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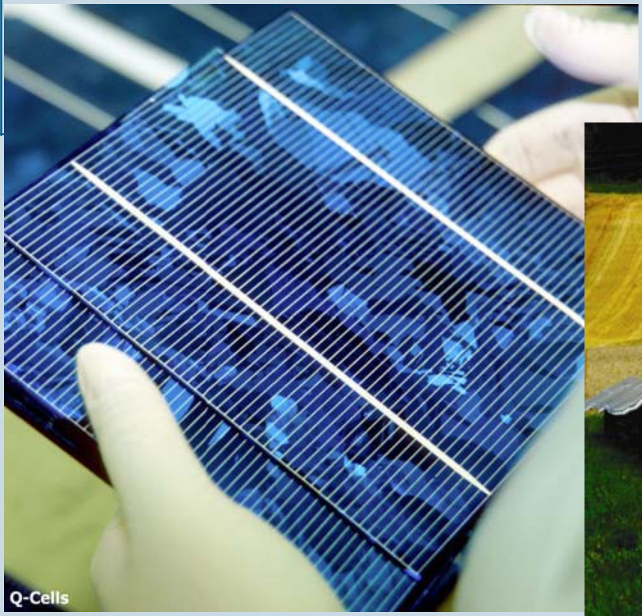
Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity



PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

Report IEA-PVPS T12-03:2011

INTERNATIONAL ENERGY AGENCY PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

Methodology Guidelines on Life-Cycle Assessment of Photovoltaic Electricity

IEA PVPS Task 12, Subtask 20, LCA
Report IEA-PVPS T12-03:2011

November 2011

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Citation: *V. Fthenakis, R. Frischknecht, M. Raugei, H. C. Kim, E. Alsema, M. Held and M. de Wild-Scholten, 2011, Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 2nd edition, IEA PVPS Task 12, International Energy Agency Photovoltaic Power systems Programme*

Executive Summary

Life Cycle Assessment (LCA) is a structured, comprehensive method of quantifying material- and energy-flows and their associated emissions in the life cycles of products (i.e., goods and services). The ISO 14040 and 14044 standards provide a framework for an LCA. However, this framework leaves the individual practitioner with a range of choices that can affect the validity and reliability of the results of such a 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 photovoltaic (PV) LCAs. The guidelines represent a consensus among the authors, PV LCA experts in North America, Europe, and Asia, for assumptions made on PV performance, process input and emissions allocation, methods of analysis, and reporting of the results.

Guidance is given on photovoltaic-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 and the allocation aspects enhances the credibility of PV LCA studies and enables balanced LCA-based comparisons of different energy life-cycles.

The document discusses metrics like greenhouse gas emissions (GHG), the cumulated energy demand (CED), the 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), the energy return on investment (EROI) and the impact mitigation potentials (IMP). The guidelines on the reporting and communication of the results serve the need for producing clear and comprehensive 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 should be reported: 1) On-plane irradiation level and location; 2) module-rated efficiency; 3) system's performance ratio; 4) time-frame of data; 5) type of system (e.g., roof-top, ground mount fixed tilt or tracker); 6) expected lifetime and degradation ratio for PV and BOS; 7) system's boundaries (whether capital goods, installation, maintenance, disposal, the transportation- and recycling-stages are included for both PV modules and balance-of-system (frame, mounting, cabling, inverter; for utility applications the transformer, site preparation, and maintenance)); 8) the place/country/region of production modeled (e.g., average grid, site specific power use (e.g., hydro, coal), and 9) explicit goal of the study (e.g., static or prospective LCA, prototype or commercial production, current performance or expected future development). These parameters should be listed in the captions of figures showing the results of the LCA. In addition, the report should identify the following: The LCA method used, especially if is not process-based; the LCA tool (e.g., Simapro, Gabi, other); databases used (e.g., Ecoinvent, GaBi, ELCD, Franklin, NREL, other); the energy payback time calculation method; commercial representativeness of the study (required if the data are from a pilot-scale production), and assumptions for production of major input materials, e.g. solar grade silicon, aluminum (primary and/or secondary production).

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 co- operation among its member countries. The European Commission also participates in the work of the IEA.)

The IEA Photovoltaic Power Systems Programme (PVPS) is one of the collaborative R & D Agreements established within the IEA. Since 1993, participants in the PVPS have been conducting a variety of joint projects in the applications of photovoltaic conversion of solar energy into electricity.

The mission of the Photovoltaic Power Systems Programme is "…to enhance the international collaboration efforts which accelerate the development and deployment of photovoltaic solar energy as a significant and sustainable renewable energy option". The underlying assumption is that the market for PV systems gradually is expanding from the niche-markets of remote applications and consumer products, to rapidly growing ones for building-integrated and centralised PV- generation systems. An Executive Committee composed of one representative from each participating country heads the overall programme: Operating Agents assume responsibility for managing individual research projects (Tasks). By the end of 2010, fourteen Tasks were established within the PVPS programme.

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 accomplish the following:

1. Quantify the environmental profile of PV in comparison to other energy-technologies;
2. Define and address environmental health & safety and 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 will be addressed by assisting the collective action of PV companies in defining material availability and product-recycling issues, and on communicating "lessons learned" from incidents or potential ones in PV- production facilities. A third objective (i.e., dissemination) will be accomplished by presentations to broad audiences, producing simple fact sheets documented by comprehensive reports, and engaging industrial associations and the media in spreading this information.

Within Task 12, there are three targets of Subtask 20 "Life Cycle Assessment": To quantify the environmental profile of electricity produced with PV systems (compared to that from other sources); to show trends in the improvement of PV's environmental profile; and, to assess this profile with the help of "external" costs, and other life-cycle-impact assessment methods.

Task 12 was initiated by Brookhaven National Laboratory under the auspices of the U.S. Department of Energy and is operated jointly by BNL and EPIA. Support from DOE and the EPIA are gratefully acknowledged.
Further information on the activities and results of the Task can be found at:

http://www.iea-pvps.org and http://www.iea-pvps-task12.org

Contents

1 Introduction

Life Cycle Assessment (LCA) is a structured, comprehensive method of quantifying material- and energy-flows and their associated emissions in the life cycles of products (i.e., goods and services). The ISO 14040- and 14044-standards provide a framework for LCA. However, this framework leaves the individual practitioner with a range of choices that can affect the validity of the results 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 photovoltaics (PV) LCAs. 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, methods of analysis, and reporting of the 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 product life cycles.

The current second edition of the guidelines expands the contents of the first edition, issued in 2008, with additional guidance on system parameters, modeling approaches 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 an adequate environmental assessment are the availability of the most up-to-date information on PV performance and LCI data, and of recent weighted averages that accurately represent the mixture of options available or in operation in the country or region of study. The major motivation to carry out the work in the IEA's PVPS Task 12, subtask 20 "LCA" is to supply the most recent and complete life-cycle-based information on PV components and systems. The following are the major objectives of this subtask:

- To undertake life-cycle assessment studies that reflect the status in PV manufacturing, based on well-documented industry averages, current LCI data, and well-documented industry best cases (actual, existing systems). This work helps in environmental evaluations of electricity-supply systems within solar photovoltaic electricity, and across the different energy-carriers and resources used to generate electricity.

- To complete life-cycle assessment studies that reflect the present status of PV systems operating in a country or region. This work helps to quantify the contribution of solar electricity to the environmental impacts of a national- or regional-grid mix or that of a utility.

3 Methodological Guidelines

All PV LCA studies should be accomplished according to the ISO standards 14040 and 14044. 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 four main areas: Subchapter 3.1 has recommendations on technical characteristics related to photovoltaic systems. Subchapter 3.2 covers aspects of modeling approaches in life-cycle-inventory analysis, and life-cycle-impact assessment. Subchapter 3.3 discusses interpretation and Subchapter 3.4 covers 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 encapsulation), life expectancy may be lower for foil-only encapsulation; this life expectancy is based on typical PV module warranties (i.e., 25 years -80% degradation or less 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 yrs (parts need to be specified) for large size plants utility PV, (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, two main recommendations are given:

- Analysis of industry average- and best case-systems:
  Assume for all systems on ground that the irradiation on an array plan is optimally

oriented for latitude (except when a specific system under study is laid out differently). Also, assume that the orientation and tilt for roof-top installations is optimized. Case- specific irradiation values should be used for analyzing façade systems.

- Analysis of the average of installed systems in a grid network:
  The actual orientation and irradiation should be used

The International Standard IEC 61724 offers a description of irradiance (W/m^2) and irradiation (also called insolation) ($kWh/m^2/yr$).

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 efficiency) and the actual (AC) electricity generation.[1] It mainly depends upon the kind of installation. Mean annual performance ratio data collected from many residential systems show an upward trend from 0.64 in 1991, to 0.74 in 2005[2]. Higher values are likely for current systems as the inverters' efficiencies have improved since 2005; values of 0.79 to 0.82 are reported[3],[4] for utility ground-mount fixed tilt systems. In general, the performance ratio increases with 1) decline in temperature, and 2) monitoring the PV systems to detect and rectify defects early. Shading, if any, would have an adverse effect on performance ratio. This means that well-designed, well-ventilated and large-scale systems have a higher performance ratio.

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 production 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.

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

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

[3] 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

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

3.1.4 Degradation

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

- Mature module technologies: Assume a linear degradation reaching 80% of the initial efficiency at the end of a 30 years lifetime (i.e., 0.7% per year)[5], 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 or not.

- Concentrated PV: (information about the degradation rate will be added when field data are available).

3.1.5 Back-up Systems

Back-up systems 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 LCI / LCA modeling aspects

3.2.1 System modeling: static / prospective (attributional / consequential), electricity mix in background data, small versus large scale

The appropriate system model depends on the goal of the LCA. The following types of LCA are considered:

A) Reporting environmental impacts of PV currently installed in a utility's network (retrospective LCA)

B) Choice of a PV electricity-supplier, comparisons of PV systems, or of electricity-generating technologies (short-term prospective LCA)

C) Long-term energy policy: comparison of future PV systems or of future electricity-generating technologies (long-term prospective LCA)

The following recommendations apply on all goals:

- Depending on the study’s goal and scope, an attributional, decisional or consequential approach should be chosen (Frischknecht 2006). Up to now, most LCA are based on the attributional approach.

- The product system shall be divided into foreground- and background- processes. We propose the following definitions: Foreground processes are those which the decision-maker or product-owner can influence directly. Background processes are all remaining

[5] Skoczek A, Sample T and Dunlop E. The results of performance measurements of field-aged crystalline silicon photovoltaic modules. *Prog Photovolt Res Appl* 2004; **17**: 227-240.

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 and standardized by the ISO.

- I/O or hybrid method: These approaches are not followed in this subtask. More confidence in employing them is needed before we recommend their application.

The following recommendations apply to goals (B) and (C):

- Use the present average mix (i.e., Europe (EU 27, including Norway and Switzerland), United States, Korea, China, or Japan) when modeling the production of current PV components. Specify the year for which the data are valid.

- If the production of a material is bound to a certain country, a limited number of companies, or if the material production generally involves a specific type of electricity supply, then an argued choice may 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 (C):

- Use an average future mix (i.e., Europe (EU 27, including Norway and Switzerland), United States, Korea, China, or Japan) when modelling future production of PV components. Specify the year for which the forecasted data are applicable.

- Adapt the performance of the power plants contributing to this future electricity mix.

- If the production of a material is expected to be bound to a certain country, a limited amount of companies, or if the material production generally uses a specific type of electricity supply, an argued choice for a country- or company-specific electricity mix should be made, e.g. hydropower for producing silicon feedstock production in Norway. However, in prospective analyses, the availability must be documented of country-specific resources to the projected scales. Country- or company-specific cases must be identified clearly, so that data are not used unintentionally for projections to different scales 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.

3.2.2 Functional unit and reference flow

The functional unit specifies the function based upon which comparisons can be made of various PV systems and other electricity-generating systems. We recommended using the ISO's language to distinguish between "functional unit" and "reference flow". The functional unit specifies the reference flow to enable comparisons. The reference flow is quantified with the functional unit "kWh electricity produced" or "m^2 module" or "kWp rated power".

- kWh is used for comparing PV technologies, module technologies, and electricity-generating technologies in general (goal B). Use the kWh of electricity fed into the grid. For PV systems with dedicated transformers (e.g., utility solar farms), use the electricity-output downstream of the transformer.

- m2 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 efficiency and in performance ratio.

- kWp (rated power) is used for quantifying the environmental impact of electrical parts, including inverter, transformer, wire, grid connection and grounding devices. The kWp units may also serve as the reference flow in quantifying the environmental impacts of module technologies. 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 analyzed.

The location, the module technology used, the voltage level, and whether or not and how the transmission and distribution losses are accounted for, should be specified.

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 or exclude from the life-cycle inventory analysis.

- Include in the product's system the panels, the mounting system, the cabling, the inverters, and all further components needed to produce electricity and supply the grid.

- Include the energy- and material-flows caused by manufacturing and storage, climate control, ventilation, lighting for production halls, on-site emissions abatement, and on-site waste treatments.

- Exclude commuting (transportation to and from work).

- Exclude administration, sales and distribution, and research and development (R&D) activities.

- Examine the environmental impacts of producing PV manufacturing equipment, if data are available (e.g. Mohr et al. 2007). If included, list these impacts separately.

3.2.4 Modeling allocation and recycling

Consistent allocation rules are demanded for all multifunction processes (those simultaneously producing several different products e.g. off-grade silicon supply), recycling of materials (e.g. using of recycled aluminum), 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) 2006).

3.2.5 Databases

The IEA PVPS Task 12 does not recommend any particular LCI database. However, 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 Task12, Subtask 20 "LCA" into the Ecoinvent database; thereby facilitating the distribution of up-to-date and transparent LCA information on photovoltaics. The subtask 20 LCA partners acknowledge and support this commitment.

3.2.6 Life-cycle impact assessment

- Use life-cycle inventory indicators, such as radionuclide emissions, nuclear-waste generation, and air-pollutant emissions (NO_X, SO_2, $PM_{2.5}$, PM_{10}).

- Employ mid-point indicators, greenhouse-gas emissions, cumulative energy demand, acidification potential (AP), ozone depletion potential (ODP), human toxicity, ecotoxicity, and ionizing radiation.

- Greenhouse gas emissions:
  The greenhouse gas (GHG) emissions during the life cycle stages of a PV system are estimated as an equivalent of CO_2 using an integrated 100-year time horizon using the most recent global warming potential factors published by the IPCC (Forster et al., 2007).

- Cumulative Energy Demand (CED):
  The CED describes the consumption of fossil, nuclear and renewable energy sources along the life cycle of a good or a service. This includes the direct uses as well as the indirect (grey) consumption of energy due to the use of materials (e.g. plastic or wood in construction), consumables necessary in manufacturing (e.g., solvents, gloves, packaging) and raw materials. A CED assessment can be a good starting point in an assessment due to its simplicity in concept and its comparability with CED results in other studies. The following two CED indicators are well known: CED, non-renewable [MJ-eq.] – fossil and nuclear and CED, renewable [MJ-eq.] – hydro, solar, wind, geothermal, biomass. (Frischknecht et al. 2007). It should always be stated which energy sources are included in the CED indicator result.

- Acidification potential (AP)
  Acidification describes a change in acidity in the soil due to atmospheric deposition of sulphates, nitrates and phosphates. Major acidifying substances are NO_X, NH_3, and SO_2.

- Ozone depletion potential (ODP)
  The thinning of the stratospheric ozone layer as a result of anthropogenic emissions is described by the stratospheric ozone depletion indicator. The impacts are potentially harmful on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and materials.
- Human toxicity
  The impacts of toxic substances on human health are covered by this indicator. The health risks of exposure in the workplace can also be included.
- Ecotoxicity

The impacts of toxic substances on aquatic, terrestrial and sediment ecosystems are covered by this indicator.

- (Abiotic) Resource Depletion:
  Existing method of impact assessment for resource depletion are considered problematic by some of the participants because data sources for scarce metals, like silver, indium, tellurium, and gallium, carry considerable uncertainty. Instead, cumulative exergy demand might be suitable, which takes minerals into account as well as energy resources.
- Land use and water use:
  These are environmental impacts of growing importance. It is recommended that withdrawal and consumption of water and occupation and transformation of land should be listed separately; examples are given by Jungbluth et al. (2004) Jungbluth (2005), Jungbluth et al (2008), Fthenakis and Kim (2009; 2010).
- When using life cycle impact assessment methods that use impact pathway analysis to quantify environmental damage, be transparent about methodology and assumptions or clearly refer to the method and its version applied.
- If external cost is calculated, use the generic damage factors generated by the NEEDS project. This also provides information on the environmental impacts of the future supply of basic materials (e.g., steel, aluminum, copper), transport services (van and lorry), and electricity mixes (Frischknecht et al., 2007).

3.3 Interpretation

Some of the impact indicators described above may further be processed into energy payback time (EPBT), Energy return on investment (EROI) or impact mitigation potentials (IMP).

3.3.1 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 = $(E_{mat}+E_{manuf}+E_{trans}+E_{inst}+E_{EOL}) / ((E_{agen} / n_G) - E_{O\&M})$

where,
E_{mat} : Primary energy demand to produce materials comprising PV system
E_{manuf} : Primary energy demand to manufacture PV system
E_{trans} : Primary energy demand to transport materials used during the life cycle
E_{inst} : Primary energy demand to install the system
E_{EOL} : Primary energy demand for end-of-life management
E_{agen} : Annual electricity generation
$E_{O\&M}$: Annual primary energy demand for operation and maintenance
n_G : Grid efficiency, the average primary energy to electricity conversion efficiency at the demand side

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 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, neither on the demand side, 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 (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 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, η_G, accounts for only non-renewable primary energy.

Both EPBT and NREPBT depend on the grid mix; 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 the conditions of 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), 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, 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 CED.

3.3.2 Energy Return on Investment (EROI)

The traditional way of calculating the EROI of PV is as follows (Lloyd and Forest, 2010):

$$EROI = lifetime / EPBT = T \cdot ((E_{agen}/n_G) - E_{O\&Mr}) / (E_{mat}+E_{manuf}+E_{trans}+E_{inst}+E_{EOL})$$

We noted that sometimes the EROI is computed without the prior conversion of the generated electricity into its primary energy-equivalent (Kubiszewski and Cleveland, 2009), resulting to an EROI lower by a factor of $1/n_G$ than the EROI calculated by the recommended equation above.

It is mandatory to specify the approach on which the calculation is based (total or nonrenewable energy) and thus keep the transparency and traceability of the calculated EROI.

3.3.3 Impact mitigation potentials (IMP)

This may comprise the mitigation potentials for climate change and high-level nuclear waste (Jungbluth et al., 2008). Clearly reference the impact assessment method applied, and specify the reference system, e.g., today's European electricity mix, or the national electricity supply mix.

3.4 Reporting and communication: Key parameters to be reported

Reporting of key parameters 1 to 9 below is mandatory and they should be listed in the captions of figures showing the results of the LCA.

1. On-plane irradiation level and location;
2. Module-rated efficiency;
3. System's performance ratio;
4. Time-frame of data;
5. Type of system (e.g., roof-top, ground mount fixed tilt or tracker);
6. Expected lifetime for PV and BOS;
7. System's boundary (whether raw material extraction and supply, manufacture, installation, maintenance, disposal, the transportation- and recycling-stages are included for both PV modules and balance-of-system (frame, mounting, cabling, inverter; for utility applications the transformer, site preparation, and maintenance)); and,
8. The place/country/region of production modeled (e.g., average grid medium voltage European grid (UCTE), site specific power use (e.g., hydro, coal)).
9. Explicit goal of the study including

- Technical and modeling assumptions (e.g., static or prospective LCA, prototype or

commercial production, current performance or expected future development).
- The name of the entity commissioning the study.

Also the following should be reported:

10. Degradation ratios; documentation should be included if life expectancies and degradation ratios differ from the recommendations of the Guidelines.
11. LCA method used if not process-based,
12. LCA tool used (e.g., Simapro, Gabi, other), and the databases used (e.g., Ecoinvent, GaBi, ELCD, Franklin, NREL, other).

13. Assumptions for production of major input materials, e.g. solar grade silicon, aluminum (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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