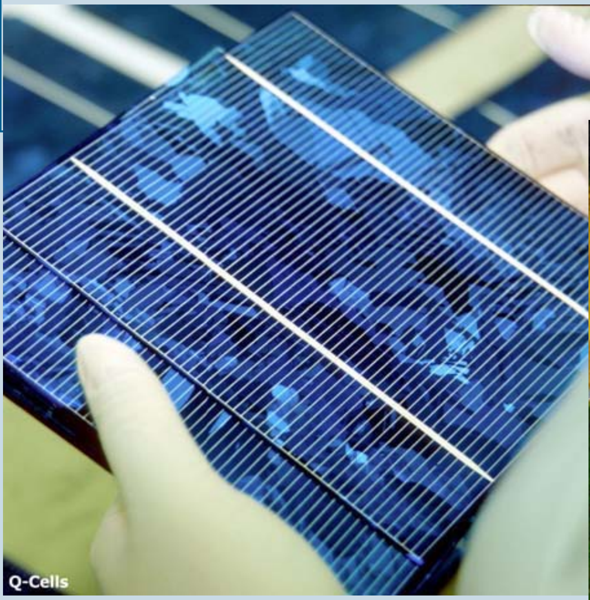
IEA INTERNATIONAL ENERGY AGENCY

Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity

3rd Edition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Karlstadt Laudenbach, Germany (810 kW); Phoenix Solar

PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

Report IEA-PVPS T12-08:2016

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

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3rd Edition

IEA PVPS Task 12, Subtask 2.0, LCA
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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 current IEA guidelines were developed 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, and Asia—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) data analysis and on implementation of modeling approaches. A consistent approach towards system modeling, the functional unit, the system boundaries, water use modeling, and the allocation aspect enhances the credibility of PV electricity LCA studies and enables balanced LCA-based comparisons of different electricity producing technologies.

The document discusses metrics like greenhouse gas emissions (GHG), cumulative energy demand (CED), acidification potential (AP), ozone depletion potential (ODP), human toxicity, ecotoxicity, and ionizing radiation. Guidance is given for the definition of the energy payback time (EPBT), the nonrenewable energy payback time (NREPBT), and the impact mitigation potentials (IMP). The indicator energy return on investment (EROI) is described in a separate International Energy Agency (IEA) PV Power Systems (PVPS) Task 12 report (Raugei et al. 2016). The guidelines on the reporting and communication of the results serve the need for producing clear, comprehensive, and transparent reports.

Transparency in reporting is of the utmost importance as parameters vary with geographical zones, and a system's boundary conditions and modeling approach can affect the findings significantly. At a minimum, the following parameters shall be reported in captions of result figures and tables: 1). PV technology (single and multi-cristalline 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; 6). Annual irradiation, and 7.) Expected annual electricity

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[1] The life cycle or products 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.

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) modeled;
- The explicit goal of the study including technical and modeling 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., ecoinvent, GaBi, ELCD, Franklin, NREL, IDEA) and impact category indicators used, always including the version numbers;
- The 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.

Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD) that carries out a comprehensive programme of energy cooperation among its member countries. The European Commission also participates in the work of the IEA.

The IEA PVPS is one of the collaborative R&D Agreements established within the IEA, and was established in 1993. The overall programme is headed by an Executive Committee composed of representatives from each participating country and/or organisation, while the management of individual research projects (Tasks) is the responsibility of Operating Agents. By early 2015, fifteen Tasks were established within the PVPS programme, of which six are currently operational.

The IEA PVPS Implementing Agreement presently has 29 members and covers the majority of countries active in PV in R&D, production, and installation. The programme deals with the relevant applications of PV, both for on-grid and off-grid markets. It operates in a task-shared mode whereby member countries and/or organisations contribute with their experts to the different Tasks. The cooperation deals with both technical and non-technical issues relevant to a widespread use of PV in these different market segments.

The mission of the IEA PVPS 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.” The underlying assumption is that the market for PV systems is rapidly expanding to significant penetrations in grid-connected markets in an increasing number of countries, connected to both the distribution and the central transmission networks. At the same time, the market is gradually shifting from a policy to a business driven approach.

Task 12 engages in fostering international collaboration in communicating and assessing the environmental, health, and safety aspects associated with PV technology over the life cycle of the PV systems. Task 12 also disseminates reliable and accurate information on the EH&S impacts of PV technology to policymakers, industry participants, and the public with the goal to improve consumer understanding and confidence, encourage industry best practices, and aid policymakers to make informed decisions in the course of the energy transition. Furthermore, Task 12 brings its expertise in assessing methods and standards for the evaluation of EH&S aspects of PV systems. The overall objectives of Task 12 are to:

- Quantify the environmental profile of PV electricity using a life cycle approach in order to contribute to the environmental sustainability of the supply chain and to compare it with the environmental profile of electricity produced with other energy technologies

- Aim for a closed-loop supply chain and help improve waste management of PV by collective action on collection and recycling, including legislative developments as well as development of technical standards
- Distinguish and address actual and perceived issues touching the EH&S aspects of PV technology that are important for market growth.

The first objective of this task is well served by LCAs that describe the energy, material, and emission flows in all the stages of the PV life cycle. The second objective will be addressed by assisting the collective action of PV companies in defining material availability and product recycling issues.

Within Task 12, a Subtask on “Life Cycle Assessment” includes three targets: to quantify the environmental profile of electricity produced with PV systems (compared to that from other sources); to evaluate trends in the environmental profile of PV; and to assess this profile with the help of "external" costs and other life cycle impact assessment (LCIA) methods. In addition, Task 12 has produced and will continue to update methodological guidelines for PV LCA. Further information on the activities and results of the Task can be found at www.iea-pvps.org.

Contents

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.

The current IEA guidelines were 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 authors—PV LCA experts in the United States, Europe, and Asia—for assumptions on PV performance, process 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 varying with 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 power plant technology).

The current third edition of the guidelines expands the contents of the second edition, issued in 2011, with additional guidance on system parameters, modeling approaches, water use, recycling, and reporting requirements.

2. Motivation and Objectives

National and regional energy policies require environmentally friendly electricity- generating technologies. The PV industry is experiencing a rapid evolution. The key prerequisites for a LCA 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:

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

- To provide guidance on how to establish the LCI of PV electricity
- To provide guidance on which environmental impacts to address in life cycle impact assessment (LCIA) and which impact category indicators to use
- To provide guidance on how and what to document with regard to the 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 LCA should be stated clearly.

The following guidelines are structured into four main areas:

- Subchapter 3.1 includes recommendations on technical characteristics related to PV systems
- Subchapter 3.2 covers aspects of modeling approaches in LCI analysis
- Subchapter 3.3 deals with LCIA and environmental indicators to address
- Subchapter 3.4 discusses interpretation aspects
- Subchapter 3.5 covers issues related to reporting and communication.

This document currently does not cover specific aspects of modelling building-integrated PV. This topic needs special attention and may be addressed in a subsequent update of these methodological guidelines.

3.1. Photovoltaics-specific aspects

3.1.1. Life expectancy

The recommended life expectancy used in LCAs of PV components and systems differentiates between the components:

- Modules: 30 years for mature module technologies (e.g., glass-glass or glass-Tedlar encapsulation); 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 warrantees

- Inverters: 15 years for small plants (residential PV); 30 years with 10% part replacement every 10 years (parts need to be specified) for plants at utility scale (>1 MW) (Mason et al. 2006)
- Transformers: 30 years
- Structure: 30 years for roof-top and façades, and between 30 to 60 years 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
- 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, three main recommendations are given:

- Analysis of industry average and best case systems
- Assume for all ground systems that the panels on an array plan are optimally oriented and tilted at angles equal to the latitude (except when a specific system under study is laid out differently). Also, assume that roof-top installations are optimally orientated and tilted. Assume either optimally oriented or case-specific orientation of panels of façade systems. Additionally, 1-axis tracking systems may be assumed.
- Analysis of the average of installed systems in a grid network (the average actual orientation, shading, and irradiation should be used).

The International Standard IEC 61724 offers a description of irradiance (W/m^2) and irradiation (also called insolation) ($kWh/m^2/yr$). Breyer et al. (2010) provides country-specific plane of array irradiation estimates for fixed-tilt and tracking PV systems.

3.1.3. Performance ratio

The performance ratio (PR) (also called derate factor) describes the difference between the modules' (DC) rated performance (the product of irradiation and module rated efficiency) and the actual (AC) electricity generation.[3] Mean, annual performance ratio data collected

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[3] The performance ratio is described in The International Standard IEC 61724

from many residential systems show an upward trend from 0.64 in 1991 to 0.74 in 2005.[4] Higher values are likely for current systems as the inverters' efficiencies have improved since 2005; values of 0.79 to 0.82 are reported[5,6] for utility ground-mount fixed-tilt systems, and values as high as 0.9 have been observed (van Sark et al. 2012, Fig. 4). In general, the performance ratio 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 have a higher PR.

Using either site-specific PR values or a default value of 0.75 is recommended for roof-top 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. When site-specific PR values, based on early years performance are used, degradation-related losses should be added to longer-term projections of the performance.

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 systems in a grid network.

3.1.4. Degradation

The degradation of the modules reduces efficiency over the lifetime. The following degradation rates are recommended:

- Mature module technologies: Assume a linear degradation declining to 80% of the initial efficiency at the end of a 30-year lifetime (i.e., 0.7% per year, or 10% on average during the entire lifetime (Skoczek et al. 2004)), unless actual data exist, in which case documentation has to be provided. When extrapolated from site-specific data, it should be clearly stated whether degradation is considered
- Use a degradation rate of 0.5% per year until the end of life (30 years) 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 and Kurtz (Jordan & Kurtz 2013).

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[4] http://www.iea-pvps-task2.org/public/download/T2_Cost_and_Performance.pdf

[5] Moore, L. M., & Post, H. N. (2008). Five years of operating experience at a large, utility-scale photovoltaic generating plant. Progress in Photovoltaics: Research and Applications, 16(3), 249-259. Retrieved from www.scopus.com

[6] Fthenakis, unpublished data collected from utility installations in the US, 2010.

3.1.5. Back-up Systems

Back-up systems such as temporal 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. If a back-up system is included, it should be explicitly mentioned.

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 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, or 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 recommended. 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 and 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 modeling 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. Since the power plants will operate 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 (worldwide) 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, in its short history, 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"[7] and "reference flow"[8]. The reference flow 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 is used for comparing PV technologies, module technologies, and electricity-generating technologies in general (goals A to D). For grid-connected systems, use the kWh of alternate current electricity fed into the grid. For PV systems with dedicated transformers (e.g., utility solar farms), use the electricity-output downstream of the transformer.

Alternatively, the reference flows "m^2" or "kWp (rated power)" may be used. However, these reference flows are not suitable for comparisons of PV technologies.

- m^2 module is used for quantifying the environmental impacts of a particular building, or of supporting structures (excluding PV modules and inverters). Square metre is not suited for comparisons of PV technologies because of differences in module and inverter efficiencies and PRs
- 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

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

[8] The reference flow is a measure of the outputs from processes in a given product system required to fulfill the function expressed by the functional unit (ISO 2006a, Clause 3.29).

the environmental impacts of an individual module technology. However, the comparisons of module technologies shall not be based on nominal power (kWp) figures because the amount of kWh fed to the grid may differ between the systems analyzed.

The location, the module of 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 technology 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 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's system. It offers guidance on what to include and exclude from the LCI analysis.

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

Product stage:

- 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 storage, climate control, ventilation, lighting for production halls, onsite emissions and their abatement, and onsite waste treatments. PV manufacturing equipment may be included if data are available.

Construction process stage:

- Transports to the power plant site (where the plant is operated)
- Construction and installation, including foundation, supporting structures and fencing

Use stage:

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

End-of-life stage:

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

The following parts should be excluded:

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

3.2.4. Modelling water use

Main reference and definitions

The main reference for modelling water use is the international standard on water footprint (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[9] can be quantified from inventory data (unit processes) (see also Flury et al. 2012). There is not yet consensus on whether to assess water withdrawal or water consumption. Indeed, often both are 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, particularly with regard to water scarcity. Following this, how to establish a water consumption inventory is described in this section. However, the basic information can easily be used to quantify water withdrawal if considered more appropriate and if the inventory information available is complete.

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[9] Water removed from, but not returned to, the same drainage basin (ISO 2014).

The LCI data should include the entire water balance (including rain water). 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" (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 (2010).

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 credits as far as possible.

In case system expansion (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)).[10]

In 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.

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[10] 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.

The Swiss partners committed themselves to implementing the LCI data compiled within Task 12, Subtask 20 "LCA" into the ecoinvent database, thereby facilitating the distribution of up-to-date and transparent LCI information on PV. As of now, data are supplied in EcoSpold v1 format and following the ecoinvent v2 guidelines.[11] The subtask 2.0 LCA partners acknowledge and support this commitment.

3.3. Life cycle impact assessment (LCIA)

In environmental LCIA of PV electricity, the midpoint indicators of the European product environmental footprint (PEF) recommendation (European Commission 2013) should be used, including the indicators proposed by the PEF pilot on PV electricity (Frischknecht & Itten 2014). The indicators are shown in Tab. 3.2.

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[11] As of October 2015, the Swiss Federal Offices are exploring the switch from ecoinvent data v2.2+ to ecoinvent data v3.3 (earliest version). No final decision is taken yet.

Tab. 3.2 List of LCIA indicators to be addressed in PV LCA studies, see (European Commission 2013; Frischknecht & Itten 2014)

Impact category	Indicator	Source
Indicators required according to the PEF guide		
Climate change	Radiative forcing as Global Warming Potential (GWP100) [kg CO_2 eq.]	IPCC 2013, Chapter 8
Ozone depletion	Ozone Depletion Potential (ODP) [kg CFC-11 eq.]	WMO 1999
Human toxicity, cancer effects	Comparative Toxic Unit for humans [CTUh, c]	Rosenbaum et al. 2008
Human toxicity, non-cancer effects	Comparative Toxic Unit for humans [CTUh, n-c]	Rosenbaum et al. 2008
Particulate matter / respiratory effects	Intake fraction for fine particles [kg PM2.5 eq]	Humbert 2009
Ionizing radiation, human health	Human exposure efficiency relative to U^{235} [kBq U^{235} eq.]	Frischknecht et al. 2000
Photochemical ozone formation	Tropospheric ozone concentration increase [kg NMVOC eq.]	Van Zelm et al. 2008 as applied in ReCiPe
Acidification	Accumulated Exceedance (AE) [mol H^+ eq.]	Posch et al. 2008; Seppälä et al. 2006
Eutrophication, terrestrial	Accumulated Exceedance (AE) [mol N eq.]	Posch et al. 2008; Seppälä et al. 2006
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)[kg P eq.]	Struijs et al. 2009 as implemented in ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N) [kg N eq.]	Struijs et al. 2009 as implemented in ReCiPe
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems [CTUe]	Rosenbaum et al. 2008
Land use	Soil Organic Matter [kg C deficit]	Milà i Canals et al. 2007
Resource depletion, water	Water abstraction related to local scarcity of water [m^3 water eq.]	Frischknecht et al. 2008
Resource depletion, mineral, fossil, renewable	Scarcity [kg Sb eq.]	Guinée et al. 2001
Additional indicators		
Cumulative energy demand, renewable	Gross energy content of renewable primary energy resources [MJ oil eq.]	Frischknecht et al. 2015b
Cumulative energy demand, non-renewable	Gross energy content of non-renewable primary energy resources [MJ oil eq.]	Frischknecht et al. 2015b
Nuclear waste	Radiotoxicity index, RTI [m^3 HAA eq.]	Frischknecht & Büsser Knöpfel 2013, 2014

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. The GWP 100 years shall be used as default and the GWP 20 years may be used in sensitivity analyses.

Resource depletion, water: 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.

CED, The indicator "CED, non-renewable" (MJ oil-eq.)[12] 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. 2015b). 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's PV Net Energy Analysis Methodology Guidelines (Raugei et al., 2016).

Long-term emissions contributing to human toxicity, ionising radiation, eutrophication, and ecotoxicity: The quantification of the environmental impacts should be based on the emissions occuring 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 LCIA 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).

3.4. Interpretation

3.4.1. Introduction

According to the ISO Standards on LCA, interpretation is the final phase of the LCA procedure, in which the results of an LCI or an LCIA, 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.

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[12] The unit "MJ oil-eq" indicates that the CED is a life cycle impact category indicator similar to the abiotic depletion potential which is expressed in kg Sb-eq (Frischknecht et al. 2015b).

Some of the impact indicators described above and calculated in the impact assessment phase may further be processed into payback times (either energy, EPBT, see Section 3.4.2, or environmental impacts such as climate change, IMP[13], see Section 3.4.3), or into energy return on investment (EROI) figures. The latter indicator is addressed in a separate IEA report (Raugei et al. 2016).

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 Subchapter 3.5. apply to these indicators too. In contrast to common 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 being replaced by PV). Information and recommendations on the Energy Return on Investment (EROI) indicator is given in the IEA Task 12 report on Methodology Guidelines for Net Energy Analysis of Photovoltaic Electricity (Raugei et al. 2016).

3.4.2. 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)[12] 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}	Annual electricity generation
$E_{O\&M}$	Annual primary energy demand (in MJ oil-eq) for operation and maintenance

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[13] IMP stands for "impact mitigation potential."

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 the set of 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 not accounted for as part of $E_{O\&M}$). The annual electricity generation (E_{agen}) is converted into its equivalent primary energy, based on the efficiency of electricity conversion at the demand side, using the current average (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 on the demand side or 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 (E_{agen}) is likewise converted to primary energy equivalent considering the non-renewable primary energy to electricity conversion efficiency of the average (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 must be identified as Non-Renewable Energy Payback Time (NREPBT) to clearly distinguish it from the EPBT derived from the first approach. The formula of NREPBT is identical to that of EPBT described above, except for replacing “primary energy” with “non-renewable primary energy”. Accordingly, grid efficiency, η_G, 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 hydropower) 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 U.S., 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 residual electricity mix, or the national electricity-supply mix) in accordance to the system modeling 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 CED.

3.4.3. Environmental impact mitigation potentials (IMP)

Similar to the energy payback times, environmental impact mitigation potentials (IMP) can be quantified. This may comprise mitigation potentials regarding climate change impacts or high-level nuclear waste (Jungbluth et al. 2008). These IMPs are quantified on a lifetime basis. 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 is 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 example of 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 CO_2-eq) of producing materials comprising PV system
CC_{manuf}	Climate change impact (in kg CO_2-eq) of manufacturing PV system
CC_{trans}	Climate change impact (in kg CO_2-eq) of transporting materials used during the life cycle
CC_{inst}	Climate change impact (in kg CO_2-eq) of installing the system
CC_{EOL}	Climate change impact (in kg CO_2-eq) of end-of-life management
CC_{agen}	Lifetime electricity generation (in kWh)

$CC_{O\&M}$ Lifetime climate change impact (in kg CO_2-eq) of operation and maintenance

γ_G Climate change impact (in kg CO_2-eq/kWh) of grid electricity at the demand side

Clearly reference the impact assessment method applied and specify the reference system (e.g., today's European electricity mix, today's European non-renewable residual electricity mix, or the national electricity supply mix).

3.5. Reporting and communication

The LCA, energy payback time, and 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, ground-mount, fixed-tilt, or tracker)
3. Module-rated efficiency and degradation rate
4. Lifetime of PV and 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 modeled (e.g., average grid medium voltage European grid (Entso-e), site-specific power use (e.g., hydropower, coal))
10. Explicit goal of the study including
    - Purpose of the study

- Technical and modeling assumptions (e.g., static 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

11. LCA approach used (process-based, environmentally-extended input-output tables, hybrid analysis)
12. LCA tool used (e.g., Simapro, GaBi, other), LCI database(s) used (e.g., ecoinvent, GaBi, ELCD, Franklin, NREL, IDEA, other), and impact category indicators used, always including the version numbers
13. 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 common materials like glass, aluminum, plastics, and steel), separating the contributions of "background" and "foreground" is recommended.

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