
Human toxicity, cancer	CTUh	2.66E+05	3.85E-05	II/III	III	III	
Human toxicity, non-cancer	CTUh	3.27E+06	4.75E-04	II/III	III	III	
Particulate matter	disease incidence	4.39E+06	6.37E-04	I	I/II	I/II	NF calculation takes into account the emission height both in the emission inventory and in the impact assessment.
Ionising radiation, human health	kBq U^{235} eq	2.91E+13	4.22E+03	II	II	III	
Photochemical ozone formation, human health	kg NMVOC eq	2.80E+11	4.06E+01	II	III	I/II	
Acidification	mol H+ eq	3.83E+11	5.55E+01	II	II	I/II	
Eutrophication, terrestrial	mol N eq	1.22E+12	1.77E+02	II	II	I/II	
Eutrophication, freshwater	kg P eq	1.76E+10	2.55E+00	II	II	III	
Eutrophication, marine	kg N eq	1.95E+11	2.83E+01	II	II	II/III	

Land use	pt	9.20E+15	1.33E+06	III	II	II	The NF is built by means of regionalised CFs.
Ecotoxicity, freshwater	CTUe	8.15E+13	1.18E+04	II/III	III	III	
Water use	m^3 world $_{eq}$	7.91E+13	1.15E+04	III	I	II	The NF is built by means of regionalised CFs.
Resource use, fossils	MJ	4.50E+14	6.53E+04	III	I	II	
Resource use, minerals and metals	kg Sb $_{eq}$	3.99E+08	5.79E-02	III			

Weighting factors for Environmental Footprint

	Aggregated weighting set	Robustness factors	Calculation	**Final weighting factors**
WITHOUT TOX CATEGORIES	(50:50)	(scale 1-0.1)		
	A	B	C=A*B	C scaled to 100
Climate change	15.75	0.87	13.65	**22.19**
Ozone depletion	6.92	0.6	4.15	**6.75**
Particulate matter	6.77	0.87	5.87	**9.54**
Ionizing radiation, human health	7.07	0.47	3.3	**5.37**
Photochemical ozone formation, human health	5.88	0.53	3.14	**5.1**
Acidification	6.13	0.67	4.08	**6.64**
Eutrophication, terrestrial	3.61	0.67	2.4	**3.91**
Eutrophication, freshwater	3.88	0.47	1.81	**2.95**
Eutrophication, marine	3.59	0.53	1.92	**3.12**
Land use	11.1	0.47	5.18	**8.42**
Water use	11.89	0.47	5.55	**9.03**
Resource use, minerals and metals	8.28	0.6	4.97	**8.08**
Resource use, fossils	9.14	0.6	5.48	**8.92**

ANNEX 2 – Check-list for the PEF study

Each PEF study shall include this annex, completed with all the requested information.

ITEM	Included in the study (Y/N)	Section	Page
Summary			
General information about the product			
General information about the company			
Diagram with system boundary and indication of the situation according to DNM			
List and description of processes included in the system boundaries			
List of co-products, by-products and waste			
List of activity data used			
List of secondary datasets used			
Data gaps			
Assumptions			
Scope of the study			
(sub)category to which			

ITEM	Included in the study (Y/N)	Section	Page
the product belongs			
DQR calculation of each dataset used for the most relevant processes and the new ones created			
DQR (of each criterion and total) of the study			

ANNEX 3 – Review Report

Scientific Review of the final draft Product Environmental Footprint Category Rules (PEFCR) for the production of photovoltaic modules used in photovoltaic power systems for electricity generation (NACE/CPA class 27.90 "*Manufacturing of other electrical equipment*") – Draft_PEFCR_PV_v.0.18

A3.1 Review Panel

Prof. Edgar Hertwich Yale School of Forestry & Environmental Studies, New Haven, Connecticut, USA edgar.hertwich@yale.edu	I am a member of the International Resource Panel, where I lead the Working Group on the Environmental Impacts of Products and Materials. I have contributed to the IPCC 5th assessment report as a lead author of the energy systems chapter and the methods annex, as well as a contributor to the Technical Summary and the Summary for Policy makers. Further, I have contributed to the Global Energy Assessment. I am a member of the editorial board of Environmental Science & Technology, the Journal of Industrial Ecology, and the Journal of Economic Structure. My research interests cover climate mitigation, life cycle assessment, sustainable consumption and production, trade and environment, and risk analysis. I am interested in understanding how activities in our society produce environmental pressures, the dynamics in our development that affect these driving forces and their resulting environmental pressures, and alternative courses of action that can reduce these pressures. What is the connection between human activities on the one hand and emissions and resource use on the other hand? What are the implications of our current development path? What do we need to change, both in terms of individual actions and policy frameworks, to achieve a more sustainable development?
Prof. Sangwon Suh Corporate Environmental Management, Industrial Ecology, Life Cycle Assessment Bren School of Environmental Science & Management, University of California, Santa Barbara, California, USA suh@bren.ucsb.edu ***Chair of the Review Panel for this review***	Sangwon Suh's research focuses on the sustainability of the human-nature complexity through understanding materials and energy exchanges between them. Over the past 15 years, he has been working on the theoretical foundations and practical applications of life-cycle assessment (LCA) and industrial ecology. In particular, Dr. Suh has contributed to the use of both economic and engineering principles in understanding the choice of technologies in the market and their human health, environmental, and resources impacts. Dr. Suh was appointed a member of the International Resource Panel (IRP) by the United Nations Environmental Programme (UNEP) and served as the Coordinating Lead Author of the Assessment Report 5 by the Intergovernmental Panel on Climate Change (IPCC). He received the Leontief Memorial Prize from the International Input-Output Association (IIOA), and the Robert A. Laudise Medal from the International Society for Industrial Ecology (ISIE).
Ugo Pretato Studio Fieschi & soci Srl Via Cesare Lombroso, 25 I-10125 Torino, Italy pretato@studiofieschi.it	Associate of the company since 2010, he is a graduate in forestry and holds an international master in Environmental Engineering (EPEA). Ugo has been working as a leading environmental consultant and LCA project manager at ANPA (now ISPRA). He has managed the environmental programs for the Olympic Winter Games of Torino in 2006 and held the positions of senior advisor at the Torino Energy Agency and scientific officer on Life Cycle Assessment at the European Commission JRC.

A3.2 Introduction

In line with the requirements for the Product Environmental Footprint Pilot Phase, the Technical Secretariat (TS) of the PEF Pilot Project "Photovoltaic Electricity Generation" approached the afore mentioned members of the Scientific Review Board in June 2018 to perform the final independent scientific review of the final draft Product Environmental Footprint Category Rules (Draft_PEFCR_PV_v.0.17) for the production of photovoltaic modules used in photovoltaic power systems for electricity generation (NACE/CPA class 27.90 "*Manufacturing of other electrical equipment*").

All review panel members were contracted by the Technical Secretariat to perform the scientific review in the period from August to September 2018. During that timeframe, the review panel had 2 meetings – involving representatives of the Technical Secretariat and the lead LCA consultant responsible for drafting the PEFCR on behalf of the TS. During the first meeting, Prof. Sangwon Suh was nominated as Chair of the Review Panel for this final scientific review.

The scientific review was carried out to confirm whether the PEFCR has been developed

- in accordance with the requirements provided in the Guidance (*Product Environmental Footprint Pilot Guidance: Guidance for the implementation of the EU Product Environmental Footprint (PEF) during the Environmental Footprint (EF) pilot phase - Version 6.3 – December 2017*) and
- supports creation of credible and consistent PEF profiles.

In addition, conformance with the following criteria has been investigated:

- The PEFCR (Draft_PEFCR_PV_v.0.18) is consistent with the guidelines provided in the PEF Guide[43] as published in Commission Recommendation 2013/179/EU on the 9 of April 2013 and the latest version available of the Guidance and deviations are justified,
- Functional unit, allocation and calculation rules are adequate for the product category under consideration,
- Primary and secondary datasets used in the screening study and the supporting studies are relevant, representative, and reliable,
- Selected LCIA indicators and additional environmental information are appropriate for the product category under consideration and the selection is done in accordance with the guidelines stated in the Guidance and the PEF Guide,
- The benchmark and performance classes are correctly defined or the lack of performance classes is appropriately justified
- Both LCA-based data and the additional environmental information prescribed by the PEFCR give a description of the significant environmental aspects associated with the product.

[43] http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32013H0179&from=DE

The next paragraphs provide a summary of the review and the detailed comments from the panel.

A3.3 Summary

The review panel confirms that the documents presented have a generally very good level of conformance with the afore mentioned requirements of the PEF Guidance and the PEF Guide. The review panel confirms a high quality of the PEFCR in relation to comprehensibility for LCA practitioners and future users of the PEFCR. A number of minor technical and editorial changes have been identified during the review and are listed in the next paragraph of this review report together with the comments and adjustments which have been implemented in the final draft to address those.

A3.4 Detailed Comments

The table below and overleaf presents the detailed comments provided by the review panel. The editorial comments as well as the technical comments have been addressed in the final draft version of the PEFCR, which will be submitted by 24th of September 2018 for acknowledgment of the steering committee. General comments on the methodology and on various scientific aspects have been included in the overview to represent the complete result of the review process.

Table 1 Consolidated Scientific Review Comments (Prof. Sangwon Suh - SS; Prof. Edgar Hertwich – EH; Ugo Pretato - UP)

Index of the comment (per person)	Page	Chapter, sub-chapter	Paragraph, figure, table	Comment, Including justification when needed	Suggestion of redaction, contribution	Follow up of the comment
UP1	15	3 - PEFCR scope	1st paragraph and footnote 7	A photovoltaic module can be mounted on a building or on the open ground. The reference system considered for the PEFCR is a module mounted on a slanted roof. It is less clear how this PEFCR can be applied to PV in open ground or other type of installations.	Add more details on the conditions for which the PEFCR may be applied to modules mounted on the open ground. For instance, is it possible to make comparison between open ground systems? Perhaps good to add some explanations in the limitations or benchmark section.	Explanation added that mounted rooftop systems are the predominant application of PV modules in Europe.
SS1	15	3	2nd para	"Mounting is considered as part of the product, [BUT] the balancing system…are not part of the product [...]." A connector is missing, and the sentence is confusing: balance of system includes all mounting to a commonly accepted definition.	Add "but", remove "the balance of" and add "such as" after "system components"	Agreed, text adapted.

SS2	16	3	first line	"average European irradiation" is incorrect or confusing.	Change it into "average irradiation in Europe weighted by installed PV capacity by country in year XXXX" to make it precise.	Agreed, text adapted.
SS3	16	3	first para	"The reference flow (kWp) is linked…" The sentence appears multipe times in the text, while the meaning of it is not immediately clear.	Might be useful to have a equation to make it more explicit, and then refer to the equation rather than saying the same sentence multiple times.	Agreed, equation added in subchapter 3.3 and referenced in chapter 3.
UP2	16	3.2.1	whole paragraph	Remove "draft" before PEFCR	Remove "draft" before PEFCR	Agreed, text adapted.
UP3	17	3.2.1	table 3.1	a-Si is the same as micro-SI?	Use a consistent terminology. If the technology is Micromorphus Silicon, use always micro-si throughout the document	Agreed, text and tables adapted.
UP4	19-20	3.2.2	tab. 3.3 - 3.4	Table 3.4 looks redundant, as all information are already included in Table 3.3. Moreover, it would be useful to add a column to table 3.3 with the BoM of the representative product	Merge the two tables and possibly add the BoM for the RP	Agreed, table 3.4 removed. No adaptation of table 3.3 (BOM for RP may be confusing because it is a virtual product).
SS4	20	3,3	footnote 11	It would be a useful caveat to mention that a direct comparison with grid electricity is not possible due to the intermittency problem, for which a consideration of capacity factor is needed.	Consider adding more precautionary note.	Environmental performance of individual electricity generation technologies usually requires storage. Analysis should be done for production portfolios of utilities.
SS5	27	4	last sentence and the following tables from the next page	I was not sure how these were generated/identified.	It would be useful to state the criteria (up to 80% contribution to each impact category) in this sentence. Also consider adding % contribution by line item, if possible. Not essential.	New subchapter added to describe the general procedure to identify the most relevant impact categories, life cycle stages and processes.

UP5	28 to 49	4 - Most relevant processes	tables 4.1 to 4.6	There may be a few potential inconsistencies between the BoM and the most relevant processes. Here below some examples: - in CdTe module, aluminium production shows up as relevant process in several impact categories, although Al is not present in the BoM - silicon carbide production shows up relevant in multi-Si module (BoM 6.2 %), but not in mono-Si, where the content is higher (BoM 10.2%) and not in the representative product, which should be dominated by mono-Si and multi-Si results (they make up 85% of the RP as from table 3.1) - Steel also appears relevant for all technologies, including for climate change, although it looks having a tiny contribution to the BoM	Double-check the remodelling results and provide an explanation	Explanation added in section 3.2.2 that the BOM only represents the materials used in the PV modules. Aluminium, steel and copper are mainly used in the mounting system and the electric installation. Silicon carbide is used in the slurry for wafer sawing, silicon (metallurgical / electronic / off grade) represents the silicon actually used in the module. Due to its use as a working material, silicon carbide is not included in the BOM.
UP6	excel LCI	general	copper datasets and others	It is unclear why for certain datasets (e.g. copper, aluminium and others) there is a reference to a "remodelling dataset made by Green Delta" instead of an EF compliant dataset from the Commission's official list	Please double check and explain	In the remodelling, GreenDelta created new foreground processes for copper, aluminium and steel in order to implement the parameters R1, R2 and A of the CFF. These life cycle inventories are then linked to the EF compliant datasets. No adaptation in the PEFCR and in the excel-file.
UP7	excel LCI	general	DQR column	The DQR values in columns L or M, in many cases are not the average of the 4 parameters TiR, TeR, GR and P	Please double-check and amend as appropriate. Perhaps add a formula for an authomatic calculation	Agreed, average DQR values re-calculated according to the formula shown in subchapter 5.4.
UP8	52	5.1	tab 5.1	Elementary flows are not mentioned in the list of mandatory company specific data to be collected. Are they fully absent?	Please double-check and if necessary add the information in § 5.1. See also the PEFCR template in Annex B to the PEFCR Guidance 6.3 (B.5.1). A separate table is requested for the elementary flows	In the previous PEFCR version, companies were asked to collect data on SF6 and NF3 emissions. We reconsidered the life cycle inventories and found that only NF3 is used in the PV supply chain and only for the micro-Si technology. NF3 emissions are listed together with other company-specific data to be collected in the sheet "company-specific data" for the process "photovoltaic panel, micro-Si, at plant" (see line 191). The PEFCR for decorative paints also lists the materials and the elementary flows, for which company-specific data are required, in one table.

						No adaptation in the PEFCR and the excel-file.
UP9	53	5.2	list of processes run by the company	The list of mandatory company specific data in 5.1 is much bigger than the list of processes expected in Situation 1 reported in 5.2. This sounds very demanding for companies applying the PEFCR	Explain the reason	Explanation added in the text. Some key parameters of PV modules, in particular the maximum power output under standard conditions and the specific weight per m2, have a strong impact on all life cycle stages. For instance, the module efficiency determines the area of mounting system needed to install the PV module.
SS6	54	5,4	Eq 2	The same equation appears multiple times.	Refer to this equation rather than repeating the same equation later.	No adaptation, because these are pre-defined sections in the PEFCR template that shall not be adapted.
SS7	54	5,4		It would be important to mention that Eq 2 only addresses parametric uncertainty; truncation (accuracy), and model uncertainty (system uncertainties) are not considered.	Consider adding more precautionary note. Also discuss how DQR is calculated for the case of data gaps (more data gaps means better DQR, as data gaps are omitted from the DQR calculation)	No adaptation, because these are pre-defined sections in the PEFCR template that shall not be adapted. Concerning data gaps, please see comment SS9.
SS8	56		first bullet	The use of % in the last sentence is confusing. It is not clear whether the sentence refers to 37.5% out of 80% (i.e., if 80% is scaled to 100%) or 37.5% out of original 100%. The sentence in the parenthesis: weight to be used for what?	Consider revising the sentence	No adaptation, because these are pre-defined sections in the PEFCR template that shall not be adapted.
UP10	65	5.9	tab 5.6	The allocation rules for electricity in the process PV modules at regional storage may be in contrast with the electricity mix hierarchy at 5.9	The actual "European residual grid mix" should be used as default modelling	The term "European supply mix" referred to the PV modules at regional storage rather than to the electricity mix. Text changed to avoid misunderstandings. The electricity mix to be used in module production shall be chosen according to the general electricity modelling requirements.
SS9	73		Table 6.1	For data gaps, it would be useful to have a asterisk or other means to supplement the table to show how DQR is calculated for them	Consider adding more precautionary note on data gaps and related DQR calculation.	Footnote added in subchapter 6.1 to explain that data gaps are not included in the average DQR value of the company-specific dataset.
UP11	77-78	packaging materials	example of calculation approaches	The example reported in this section on the reuse of glass bottles is irrelevant for the photovoltaic sector and potentially confusing for PEFCR applicants.	Replace the example of glass bottles with another packaging material more appropriate for the sector or delete the example.	Agreed, example replaced by a reference to section 7.16.2 of the PEFCR Guidance.

UP12	excel LCI	datasheet "main product" and others	electricity datasets	Based on the above comment UP10, the electricity consumption datasets to be used should be referred to the country residual mixes, as long as these are available in the EF compliant database	Double check and amend where necessary	Excel file checked and default datasets for electricity changed to residual mix in some instances (LCIs of residual mixes are only available for European countries, but not for CN, JP, KR, US etc.).
SS10	89	6,5		The complexity of how recycling is handled in the current analysis is not clear just by reading the secton (currently landfill is not legal while recycling data is not available, therefore it is assumed to be landfilled)	Add more accurate description of how recycling is handled and explain the data problem.	Explanation added that PV modules were assumed to be landfilled in the remodelling.
SS11	90			2 in "R2" should be a subscript		Agreed, text adapted.
SS12	92ff		Table 6.11	"Remodeling of PV product system by GreenDelta" is not self-explanatory	Consider adding an explanation.	Footnote added in subchapter 6.1 to explain the purpose of the remodelling.
SS13	93	7,1	Second paragraph and other sections	The use of the term, "Applicant" is unusual to US English.	Consider replacing it by "Users"	No adaptation, because this term is used in the PEFCR template that shall not be adapted.
SS14	93	7,1	Second paragraph and other sections	It is not possible to run a monte carlo simulation without stochastic variables presented to the study	Either provide stochastic parameters such as GSDs and means, or remove the requirement of running MCS with 95% confidence level.	Agreed, requirement for Monte Carlo simulation removed.
SS15	95	7.1.2	Tables under section 7	Negatives are neither immediately intuitive in these tables nor clearly explained elsewhere.	Explain why negatives occur.	Explanation for negative values added in a footnote in subchapter 7.1.
UP13	93-103	7.1	Use stage results	A few benchmark values for the use stage are overall negative, i.e. particulate matter, terrestrial eutrophication and land use. Is it due to hidden credits in the treatment process of water used for cleaning the PV modules?	Please provide an explanation	Explanation for negative values added in a footnote in subchapter 7.1.
UP14	94-104	7.1	weighted benchmark values	The weighted impact tables shall also provide the total result, as requested in Guidance 6.3	Please add the total weighted impact to tables 7.3-6-9-12-15-18	Total weighted impacts added to tables showing the benchmark results.
UP15	107	7.4.1	tab 7.19	There are two flows "Peat" with the same name and different characterization factors	Differentiate the flow namings or remove one of them	Flow names differentiated (one referred to biotic peat).

UP16	108-109	7.4.2	general	The additional indicator on RTI of nuclear waste is interesting but its applicability is not fully clear. Most of the data for this indicator are expected to come from upstream processes in the PV modules supply chain, especially from nuclear energy systems. It is unllkely that the EF compliant datasets indicated by the PEFCR contain such information.	Provide more clear guidance on how to get inventory data for applying the RTI indicator	check the default dataset, try to find matching substances and adjust substance list in Tab. 7.21 - done
SS16	110	8	DQR requirement after the bullet points	Under the current requirement, a user is incentivized to remove low-quality data and treat them as data gaps, as they do not contribute to the DQR. I think that it would be important to mention this fitfall in the text.	Consider adding a sentence or two on the potential limitations of this approach due to the fact that DQR does not consider data gaps.	No adaptation, because these are pre-defined sections in the PEFCR template that shall not be adapted.
SS17	112	9	References	There is no reference on MCS or on some of other PV LCAs.	Consider adding some of the references. Here are some that I know or I have contributed to. Henriksson, P. J., Heijungs, R., Dao, H. M., Phan, L. T., de Snoo, G. R., & Guinée, J. B. (2015). Product carbon footprints and their uncertainties in comparative decision contexts. PLoS One, 10(3), e0121221. Heijungs, R., & Huijbregts, M. A. (2004). A review of approaches to treat uncertainty in LCA. Hung, M. L., & Ma, H. W. (2009). Quantifying system uncertainty of life cycle assessment based on Monte Carlo simulation. The International Journal of Life Cycle Assessment, 14(1), 19. Huijbregts, M. (2002). Uncertainty and variability in environmental life-cycle assessment. The International Journal of Life Cycle Assessment, 7(3), 173-173. Qin, Y., & Suh, S. (2017). What distribution function do life cycle inventories follow?. The International Journal of Life Cycle Assessment, 22(7), 1138-1145. Heijungs, R., Henriksson, P. J., & Guinée, J. B. (2017). Pre-	Declined, there is no need to cite studies that have not been used in the development of this PEFCR. The requirement to do a monte carlo simulation for comparisons is removed (see comment SS14).

					calculated LCI systems with uncertainties cannot be used in comparative LCA. The International Journal of Life Cycle Assessment, 22(3), 461-461. Suh, S., & Qin, Y. (2017). Pre-calculated LCIs with uncertainties revisited. The International Journal of Life Cycle Assessment, 22(5), 827-831. Bergesen, J. D., Heath, G. A., Gibon, T., & Suh, S. (2014). Thin-film photovoltaic power generation offers decreasing greenhouse gas emissions and increasing environmental co-benefits in the long term. Environmental science & technology, 48(16), 9834-9843. Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., ... & Shi, L. (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proceedings of the National Academy of Sciences, 112(20), 6277-6282. Bergesen, J. D., & Suh, S. (2016). A framework for technological learning in the supply chain: A case study on CdTe photovoltaics. Applied Energy, 169, 721-728.	