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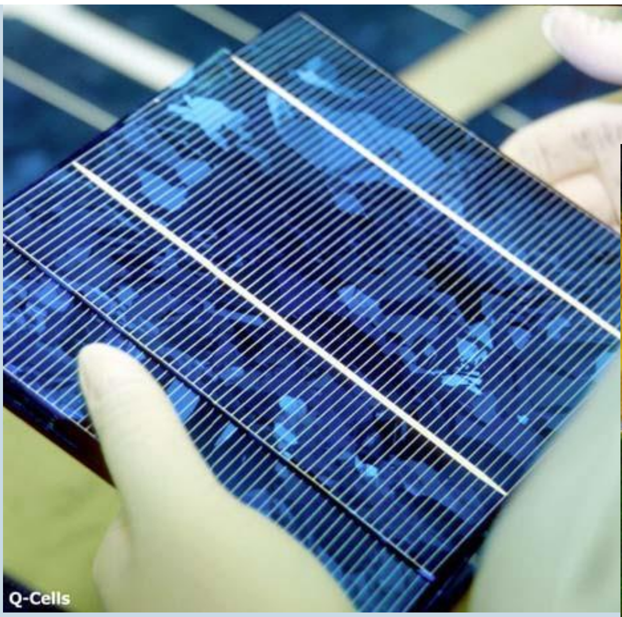
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Karlstadt Laudenbach, Germany (810 kW); Phoenix Solar

Task 12 PV Sustainability

PVPS

Methodology Guidelines on Life Cycle Assessment of Photovoltaic

2020

Report IEA-PVPS T12-18: 2020

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Mexico, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance (SEPA), the Solar Energy Industries Association and the Cop- per Alliance are also members.

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What is IEA PVPS Task 12?

Task 12 aims at fostering international collaboration in safety and sustainability that are crucial for assuring that PV grows to levels enabling it to make a major contribution to the needs of the member countries and the world. The overall objectives of Task 12 are to 1. Quantify the environmental profile of PV in comparison to other energy technologies; 2. Investigate end of life management options for PV systems as deployment increases and older systems are decommissioned; 3. Define and address environmental health & safety and other sustainability issues that are important for market growth. The first objective of this task is well served by life cycle assessments (LCAs) that describe the energy-, material-, and emission-flows in all the stages of the life of PV. The second objective is addressed through analysis of including recycling and other circular economy pathways. For the third objective, Task 12 develops methods to quantify risks and opportunities on topics of stakeholder interest. Task 12 is operated jointly by the National Renewable Energy Laboratory (NREL) and the University of New South Wales (UNSW Sydney). Support from DOE and UNSW are gratefully acknowledged.

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COVER PICTURE

Left : Q-cells Right : Phoenix Solar

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EXECUTIVE SUMMARY

Life Cycle Assessment (LCA) is a structured, comprehensive method of quantifying material- and energy-flows and their associated emissions caused in the life cycle[1] of goods and services. The ISO 14040 and 14044 standards provide the framework for LCA. However, this framework leaves the individual practitioner with a range of choices that can affect the results and thus the conclusions of an LCA study. The present version of the IEA LCA guidelines is the result of the third update. They were developed and are updated to provide guidance on assuring consistency, balance, and quality to enhance the credibility and reliability of the results from LCAs on photovoltaic (PV) electricity generation systems. The guidelines represent a consensus among the authors—PV LCA experts in North America, Europe, Asia and Australia—for assumptions made on PV performance, decisions on process input and emissions allocation, methods of analysis, and reporting of the results.

Guidance is given on PV-specific parameters used as inputs in LCA and on choices and assumptions in life cycle inventory (LCI) analysis and on implementation of modelling approaches. A consistent approach towards system modelling, the functional unit, the system boundaries, water use modelling and the allocation aspects enhances the credibility of PV electricity LCA studies and enables balanced LCA-based comparisons of different electricity producing technologies. The current guidelines cover electricity production with ground mounted, building attached as well as building integrated PV systems. They are intended to be applied on assessing commercially deployed PV technologies.

The document discusses metrics like greenhouse gas emissions (GHG), cumulative energy demand (CED), use of mineral and metal resources, particulate matter, acidification and water use. Guidance is given for the definition of the energy payback time (EPBT), the non-renewable energy payback time (NREPBT), and the environmental impact mitigation potentials (IMP). The indicator energy return on investment (EROI) is described in a separate IEA report (Raugei et al. 2015). The interpretation of results should account for the fact that the environmental impacts may be significantly influenced by parameters that depend on the geographical zone and panel orientation as well as by a system's boundary conditions and the modelling approach.

Transparency in reporting is therefore of the utmost importance. Following the guidelines in the chapter on the reporting and communication of the results serves the need for producing clear, comprehensive, and transparent reports. At a minimum, the following parameters shall be reported in captions of result figures and tables:

1) PV technology (single and multi-crystalline silicon, CdTe, CIS, micromorphous silicon);

2) Type of system (e.g., roof-top, ground mount, fixed tilt or tracker);

3) Module-rated efficiency and degradation rate;

4) Lifetime of PV and BOS;

5) Location of installation;

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[1] The life cycle of goods and services covers raw material and primary energy extraction, material and energy supply, manufacture, use and end of life, including transport and waste management services where needed.

6) Annual irradiation and expected annual electricity production with the given orientation and inclination or system's performance ratio.

Further important information that should be documented in the LCA report are: the time-frame of data; the life cycle stages included; the place/country/region of production (manufacturing components) modelled; the explicit goal of the study including technical and modelling assumptions and the name of the entity commissioning the study; the LCA approach used if not process-based; the LCA software tool (e.g., Simapro, GaBi, other); the LCI database(s) (e.g., UVEK LCI data DQRv2:2018, ecoinvent, GaBi, ELCD, Franklin, US LCI, IDEA) and impact category indicators used, always including the version numbers; the general information and assumptions related to the production of major input materials (e.g., solar grade silicon, aluminium (primary and/or secondary production)); and electricity source if known.

1.INTRODUCTION

Life Cycle Assessment (LCA) is a structured, comprehensive method of quantifying material- and energy-flows and their associated emissions caused in the life cycle[2] of goods and services. The ISO 14040- and 14044-standards provide the framework for LCA. However, this framework leaves the individual practitioner with a range of choices that can affect the results and thus the conclusions of an LCA study. Additional standards and guidelines have later been published such as the ISO 21930 (Environmental Product Declaration on Construction Products", International Organization for Standardization (ISO) 2017), and the Product Environmental Footprint Category Rules (PEFCR) for PV electricity (TS PEF Pilot PV 2018).

The current IEA PVPS guidelines have been developed to offer guidance for consistency, balance, and quality to enhance the credibility of the findings from LCAs on photovoltaic (PV) electricity generation systems. The guidelines represent a consensus among the experts of Task 12, whom are PV LCA experts in the United States, Europe, Asia and Australia, with regard to assumptions on PV performance, pro-cess input and emissions allocation, impact assessment methods, and reporting and communication of LCA-studies and their results. The latter is of the utmost importance as parameters such as geographical zones and system boundary conditions can significantly affect the results. Accordingly, transparency is essential in comparing life cycle-based environmental impacts of the production of electricity (be it produced with PV or any other electricity generation technology).

This guideline document forms the basis for the update (Frischknecht et al. 2020) of the IEA PVPS Task 12 report T12-04:2015 on Life cycle inventories of Photovoltaic electricity generation (Frischknecht et al. 2015b).

The current, fourth edition of the guidelines expands the contents of the third edition, issued in 2015, with additional guidance on system parameters, building integrated PV, selected modelling approaches, water use, recycling, and reporting requirements.

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[2] The life cycle of goods and services covers raw material and primary energy extraction, material and energy supply, manufacture, use and end of life, including transport and waste management services where needed.

2. MOTIVATION AND OBJECTIVES

National and regional energy policies require environmentally friendly electricity generating technologies. The PV industry is experiencing rapid growth and evolution. The key prerequisites for a life cycle assessment on environmental performance are the availability of the most up-to-date information on PV performance and life cycle inventory (LCI) data, and of recent, weighted-average data that accurately represent the mixture of PV technologies available in operation in the country or region of study. The major motivation to provide these methodological guidelines on LCA of PV electricity is due to the variety of approaches and the need for transparent reporting of assumptions and key choices.

The following are the major objectives of this report:

- To provide guidance on how to establish the life cycle inventory of PV electricity.
- To provide guidance on which environmental impacts to address in life cycle impact assessment and which impact category indicators to use.
- To provide guidance on how and what to document when reporting and interpreting LCA of PV electricity.

3. METHODOLOGICAL GUIDELINES

All PV LCA studies should be accomplished according to the general LCA ISO standards 14040 and 14044 as well as to the ISO standard 14046 on water use. Deviations from the nomenclature, procedures and methodologies compared to these standards for life cycle assessment should be stated clearly.

The following guidelines are structured into six main areas:

- Subchapter 3.1 includes recommendations on default technical characteristics used in the LCA of photovoltaic systems;
- Subchapter 3.2 covers aspects of modelling approaches in life cycle inventory analysis;
- Subchapter 3.3 covers aspects specific to electricity production with building integrated PV systems;
- Subchapter 3.4 deals with life cycle impact assessment and which environmental indicators to address;
- Subchapter 3.5 discusses interpretation aspects;
- Subchapter 3.6 covers issues related to reporting and communication.

3.1. Photovoltaics-specific aspects

3.1.1. Life expectancy

The recommended life expectancy used in life cycle assessments of photovoltaic components and systems differentiates between the components:

- Modules: 30 years for mature module technologies (e.g., glass-glass or glass-Tedlar backsheet) used in ground mounted, building attached and building integrated PV modules[3] ; life expectancy may be lower for foil-only encapsulation; this life expectancy is based on typical PV module warranties (i.e., 20 % or less efficiency degradation after 25 years) and the expectation that modules last beyond their warranties.
- Inverters: 15 years for small plants (residential PV); 30 years with 10 % part replacement every 10 years (the parts that are assumed to be replaced need to be specified) for large size plants utility PV (Mason et al. 2006);
- Transformers: 30 years;
- Mounting and supporting structures: 30 years for building attached roof-top and façade installations, and between 30 to 60 years for building integrated installations and for ground-mount installations on metal supports. Sensitivity analyses should be carried out by varying the service life of the ground-mount supporting structures within the same time span;

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[3] Building integrated PV modules may be used longer than 30 years reflecting the longer service life of the building elements (façades, roofs) they are used in. They will possibly show a substantially lower specific yield beyond 30 years. Whether or not building integrated PV modules have a longer service life is uncertain. A service life of 30 years is recommended due to this uncertainty and for the sake of comparability with other PV systems

- Cabling: 30 years;
- Manufacturing plants (capital equipment): The lifetime may be shorter than 30 years due to the rapid development of technology. Assumptions need to be listed.

3.1.2. Irradiation

The irradiation collected by modules depends on their location and orientation. Depending on the goal of the study, four main recommendations are given:

- Analysis of systems based on average technologies or on specific products: Assume for all ground-mounted systems that the panels on an array plane are optimally oriented and tilted at angles equal to the latitude (except when a specific system under study is laid out differently, which should be reported). Also, assume that roof-top installations are optimally oriented and tilted. Assume either optimally oriented or case-specific orientation of panels of façade systems. Additionally, 1-axis tracking systems may be assumed. All assumptions, especially deviations from these general recommendations, should be reported.
- Analysis of the average of installed systems in a grid network: The average actual orientation, shading and irradiation should be used;
- Analysis of building-integrated PV systems in a given building context: annual irradiation incident on the PV surface should be determined using state-of-the-art modelling software (the choice of software may depend on the planning stage of the building);
- Analysis of bifacial PV modules: annual irradiation, in particular the additional irradiation on the backside, should be determined using state-of-the-art modelling software.

The International Standard IEC 61724 offers a description of irradiance (W/m2) and irradiation (also called insolation) (kWh/m2/yr). Breyer and Schmid (2010) provide country-specific plane of array irradiation estimates for fixed-tilt and tracking PV systems.

3.1.3. Performance ratio

The performance ratio (PR) is defined by IEC 61724 as the ratio between the system's final yield (actual AC generation) and the reference or ideal yield (DC rated performance) and is widely used as a performance metric to quantify the overall system losses due to temperature effects, soiling, shading and inefficiency of its components. In general, PR increases with 1) decline in temperature and 2) early monitoring of PV systems to detect and rectify defects. Shading, if any, and soiling would have an adverse effect on PR. This means that well-designed, well-ventilated, well-maintained, and large-scale systems generally have a higher PR. Average annual PR data collected from many residential systems show an upward trend from typical 0.7 in the 1990'ies with widely ranging values, to current values between 0.8 and 0.9 with less variance (Fraunhofer ISE 2019).

Using either site-specific PR values or a default value of 0.75 is recommended for roof-top installations and 0.80 for ground-mounted utility installations (Fthenakis et al. 2008; Mason et al. 2006; Pfatischer 2008); these default values include degradation caused by age. The performance ratio of building-integrated PV systems and bifacial PV panels should be determined individually for each application, due to the impacts of irradiance for each case and the changes in DC:AC ratios that these systems might require. When site-specific PR values are used based on performance from previous years, degradation-related losses should be added to longer-term projections of the performance.

It is recommended to use actual performance data (actual energy yield in kWh per kWp) of installed technology whenever available or make reasonable assumptions that reflect actual performance data when analyzing the average of installed PV systems in a grid network. This can be aided by the use of PV system modelling software. Such software can calculate the output of the system over the duration of the project, making the calculation of the average PR possible.

The PR is used in combination with solar irradiation data to determine actual yields.

3.1.4. Degradation

PV modules degrade over time reducing their efficiency and hence their output over their lifetime. Hence, the annual degradation rate must be considered when estimating the total yield of a PV system during the assessed period. The following degradation rates are recommended:

- Mature module technologies: Assume a linear degradation of 0.7 %-points per year unless long-term scientific evidence and independently verified test results prove a different value. A degradation of 0.7 %-points per year leads to a loss in yield of 21 % during the last year of operation, which corresponds to an average reduction of the initial efficiency of 10.5 % over the lifetime of 30 years. When annual yields are extrapolated from site-specific data to calculate the total yield over the lifetime, it should be clearly stated whether annual degradation rate is considered or not.
- Use an annual degradation rate of 0.5 %-points (instead of 0.7 %-points) in a sensitivity analysis, resulting in an average reduction in the annual yield of 7.5 %.

More information on degradation rates for different PV technologies is available in Jordan et al. (Jordan et al. 2016). It confirms the average degradation rate of 0.7 %-points per year.

In case actual, measured yields are reported for a PV plant for its whole lifetime, then no additional calculations are required either using degradation rates or performance ratio (see Section 3.1.3).

3.1.5. Curtailing and DC:AC ratio

The ratio of direct current (DC) nominal output of the PV panels to the alternate current (AC) inverter capacity is an important factor, in particular when the DC output of the PV panels is significantly higher than the AC capacity of the inverter. PV electricity generated by a system with a DC output of PV panels that is 1.2 times the AC capacity of its inverter is dependent only upon the inverter capacity and its efficiency.

Utilities may apply curtailing PV electricity to be fed into their grid for various reasons. If this situation applies, the reference flow should be represented including the curtailed amounts of AC electricity.

3.1.6. Back-up Systems

Back-up systems such as temporal electricity storage, hydroelectric or gas combined cycle power plants, or hybrid PV (combinations of PV and diesel aggregates) are considered to be outside the system boundary of PV LCA (and for any other electricity generating technology).

The environmental performance of the combination of electricity generating technologies is best assessed at the level of a utility's (or micro-grid's) power plant portfolio (see also Section 3.2.2). If a back-up system is included in a PV LCA, it should be explicitly and clearly described.

3.2. Life cycle inventory modelling aspects

3.2.1. System models

The appropriate system model depends on the goal of the LCA. Depending on the study's goal and scope, an attributional, decisional or consequential approach can be chosen (Frischknecht & Stucki 2010; Sonnemann & Vigon 2011). Up to now, most LCAs are based on the attributional approach.

The following goals can be distinguished which lend themselves to the use of different types of LCAs on PV electricity (in parentheses):

A. Reporting environmental impacts of PV currently installed in a utility's network, comparisons of different PV systems, or of electricity-generating technologies (retrospective / attributional LCA)

B. Choice of a PV electricity-supplier, switch of raw material or energy suppliers (short-term prospective / decisional LCA)

C. Future energy supply situation: comparison of future PV systems or of future electricity-generating technologies (use long-term prospective LCA / future attributional LCA to model future static situations)

D. Large scale, long-term energy supply transition: large scale-up of PV in electricity grids of nations and regions (use consequential LCA to model such transitions)

The following recommendations apply on all goals:

- The product system shall be divided into foreground- and background-processes. In line with Sonnemann & Vigon (2011) the following definitions are proposed:
  - Foreground processes are those which the decision-maker or product-owner can influence directly.
  - Background processes are all remaining processes of the particular product system.
  - Additional discussion on background/foreground can be found in (Frischknecht 1998).
- We recommend using the conventional process-based LCA developed by SETAC (1993) and standardized by the ISO (International Organization for Standardization (ISO) 2006a, b).
- Input-Output-based LCA method: This approach is not followed in this subtask within IEA PVPS. More confidence in employing it is needed before its application is recommend. This recommendation is in line with the Global Guidance Principles for Life Cycle Assessment Databases published by the UNEP-SETAC Life Cycle Initiative (Sonnemann & Vigon 2011).
- Hybrid method (combining Input-Output LCA and process based LCA, see e.g. Hertwich et al. 2014; Wiedmann et al. 2011): If a hybrid approach is chosen, report transparently and provide justification for using it.

The following recommendations apply to goal A described above (i.e., Reporting environmental impacts of PV currently installed; comparisons of PV systems):

- Assume the present average electricity grid mix for the relevant country (e.g., Europe (EU 28, including Norway and Switzerland), United States, Korea, China, or Japan) when modelling the manufacture of current PV components. Specify the year for which the data are valid.
- If a PV material is produced in a specific country, by a limited number of companies, or if the PV material production generally involves a specific type of electricity supply, then an argument can be made for selecting a country or company-specific electricity mix. An example here is hydropower for producing silicon feedstock in Norway.
- However, country- or company-specific cases must be clearly reported so that data are not unintentionally projected to different scales and regions.

The following recommendations apply to goal B (Choice of a PV electricity-supplier; switch of feedstock or energy suppliers):

- Assume an annual marginal electricity grid mix for the relevant country. Specify the time span for which the changes in the grid mix are applicable. Use grid mix data from relevant national or regional electricity scenario reports to derive the marginal mix (see Frischknecht & Stucki (2010) for an example).
- Specify the environmental performance and energy efficiency of the power plants contributing to this marginal electricity mix. The performance of these specific power plants may differ from national or utility portfolio averages.
- Specify mid-term future, marginal market mixes of PV material feedstocks, chemicals, energy carriers etc. which may contribute significantly to the PV life cycle-based environmental impacts and where average and marginal mixes may differ substantially.

The following recommendations apply to goal C (Future energy supply situation):

- Use an annual-average future electricity mix for the relevant country when modelling future production of PV components. Specify the year for which the forecasted data are applicable. Use grid mix data from relevant national or regional electricity future scenario reports.
- Specify the environmental performance and energy efficiency of the power plants contributing to this future electricity mix. Being power plants operated in the future, they should represent possible future states (see e.g. Frischknecht et al. 2015a).
- If a PV material is expected to be produced in a specific country, by a limited number of companies, or if the material production generally uses a specific type of electricity supply, an argument can be made for choosing a country- or company-specific electricity mix, e.g., hydropower for producing silicon feedstock production in Norway. However, in prospective analyses, the availability of country-specific resources to the projected market volumes must be documented. Country- or company-specific cases must be identified clearly, so that data are not used unintentionally for projections to different market volumes and regions.
- Adapt the efficiency of material supply-, transport-, and waste-management-services so that they represent a possible future state, consistent with the underlying energy-policy scenario (see e.g. Frischknecht & Stucki 2010; Frischknecht et al. 2015a; Hertwich et al. 2014).

The following recommendations apply to goal D (Large scale, long-term energy supply transition):

- Identify the main and significant changes in the economy (world-wide) which are caused by a large scale-up of PV panel installation and production and consequently electricity production. This may be done by expert interviews, general or partial equilibrium models, or backcasting techniques.
- Identify marginal technologies within the most relevant markets affected by the changes in the economy. Use forecasting reports published by official bodies or industry associations.
- Establish life cycle inventories of these marginal technologies.
- Adapt the efficiency of future production of materials, transport-, and waste-management-services so that they represent a possible future state, consistent with the underlying economic scenario (see e.g. Frischknecht & Stucki 2010; Frischknecht et al. 2015a; Hertwich et al. 2014).
- Further aspects such as rebound effects and spillover effects may be taken into account using economic models (e.g., general or partial equilibrium models), scenario techniques or other suitable approaches (Girod 2009).
- Because consequential LCA is an emerging field and has not typically been applied to PV, analysts should conduct a careful literature review to be aware of the latest developments in the field (see e.g. Ekvall & Weidema 2004, Suh & Yang 2014, Zamagni et al. 2012). Examples of consequential LCAs are, for instance, Vázquez-Rowe et al. 2013, Lund et al. 2010, and Blanc (ed.) (2015).

3.2.2. Functional unit and reference flow

The functional unit allows consistent comparisons to be made of various PV systems and of other electricity-generating systems that can provide the same function. We recommend using the ISO’s language to distinguish between “functional unit”[4] and “reference flow”. The reference flow[5] is used as the denominator of the cumulative emissions and resource consumptions and the environmental impacts of the product system under study, whereas the functional unit specifies the quantified performance of a product system.

We recommend the following functional unit for PV systems:

- AC electricity delivered to the grid quantified in kWh for comparison of PV technologies, module technologies, and electricity-generating technologies in general (goals A to D). For PV systems with dedicated transformers (e.g., utility solar farms), use the electricity-output downstream of the transformer.

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[4] The functional unit is the quantified performance of a product system for use as a reference unit (International Organization for Standardization (ISO) 2006a, Clause 3.20).

5 The reference flow is a measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit (International Organization for Standardization (ISO) 2006a, Clause 3.29).

Alternatively, the reference flows “m^2” or “kWp (rated power)” may be used. However, these reference flows are not suitable for comparisons of other technologies to PV nor for comparisons among PV technologies.

- m^2 module can be used for quantifying the environmental impacts of the construction and end of life efforts of PV systems attached to or integrated in a particular building, including building integrated PV (BIPV) building elements, or of supporting structures (excluding PV modules and inverters). Square metre (m2) shall not be used for comparisons among PV and BIPV technologies covering manufacture, use and end of life, because of differences in module and inverter efficiencies and performance ratios.
- kWp (rated power, DC) is used for quantifying the environmental impacts of electrical parts, including inverter, transformer, wire, grid connection and grounding devices. The kWp may also serve as the reference flow in quantifying the environmental impacts of an individual module technology. However, the comparisons of module technologies should not be based on nominal power (kWp) figures because the amount of kWh fed to the grid may differ between the systems analysed.

The location, the module technology used, the voltage level, and whether and how the transmission and distribution losses are accounted for, shall be specified.

AC electricity may differ in dispatchability and intermittency. Electricity production with one particular technology (PV or wind or nuclear) hardly meets all the demand at all times; thus mixtures of power generating technologies are typically deployed. Aspects of dispatchability or intermittency of AC electricity produced with different technologies shall not be addressed on a technology level but on the level of grid mixes provided by utilities (see also Carbajales-Dale et al. 2015).

3.2.3. System boundaries

This section defines the scope of the analysis for the product system of PV and BIPV electricity. It offers guidance on what to include and exclude from the life cycle inventory analysis.

The following parts should be included in the system boundaries (stages according to EN 15804, 2013):

Product stage (Modules A1 to A3):

- Raw material and energy supply;
- Manufacture of the panels;
- Manufacture of the mounting system;
- Manufacture of the cabling;
- Manufacture of the inverters;
- Manufacture of all further components needed to produce electricity and supply it to the grid (e.g., transformers for utility-scale PV).

Manufacturing in the product stage of the LCI should cover the following: energy- and material-flows caused by manufacturing and warehousing, climate control, ventilation, lighting for production halls, on-site emissions and their abatement, and on-site waste treatments. PV manufacturing equipment should be included if data are available.

Construction stage (Modules A4 and A5):

- Transports to the PV power plant site (where the PV plant will be operated);
- Construction and installation, including foundation, supporting structures and fencing.

Use stage (Module B):

- Auxiliary electricity demand;
- Cleaning of panels;
- Maintenance;
- Repair and replacements, if any.

End of life stage (Module C):

- Deconstruction, dismantling;
- Transports;
- Waste processing;
- Recycling (see Section 3.2.5) and reuse;
- Disposal.

The following parts should be excluded:

- Commuting by employees (transportation to and from work);
- Administration, marketing, and research and development (R&D) activities.

3.2.4. Modelling water use

Water use and PV systems

Water use occurs during all life cycle stages of PV electricity. Water is used in industrial processes of the supply chains of PV panels, for cleaning purposes during the operation of PV systems and in the end of life stage in PV panel recycling.

Main reference and definitions

The main reference for modelling water use is the international standard on water footprint (International Organization for Standardization (ISO) 2014). The terms used in this document refer to the ISO standard on water footprint.

Water use inventory

This section explains how water consumption[6] can be quantified from inventory data (unit processes) (see also Flury et al. 2012). Both water withdrawal or water consumption are often assessed because both are relevant to different water-related impacts. Nevertheless, if one has to choose, the IEA PVPS Task 12 experts consider water consumption preferential as a single indicator, in particular with regard to water scarcity. This is in line with the Environmental Footprint method, which assesses water consumption with the AWARE indicator[7] (see

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[6] Water removed from, but not returned to, the same drainage basin (ISO 14046, International Organization for Standardization (ISO) 2014

[7] The AWARE indicator is recommended by the Life Cycle Initiative, hosted by UN Environment.

Subchapter 3.4). Following this, how to establish a water consumption inventory is described in this section. The basic information can however easily be used to quantify water withdrawal, if considered more appropriate and if the inventory information available is complete.

The life cycle inventory data should include the entire water balance (including rainwater). To do so, new elementary flows with country and/or regional codes must be introduced so that a regional assessment is possible. Input of water is now no longer differentiated by source, but rather subsumed under one elementary flow. Embodied water, i.e., water contained in products, is also considered a water input.

Tab. 3.1 provides an overview of elementary flows required for an industrial and agricultural process as an example. The water input (1 + 2) should match the water output (sum of 3 to 7). If rain water is also covered, it must be taken into account in the output as well, i.e., included in the amount of evaporated (3), discharged (4, 5), infiltrated (6) and embodied (7) water, respectively.

The following is the minimum information required for a complete inventory and a flexible assessment of processes:

- Water withdrawal, country- or region-specific (1)
- Evaporation: emission of water into the air, country-specific (3)
- Water released to the sea (and thus being lost), (5)
- Water contained in the product, country-specific (2, 7)

Tab. 3.1 Elementary flows for a complete inventory of water used in industrial and agricultural processes

No.	Elementary flow	Industrial process	Agricultural process
Input			
1	Water, unspecified natural source, country XY	Water for production process (e.g. cleaning devices, containers, etc.)	Water for irrigation
-	Water, rain	Not taken into account	Taken into account for complete inventory
2	Water, embodied, country XY	Water embodied in raw materials (including water supply from water works)	Water embodied in seeds
Output			
3	Water, country XY (emitted to air)	Emission: water vaporized during the production process	Emission: evaporated irrigation water from farmed fields
4	Water, river/lake	Discharged directly from the industry into surface waters	Discharged from fields into surface waters
5	Water, sea	Discharged directly from industry into the sea	Discharged from the fields into the sea
6	Water, soil	Direct infiltration in the soil	Infiltration in the soil from fields
7	Water, embodied, country XY	Water embodied in the product	Water embodied in the product
Total			
	Water withdrawal	1	1
	Consumptive water use	3+5+7-2 = 1-4-6	3+5+7-2 = 1-4-6

3.2.5. Modelling allocation and recycling

Consistent allocation rules are demanded for all multifunction processes (those simultaneously producing several different products, e.g., electronic and off-grade silicon supply), recycling of materials (e.g., using recycled aluminium or copper), and employing waste heat (e.g., heat recovery in municipal-waste incinerators). We recommend following the ISO standard 14044, Clause 4.3.4 “Allocation” (International Organization for Standardization (ISO) 2006b).

It is recommended to perform several analyses on material recycling using the recycled content (cut-off) allocation approach as default and the end-of-life (avoided burden) recycling approach in a sensitivity analysis. A description and characterisation of both approaches is given in Frischknecht (Frischknecht 2010). An example of the application of the recycled content and the end of life approach to the current generation recycling of PV modules is provided in Stolz et al. (2018). The life cycle inventories of PV systems published by Frischknecht et al. (2015b and 2020) are based on the recycled content approach and should be combined with the corresponding life cycle inventories for PV module recycling. The end-of-life approach is recommended to be used when identifying the environmentally preferable end-of-life treatment option of PV panels.

Building integrated PV (BIPV) is a special case of multifunctionality as these PV modules serve as weather protection and energy producing elements. If required, an allocation of the manufacturing efforts of BIPV panels shall be done based on clearly described criteria, avoiding the derivation and application of credits as much as possible (see Subchapter 3.3).

In case system expansion (International Organization for Standardization (ISO) 2006b, Clause 4.3.4.2) is applied and environmental benefits and environmental impacts beyond the system boundary are quantified (e.g., using the end-of-life (avoided burden) recycling approach), these benefits and loads shall be reported separately. The benefits and impacts shall be quantified in relation to the net amount of surplus secondary materials or fuels leaving the product system (all outputs of a secondary material minus all inputs of that secondary material, see also EN 15804 (2013)).[8]

For the case of consequential LCAs (goal D in Section 3.2.1), allocation of multi-output and recycling processes are typically based on system expansion according to, e.g., Ekvall & Weidema (2004). In such cases the identification of technologies being displaced is key and choices and assumptions should be reasoned and described.

3.2.6. Databases

The IEA PVPS Task 12 does not recommend any particular LCI database. However, in choosing an LCI database, of the utmost importance is the transparency of the documentation and availability of the unit process information and data.

The Swiss partners committed themselves to implementing the LCI data compiled within Task 12, Subtask 2 “LCA” (Frischknecht et al. 2015b) into a database used by the public authorities, thereby facilitating the distribution of up-to-date and transparent LCI information on photovoltaics. As of now, data are supplied in EcoSpold v1 format and following the ecoinvent

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[8] In end of life allocation, the benefit of recycling is realized from recycled material displacing primary production in the future, with the environmental burdens and benefits of recycling allocated to the product producing the waste at its end of life. In recycled content allocation, the recycling benefit is realized by the product using the recycled content in its production

v2 guidelines and the KBOB guidelines[9]. The Subtask 2 LCA partners acknowledge and support this commitment.

Product Environmental Footprint (PEF) studies shall use the secondary datasets listed in the PEFCR (TS PEF Pilot PV 2018). The PEF-compliant datasets are freely available for use in PEF studies. They can be downloaded on different nodes of the Life Cycle Data Network[10]. Most of these datasets are at least partially aggregated, i.e. showing the life cycle inventory results from cradle to gate rather than individual gate to gate unit process data.

3.3. Building-integrated PV systems

3.3.1. Goal and scope

Building-integrated photovoltaics (BIPV) may contribute to reducing the environmental footprint of buildings during their entire life cycle (i.e., manufacture, construction, operation and end of life). Environmental life cycle assessment may help to quantify the environmental footprint of BIPV by answering the following questions:

- How big is the environmental footprint of a BIPV building element?
- How big is the environmental footprint of BIPV-generated electricity?
- How does the environmental performance of a building with BIPV compare to a building with identical characteristics but without BIPV?

The life cycle assessment methodology of BIPV depends on the question to be answered. In the following sections the main steps are explained for the questions about environmental footprint of BIPV-generated electricity.

3.3.2. General recommendations

- The present PV LCA methodology guidelines and the EROI methodology guidelines (Raugei et al. 2015) shall be applied unless otherwise stated in this Subchapter.
- The BIPV module, the substructure, cabling, and electronics should be modelled in individual unit processes.
- Efficiency of BIPV modules should be based on manufacturer’s data.
- Any proven difference in lifetime of the BIPV elements versus traditional PV modules should be considered.
- The LCA of the manufacture of BIPV modules should as far as possible and feasible be based on primary data.

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[9] As of October 2019, the Swiss Federal Offices and ecoinvent are working on merging the contents of ecoinvent data v3.6 (ecoinvent Centre 2019) and UVEK LCI data DQRv2:2018 (KBOB et al. 2018).

[10] https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm (accessed on 16.10.2019).

3.3.3. BIPV electricity

We recommend the LCA of BIPV electricity to adhere to the following terms:

- Functional unit: 1 kWh of AC electricity produced by BIPV on a specific building.
- Scope: The LCA should include the BIPV module (building element), the substructure (specific to the BIPV building element), cabling and electronics (inverters, microinverters, optimisers, etc.).
- Life cycle phases: the LCA should cover material supply and module production, installation and mounting, operation, and EOL management.
- We recommend calculating the electricity production (specific yield) of BIPV installed on a specific building using state-of-the-art modelling software (the choice of software may depend on the planning stage of the building) or using measurements covering several years.
- Other operational aspects like cleaning and regular inspections should be taken into account in the operation phase.
- Allocation: we recommend determining the share of the environmental footprint of the BIPV building element attributable to the electricity production, by identifying the active elements required to produce electricity (semiconductor material, EVA foil, cabling, electronics). The remaining parts (weather protection: glass layer; substructure) are attributed to the building.

3.4. Life cycle impact assessment (LCIA)

In environmental life cycle impact assessment of PV electricity, the midpoint indicators of the PEFCR (TS PEF Pilot PV 2018; European Commission 2017; Fazio et al. 2018) should be used.

The default midpoint indicators are complemented by additional indicators to quantify the radiotoxicity potential of nuclear waste, the renewable and non-renewable cumulative energy demand and the biodiversity damage potential caused by land use. The last indicator is intended to replace the land use indicator used in the PEFCR. The biodiversity damage potential caused by land use reached the level of “recommendation“ in the harmonisation effort of life cycle impact assessment indicators within the Life Cycle Initiative hosted by UN Environment (see Frischknecht & Jolliet 2016). The indicators are shown in Tab. 3.2.

Tab. 3.2 List of life cycle impact assessment indicators to be addressed in PV LCA studies (TS PEF Pilot PV 2018; European Commission 2017; Fazio et al. 2018; Zampori & Pant 2019) CFC: Chlorofluorocarbon; kBq: kilo Bequerel; NMVOC: non methane volatile organic carbon; Sb: Antimony; n.i.: not indicated in Zampori & Pant (2019)

Impact category	**Indicator**	**Unit**	**Recommended default LCIA method**	**Robust-ness**
Indicators required according to the PEF guide and PEFCR				
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg $CO_{2\,eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)	I
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11_{eq}	Steady-state ODPs 1999 as in WMO assessment	I
Human toxicity, cancer	Comparative Toxic Unit for humans (CTU_h)	CTU_h	USEtox model (Rosenbaum et al. 2008)	III
Human toxicity, non- cancer	Comparative Toxic Unit for humans (CTU_h)	CTU_h	USEtox model (Rosenbaum et al. 2008)	III
Particulate matter	Impact on human health	disease incidence	UNEP recommended model (Fantke et al. 2016)	I
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)	II
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg $NMVOC_{eq}$	LOTOS-EUROS model (Van Zelm et al. 2008) as implemented in ReCiPe	II
Acidification	Accumulated Exceedance (AE)	mol $H+_{eq}$	Accumulated Exceedance (Posch et al. 2008; Seppälä et al. 2006)	II
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N_{eq}	Accumulated Exceedance (Posch et al. 2008; Seppälä et al. 2006)	II
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P_{eq}	EUTREND model (Struijs et al. 2009) as implemented in ReCiPe	II
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N_{eq}	EUTREND model (Struijs et al. 2009) as implemented in ReCiPe	II
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTU_e)	CTU_e	USEtox model (Rosenbaum et al. 2008)	III
Land use	PEFCR indicator/method replaced by biodiversity loss indicator, see additional indicators below			
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world$_{eq}$	Available WAter REmaining (AWARE) (Boulay et al. 2017)	III
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb_{eq}	CML 2002 (Guinée et al. 2001) and (van Oers et al. 2002)	III
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinée et al. 2001) and (van Oers et al. 2002)	III

Additional indicators				
Land use	Biodiversity loss	PDF years	Chaudhary et al. 2015; Chaudhary et al. 2016; Chaudhary & Brooks 2018	n.i.
Cumulative energy demand, renewable	Gross energy content of renewable primary energy resources	MJ oil eq.	Frischknecht et al. 2015d	n.i.
Cumulative energy demand, non-renewable	Gross energy content of non-renewable primary energy resources	MJ oil eq.	Frischknecht et al. 2015d	n.i.
Nuclear waste	Radiotoxicity index, RTI	m^3 HAA eq.	Frischknecht & Büsser Knöpfel 2013, 2014	n.i.

Most of the indicators listed in Tab. 3.2 are described in Hauschild et al. (2011). Some practical aspects related to selected impact category indicators are described below.

Climate change: The most recent global warming potential (GWP) factors published by the IPCC (2013, Chapter 8) should be used. Global Temperature increase potential (GTP) has additionally been recommended as a useful metric in LCA (Cherubini et al. 2016). In line with the Kyoto protocol and international agreements (United Nations 1998), GWP 100 year is recommended as default and GTP 100 for use in sensitivity analyses.

Water use: This indicator should assess water scarcity due to consumptive water use. The water turbined in hydroelectric power plants shall be excluded from the assessment. However, the share of water evaporated from water reservoirs of hydroelectric power plants should be included. Depending on the LCI database used, the characterisation factors for the impact category “water use” of the PEF method may need to be adapted or amended in order to quantify water consumption and account for all relevant elementary flows. More information may be obtained from the database providers.

Cumulative Energy Demand (CED): The indicator “CED, non-renewable” (MJ oil-eq.)[11] includes fossil and nuclear and the indicator “CED, renewable” (MJ oil-eq.) includes hydropower, solar, wind, geothermal, and biomass. The indicators are quantifying the amount or primary energy harvested (Frischknecht et al. 2007a; Frischknecht et al. 2007b; Frischknecht et al. 2015c). It should always be stated which energy sources are included in the CED indicator result. See also the discussion of CED in the context of Task 12 Net Energy Analysis Guidelines (Raugei et al. 2015).

Long-term emissions contributing to human toxicity, ionising radiation, eutrophication, and ecotoxicity: The quantification of the environmental impacts should be based on the emissions occurring within 100 years. Environmental impacts due to long--term emissions, i.e. beyond 100 years, may be quantified. If so, long-term environmental impacts shall be reported separately.

In addition to the indicator-specific recommendations above, when using life cycle impact assessment methods that use impact pathway analysis to estimating environmental damage, be transparent about methodology and assumptions or clearly refer to the method and its version applied.

To quantify environmental external costs, we recommend using the generic external cost factors published by the NEEDS project (NEEDS 2009).

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[11] The unit “MJ oil-eq” indicates that the cumulative energy demand is a life cycle impact category indicator similar to the abiotic depletion potential which is expressed in kg Sb-eq (Frischknecht et al. 2015c).

3.5. Interpretation

3.5.1. Introduction

According to the ISO Standards on life cycle assessment, interpretation is the final phase of the LCA procedure, in which the results of an LCI (life cycle inventory analysis) or an LCIA (life cycle impact assessment), or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the definition of the goal and scope of the LCA.

Some of the impact indicators described above and calculated in the impact assessment phase may further be processed into energy payback times (EPBT, see Section 3.5.2), or environmental impact mitigation potentials (IMPs) such as climate change (see Section 3.5.3), or into energy return on investment (EROI) figures.

The two following sections describe the energy and the non-renewable energy payback time indicators and then the environmental impact mitigation indicator. The reporting requirements described in Section 3.6. apply to these indicators too. In contrast to com-mon life cycle impact category indicators, the payback and mitigation indicators are very much dependent on the context, i.e. on the energy and environmental efficiency of the electricity supplying system assumed to be replaced by photovoltaics. Information and recommendations on the Energy Return on Investment (EROI) indicator is given in the IEA PVPS report on Net Energy Analysis (Raugei et al. 2015).

3.5.2. Energy Payback Time (EPBT) and Non-Renewable Energy Payback Time (NREPBT)

Energy payback time is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of primary energy equivalent) that was used to produce the system itself.

Energy Payback Time = $(E_{mat} + E_{manuf} + E_{trans} + E_{inst} + E_{EOL}) / ((E_{agen} / \eta_G) - E_{O\&M})$

where,

E_{mat} Primary energy demand (in MJ oil-eq) to produce materials comprising PV system

E_{manuf} Primary energy demand (in MJ oil-eq) to manufacture PV system

E_{trans} Primary energy demand (in MJ oil-eq) to transport materials used during the life cycle

E_{inst} Primary energy demand (in MJ oil-eq) to install the system

E_{EOL} Primary energy demand (in MJ oil-eq) for end-of-life management

E_{agen} Mean annual electricity generation

$E_{O\&M}$ Annual primary energy demand (in MJ oil-eq) for operation and maintenance

η_G Grid efficiency, the primary energy to electricity conversion efficiency at the demand side (kWh electricity per MJ oil-eq)

The reasoning and assumptions applied to identify the relevant grid mix shall be documented.

Based on the above definition, there are two existing conceptual approaches to calculate the EPBT of PV power systems.

1. *PV as replacement of all energy resources used in the power grid mix.* This approach calculates the time needed to compensate for the total (renewable and non-renewable) primary energy required during the life cycle of a PV system (except the direct solar radiation input during the operation phase, which is disregarded and thus not accounted for as part of EO&M). The annual electricity generation (Eagen) is converted into its equivalent primary energy, based on the efficiency of electricity conversion at the demand side, using the current average or average non-renewable (in attributional LCAs) or the long term marginal (in decisional/consequential LCAs) grid mix where the PV plant is being installed.
2. *PV as replacement of the non-renewable energy resources used in the power grid mix*. This approach calculates the EPBT by using the non-renewable primary energy only (as recommended by Frischknecht et al. (1998)); renewable primary energy is not accounted for, neither on the demand side (during manufacturing), nor during the operation phase. This approach calculates the time needed to compensate for the non-renewable energy required during the life cycle of a PV system. The annual electricity generation (Eagen) is likewise converted to primary energy equivalent considering the non-renewable primary energy to electricity conversion efficiency of the average or average non-renewable (in attributional LCAs) or the long term marginal (in decisional/ consequential LCAs) grid mix where the PV plant is being installed. The result of using this approach shall be identified as Non-Renewable Energy Payback Time (NREPBT) to clearly distinguish it from the EPBT derived from the 1st approach. The formula of NREPBT is identical to that of EPBT described above except replacing “primary energy” with “non-renewable primary energy”. Accordingly, grid efficiency, ηG, accounts for only non-renewable primary energy.

Both EPBT and NREPBT depend on the grid mix underlying the electricity conversion on the demand side; however, excluding the renewable primary energy makes NREPBT more sensitive to local or regional (e.g., product-specific use of hydro-power) conditions, which may not be extrapolated to large global scales. On the other hand, EPBT metric with an average large-scale (e.g. EU, or US, or World) grid conversion efficiency may not capture local or regional conditions.

The calculated EPBT and NREPBT do not differ significantly in case the power plant mix of a country or region is dominated by non-renewable power generation. However, as an increasing share of renewable energies is expected in future power grid mixes as well as within the PV supply chain, the two opposing effects of a reduction in the CED of PV and an increase in grid efficiency will require careful consideration (Raugei 2011, 2013), and the numerical values of EPBT or NREPBT may come to vary considerably according to the chosen approach.

Therefore, it is important to choose the approach that most accurately describes the system parameters and satisfies the goal of the LCA study. LCA practitioners may want to apply both approaches and compare the results for transparency and clarity. In any case, it is mandatory to specify the approach on which the calculation is based. In addition, specify the reference system, e.g., today’s European electricity mix, today’s European non-renewable electricity (the European electricity mix excluding electricity produced with renewable energies) mix or the national electricity-supply mix in accordance to the system modelling and the goal of the LCA (attributional/decisional/consequential). Specify and give the reference for the primary energy-to-electricity conversion factor, and specify the energy contents of energy resources used to quantify the non-renewable and renewable cumulative energy demand.

3.5.3. Environmental impact mitigation potentials (IMP)

Environmental impact mitigation potentials (IMP) are quantified similar to the energy payback times. This may comprise mitigation potentials regarding climate change impacts or high-level nuclear waste (Jungbluth et al. 2008). These IMPs are quantified on a life time basis of the PV system. On one hand the life cycle-based impacts potentially avoided with the lifetime production of electricity with a PV system in a given economic, national or regional context are quantified. On the other hand, the life cycle-based impacts caused by material supply, manufacturing, installation, operation, maintenance and end-of-life management are determined. Below the formula to quantify the climate change mitigation potential is shown.

$$\text{Climate Change IMP} = CC_{agen} * \gamma_{G} - (CC_{mat} + CC_{manuf} + CC_{trans} + CC_{inst} + CC_{EOL} + CC_{O\&M})$$

where,

CC_{mat}	Climate change impact (in kg CO2-eq) of producing materials comprising PV system
CC_{manuf}	Climate change impact (in kg CO2-eq) of manufacturing PV system
CC_{trans}	Climate change impact (in kg CO2-eq) of transporting materials used during the life cycle
CC_{inst}	Climate change impact (in kg CO2-eq) of installing the system
CC_{EOL}	Climate change impact (in kg CO2-eq) of end-of-life management
CC_{agen}	Life time electricity generation (in kWh)
$CC_{O\&M}$	Life time climate change impact (in kg CO2-eq) of operation and maintenance
γ_{G}	Climate change impact (in kg CO2-eq/kWh) of grid electricity at the demand side

The impact assessment method applied should be clearly referenced, and the reference system, e.g., today's European electricity mix, today's European non-renewable electricity mix or the national electricity supply mix should be specified.

3.6. Reporting and communication

The life cycle assessment, energy payback time, environmental impact mitigation potential results should come along with information about key parameters and other important aspects characterising the PV system(s) analysed. The list of items is separated in key parameters required in the captions of figures and tables showing the results of the LCA (items 1 to 6) and further important aspects which should be documented elsewhere in the same LCA report.

Key parameters to be documented in captions of figures and tables:

1. PV technology (e.g., single and multi-crystalline silicon, CdTe, CIS, amorphous silicon, micromorphous silicon);
2. Type of system (e.g., roof-top (attached or integrated), ground mount, fixed tilt or tracker);
3. Module-rated efficiency and degradation rate;
4. Lifetime of PV and balance of system (BOS);
5. Location of installation;

6. Annual irradiation, and expected annual electricity production with the given orientation and inclination or system's performance ratio;

Important aspects to be documented in the LCA report:

7. Time-frame of data;
8. Life cycle stages included;
9. The place/country/region of production modelled;
10. Type of electricity used and modelled in the supply chain (e.g., average grid medium voltage European grid (Entso-e), site-specific power use (e.g., hydropower, coal));
11. Explicit goal of the study including
    - Purpose of the study;
    - Technical and modelling assumptions (e.g., historical or prospective LCA, prototype or commercial production, current performance or expected future development);
    - Type of LCA model applied (attributional, consequential, etc.);
    - The name of the entity commissioning the study;
12. LCA approach used (process-based, environmentally-extended input-output tables, hybrid analysis);
13. LCA tool used (e.g., Simapro, GaBi, other), LCI database(s) used (e.g., UVEK LCI data DQRv2:2018, ecoinvent, GaBi, ELCD, Franklin, NREL, IDEA, other), and impact category indicators used, always including the version numbers;
14. Assumptions related to the production of major input materials, e.g. solar grade silicon, aluminium (primary and/or secondary production), and electricity source if known.

Since a major part of the environmental impacts of PV systems is due to emissions from the "background system", (i.e., from producing electricity and from the production of commodity materials like glass, aluminium, plastics, and steel), separating the contributions of "background" and "foreground" is recommended.

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