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PV Quality and Economy

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1. IMPACT OF QUALITY ON (TRUE) ECONOMY

Globally, annual PV installations grew at a 43% Compound Annual Growth Rate (CAGR) from 2007 through 2017, accompanied by a steep reduction in the Levelized Cost of PV Electricity (LCOE). The market for PV installations in Europe enjoyed strong growth in the early 2000s, peaking in 2011 at 19 GW/a, and dropped to 9 GW/a in 2017 (Figure 1).

Energy transition models project an installed PV capacity of potentially 1000 GW for Europe by 2050 [1], requiring a net area in the range of 5000 km^2. If the transition is to be completed by 2050, annual installation levels have to approach 30 GW. If a service life of 30 years is assumed for the PV modules, annual end-of-life replacement demand will grow in parallel to a scale of 30 GWp, which corresponds to an annual waste quantity in the range of 50 million tons.

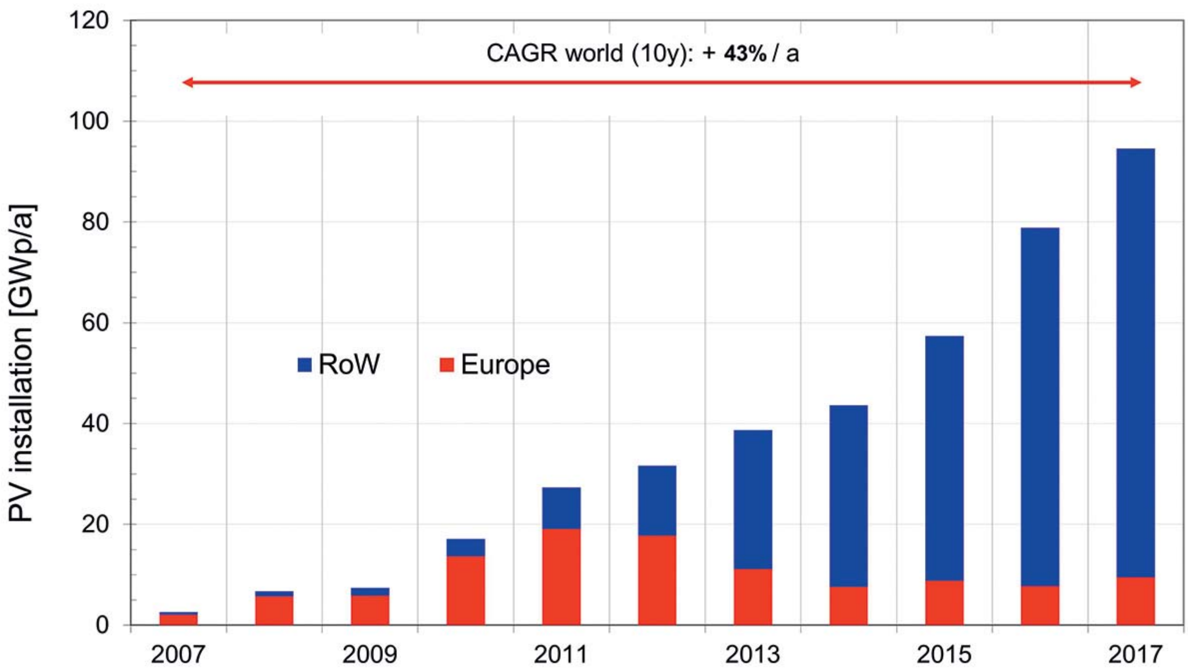


Figure 1: Annual PV installation in Europe and in the Rest of the World (RoW), data from EPIA/IHS

The strong growth of the PV sector is accompanied by high cost pressure, accelerated innovation cycles and dynamic deployment, clearly indicating that the quality of PV products and the holistic economy of PV electricity deserve special attention. PV is expected to deliver electricity at low LCOE, Energy Pay-Back Time (EPBT) and Product Environmental Footprint (PEF). We define quality as the ability of a product to meet demanding customer expectations while focusing on the impact of quality parameters on monetary, energy and environmental cost.

1.1. LCOE

An LCOE model for PV electricity production was published in a previous white paper of ETIP PV [2]. The cost model is updated below with the addition of an end-of-life cost and value (1).

$$LCOE_{real} = \frac{\text{cost of produced electric energy}}{\text{produced electric energy}} = \frac{i_0 + c_0 \sum_{t=1}^{n} \frac{1}{(1+r_{real})^t} + \frac{i_{dis}}{(1+r_{real})^{n+1}}}{u_0 \cdot \sum_{t=1}^{n} \frac{(1-d)^t}{(1+r_{real})^t}} \quad (1)$$

$LCOE_{real}$	real Levelized Cost of Energy	[€/kWh]
n	service life of power plant	[years]
r_{real}	real weighted average cost of capital	[%]
d	annual degradation rate (>0)	[%]
i_0	specific initial investment for power plant (CAPEX)	[€/kWp]
i_{dis}	dismounting cost, recycling cost, residual value	[€/kWp]
c_0	specific initial annual operation & maintenance cost (OPEX)	[€/kWp]
u_0	initial utilization rate of plant (specific yield)	[kWh/kWp]

LCOE cost is estimated to rise by 6-7% if annual degradation increases by 0.5% abs., lifetime decreases by 5 years, Operational Expenditure (OPEX) increases by 0.5% abs. or the performance ratio decreases by 5% abs. with respect to the indicated reference values (Figure 2).

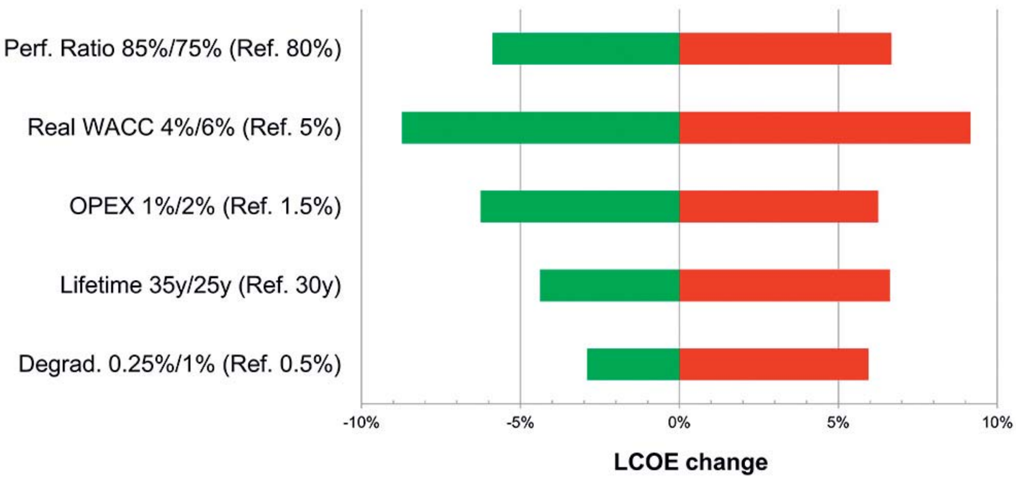


Figure 2: LCOE sensitivity for Toulouse location (1580 kWh/m² POA) and 1 €/Wp investment for power plant (CAPEX)

Losses caused by system down time, soiling or grid curtailment, for example, are directly related to yield and Performance Ratio (PR). Early component failures require repair or replacement and raise OPEX. In contrast to the LCOE model presented in this paper, OPEX may vary from year to year as uncertainty is connected to system quality. Savings in CAPEX related to poor quality components or installation practices translate into rising OPEX.

Perceived prediction uncertainty for average annual irradiation, soiling, true installed nominal module power, annual degradation rates and grid curtailment is usually presented in terms of exceedance probability. Uncertainty concerning these parameters generates risk and raises the cost of capital and insurance for the project, which in turn has an effect on the projects weighted cost of capital (WACC), and the projects OPEX. Irradiation variability exposes the project cash flow to additional risks.

End-of-life management of photovoltaic panels typically follows a business-to-business (B2B) waste management scenario [3]. In Europe the current raw material recovery rate for PV module recycling is 75% to 90% by mass, in line with the EU WEEE Directive. PV panels and the balance-of-system (BOS) components offer a potential secondary raw material value stream after system decommissioning.

System design and component choice before and during construction help improve project efficiencies and potentially reduce recycling costs. For example, holding module and other components in inventory, avoiding the use of hazardous materials, using recyclable materials, and design systems for ease of dismantling as well as replacing components are factors and eventually lead to negative net costs i_{dis}. A first step on this learning curve is the implementation of the EN 50626 treatment standard and the associated de-pollution requirements for photovoltaic panels which already presents a comprehensive framework for low cost and high value recycling and end-of-life panel treatment [4].

1.2. Energy Return on Investment (ERoI) and Energy Pay-Back Time (EPBT)

Photovoltaic systems do not require fuel other than sunlight for their operation, but they do require energy investment for their production, installation, maintenance and end-of-life treatment. The ratio of the total energy produced over the lifetime of the system and the total energy invested over that lifetime is called the Energy Return on Investment (ERoI), or the Energy Return on Energy Invested (ERoEI) (2).

$$ERoI = \frac{\text{energy produced over system lifetime}}{\text{energy invested over system lifetime}} \quad (2)$$

Note that the ERoI is defined on the level of the system. The PV modules are typically the main contributor to the energy investment [5].The (obvious) reasons to define ERoI on system level rather than on module level are that the system is the unit of operation, that most systems include DC/AC conversion and that different system configurations as well as different module efficiencies (determining the system area per unit of installed peak power) have an effect on ERoI.

Although this definition of ERoI seems straightforward, one must be aware that energy comes in different forms and that the simple interpretation that for a system to be a net producer of renewable electricity the ERoI should be >1, may not be valid. In particular, while the energy produced is purely in the form of electricity (assuming the byproduct heat from PV is not used), the energy invested may be at least in part from fossil fuels used to generate the electricity or heat required. In those cases, the fossil fuels used would be called the primary energy. To support a consistent comparison between different systems and regions, the IEA PVPS has published Methodological Guidelines on Net Energy Analysis of Photovoltaic Electricity [6] . Following these guidelines one has to convert both the energy produced and the energy invested into, respectively, the equivalent amounts of primary energy saved/ replaced and consumed. The clear advantage of this approach is that any ERoI >1 corresponds to a net (renewable) energy producer. The downside of this approach is that the absolute benefit of PV can no longer be inferred directly from the ERoI value, since the conversion factors are dependent on the energy and technology mixes in the regions of interest. Further, the region of manufacturing may be different from that of use. In other words, the ERoI becomes a relative performance indicator in the context of these mixes.

Another parameter that is often used in the context of energy investments for PV is the Energy Pay-Back Time (EPBT). The EPBT is typically defined as the number of years a system has to operate in order to produce the same amount of energy as was needed for its manufacturing and installation that is, the number of years before it starts to be a net energy producer. Although the EPBT has the advantage of being rather easy to grasp intuitively, it requires clear specification of the definitions and methodology used to enable correct interpretation and comparison between different cases.

It is noted that the amount and type of energy invested together determines the equivalent carbon emissions for each kWh of solar electricity produced (the CO_2 footprint of PV). In this, the total carbon emissions associated with the primary energy invested are attributed to the total amount of electricity produced. If all energy invested is generated from renewables the equivalent emissions would be very small or even zero, but if all energy invested is generated from coal, the equivalent emissions would be significant. The subject of equivalent emissions is further detailed in the next paragraph. The invested energy, associated emissions and the produced energy are directly linked to a set of PV quality parameters (Table 1).

Table 1: PV quality parameters and their impact on Energy Return on Energy Investment, Energy Pay-Back Time and carbon footprint.

Quality paramenters	Impact on		
	ERoI	EPBT	CO_2 footprint
Energy efficiency*) in production, installation, Operation & Maintenance (O&M), demounting, recycling	Energy invested	Energy invested	Emissions associated with energy invested
Type of energy used: fossil, nuclear, renewable	---	---	
Initial component efficiency and performance ratio, annual degradation rate, system down time, soiling-related losses	Energy produced	Energy produced	Energy produced

**) "Energy efficiency" may refer to the (relative) efficiency differences of a specific process or activity as well as to absolute energy consumption differences between different processes or activities.*

A number of studies, reviews and reports have quantified the ERoI and EPBT of PV plants, see e.g. [5] [7] [8] [9] [10] [11] [12] [13] and references therein.

To extract typical ERoI and EPBT ranges for recent (max 5 years old) and state-of-the-art PV technologies and for future PV technologies, it is necessary to harmonize the calculation parameters used in the different studies (in particular insolation (e.g. 1100 and 1700 kWh m^{-2} yr^{-1}), system lifetime and system performance ratio). Although absolute values vary, results are consistent in that in comparable cases thin-film cadmium telluride (CdTe) based systems are found to have the highest ERoI and shortest EPBT and wafer monocrystalline silicon (c-Si) based systems the lowest ERoI and the longest EPBT.

Table 2 presents estimated typical ERoI and EPBT ranges for recent (max 5 years old) and state-of-the-art PV technologies and for future PV technologies in brackets, combining different literature sources; rounded numbers. Ranges correspond to different technologies (thin-film and crystalline silicon) and literature sources and some other variables.

Table 2: Estimated typical ERoI and EPBT ranges

	ERoI	EPBT (yrs)
High insolation regions, e.g. S-Europe (1700 kWh m^{-2} yr^{-1})	10 ~ 40 [30 ~ 60]	0.7 ~ 3 [0.5 ~ 1]
Moderate insolation, e.g. NW-Europe (1100 kWh m^{-2} yr^{-1})	7 ~ 25 [20 ~ 40]	1 ~ 4 [0.8 ~ 1.5]

1.3. Product Environmental Footprint

In line with the Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organizations and the Product Environmental Footprint Guide, the environmental impacts of electricity generated with photovoltaic systems installed in Europe should be evaluated through a harmonized set of rules, depicted as Product Environmental Footprint Category Rules (PEFCRs) [14].

Following the Product Environmental Footprint Pilot phase, these PEFCRs are now available for photovoltaic electricity generation in the European Union. The PEFCR provides a harmonized set of rules to evaluate the environmental impacts of PV modules installed in the region of the EU28 and EFTA countries. To achieve this objective, a set of PV specific framework parameters were established and incorporated into the PEFCR. The following default parameters are used to establish the environmental impact of a European PV module:

- Annual yield of the PV system: 975 kWh/kWp (including degradation);
- Annual degradation rate of the PV system: 0.7% per year;
- Expected lifetime of the PV system: 30 years.

The annual average yield of optimally oriented modules in Europe was weighted according to the cumulative installed PV power and corresponds to 1090 kWh/kWp (excluding degradation effects). This average yield and the expected system lifetime should not be adjusted when carrying out a PEFCR-compliant Life Cycle Assessment (LCA). A deviation from the default degradation rate is only valid if verification documentation (as defined in the PEFCR) is published along with the assessment. The definition of common framework parameters and default impact categories is of paramount importance because the use of varying and poorly documented framework parameters limits the comparability of the publicly available life cycle assessments of different PV technologies and the applicability of the results for policy or regulatory decisions. The default environmental footprint impact categories depicted in the PEF Guidance were applied throughout the pilot process, in line with various life cycle impact assessment methodologies [15].

A comprehensive overview on the life cycle assessment indicators that are relevant to determine the environmental footprint of a photovoltaic system are provided in the Annex to this document. Based on this indicator list, specific impacts can be depicted, i.e. the product carbon footprint, which would use the climate change impact category, or the land use change category which could be translated into an ecological footprint.

For a comprehensive environmental footprint analysis, the use of the PEFCRs for PV module production is recommended [16]. To optimize the environmental footprint of the PV system, the product environmental footprint analysis provides a useful framework to identify so-called hotspots in the life cycle of the system. This hotspot analysis can be undertaken by each manufacturer based on a comprehensive life cycle assessment, which could be based on the Product Environmental Footprint Category Rules (PEFCRs) referenced above. The Screening Study [17] undertaken as part of the PEF Pilot Phase, has done a hotspot analysis for today's commercially available PV technologies and has identified a number of impact categories which are common to all technologies as hotspots. Figure 9 in the Annex provides an overview on the hotspots and the respective life cycle stage for the average PV system in the EU (weighted by the market shares of the different commercial PV technologies).

Based on the weighted results of the screening study, the most relevant impact categories for all PV technologies include:

- Mineral and fossil resource depletion;
- Human toxicity, cancer effects;
- Human toxicity, non-cancer effects;
- Freshwater ecotoxicity;
- Particulate matter potential;
- Acidification potential.

When looking at the respective life cycle stage when the hotspot occurs, it becomes clear that the majority of the impacts relate to the supply chain of electricity (i.e. the grid mix which is used for PV manufacturing) as well as the supply chain of materials (mainly the supply chain of copper and steel) which are driving those impacts.

2. CRITICAL QUALITY ASPECTS ALONG PV PROJECT PHASES

2.1. Engineering and Development of a PV project

Large photovoltaic plants are complex projects typically planned and carried out by project developers. In order to successfully develop such a project, technical as well as commercial and legal know-how are required.

Various market players throughout the entire value chain may influence the reliability of the plant. The use of low-quality materials and components can lead to inherent error susceptibility in the overall system. After installation and commissioning, the effect of planning and design errors on the system performance can often only be remedied with major structural changes to the overall system. Professional planning and construction can ensure that most requirements are considered for the reliable operation of the plant. Minimizing risk in the planning and construction of photovoltaic systems increasingly plays a role in the investment decision.

2.1.1. Securing project financing

Quality is the key for turning PV projects from a risk investment to a reliable asset. With the help of experts, banks have updated their lending criteria and have reassessed the project financing process. The bankability of projects is mainly justified by the outstanding quality of system components and the competence of the main contractor. While banks are typically interested in stable, long-term loan repayments and reliable market conditions, investors are focused on their return on invest and possible tax incentives. The capital is usually provided by the project initiators themselves or by third parties such as project developers, utilities, institutional or private investors. For initiators of PV projects, communication with their target groups is crucial. Competence and the quality of the components used are important arguments for successfully implementing a project. For all stakeholders, the reliability of a project is essential from a legal, technical and economic point of view, as summarized by the Solar Bankability R&D project "Bankability becomes the key to project financing [18].

As part of the approval planning, all prerequisites for the financing, construction and operation of the PV system must be prepared and all necessary documents must be provided. Already in the early planning phase of a solar power plant, the course is set for success and long-term profitability. Depending on the type of installation (roof or ground-mounted system) the following items need to be considered:

- Intended areas must be surveyed;
- Statics must be checked;
- Soil expertise must be created (possibly by pile driving test);
- Coupling point with the grid must be discussed with the utility and
- Long term yield assessments must be prepared providing P50 and P90 exceedance probabilities.

Negligence already in this project phase often leads to unnecessarily high follow-up costs.

A particular challenge in the planning and implementation of photovoltaic projects is the coordinated interaction of the involved lots. An object-related, exact and need-based definition and delineation of the respective services is essential.

For many projects, a general contractor is already involved in the design phase, allowing a seamless transition to the planning phase. General contractors accompany and supervise projects from the idea to the development and far beyond the project planning offering competent advice and realization of turnkey photovoltaic systems. In addition, plant monitoring, as well as maintenance and repair services are offered. General contractors should work with experienced subcontractors with whom they have already completed projects successfully. This is especially important for execution services where the majority of mistakes are made, often associated with considerable follow-up costs.

A general contractor must therefore be chosen carefully. Many years of presence on the market and numerous references can be helpful in the decision-making process.

2.1.2. Planning and design

Planning and design have a significant impact on how well a photovoltaic system works over the years. At this stage of the PV project, the foundations are laid for:

- Long lifetime and reliability of the equipment
- Functional operation management
- High efficiency of the products and the overall system

Assessing the technical availability of PV systems may be very difficult. On one hand, the quality criteria for the components used are not defined in detail, and on the other hand, generic design and dimensioning rules are applied to PV applications with specific requirements. Performance guarantees from module manufacturers must never be equated with a quality statement. Another concern is the fact that the reliability of a PV system is often reduced to just the modules and possibly even the inverter.

In several recently completed studies, attempts have been made to quantify and identify the faults found in numerous assessments of PV systems [19] [20]. The findings so far show that total or partial failures have very different causes. Reasons for this are, among others, development deficits due to enormous cost and margin pressure, which may lead to serial defects of the affected component.

2.1.3. Yield assessment

Some technical risks have an impact on the overall uncertainty of the forecasted or actual energy yield. In the following section, we report upon the most important quantities affecting the energy yield.

2.1.3.1. Resource assessment: long-term solar irradiation

The most common sources for these data are climate databases with long-term observations from public meteo (weather) stations and satellite observations. They are available from different commercial providers. Significant differences can be observed when comparing these sources to each other or to reference meteorological observations. Often several databases are combined in order to reduce the uncertainty in the solar resource estimation.

The annual insolation variability is represented by the standard deviation of the irradiation over a long period of time. Typical values range between 4-7%

as shown for example by Richter [21] and Suri [22]. For risk assessment, the annual insolation variability could represent the main source of uncertainty when analyzing the risk associated with the cash flow during a single year. In long term yield assessments and cumulated cashflow, the uncertainty is relatively low as years with low insolation are compensated for by years with higher insolation.

Another point that needs to be considered in long term insolation estimation is the presence of long term trends defined as brightening or dimming which highly depend on the location. Values of 3% of brightening per decade are not uncommon [23].

2.1.3.2. Degradation models

Degradation and performance loss rate will be discussed under procurement. In yield assessment, typically a value ranging between 0.2 to 0.7% is selected. It has to be highlighted that this value is typically given without knowledge on uncertainty and thus exceedance probability [24]. More efforts are, thus, needed in this direction to improve the confidence depending on the module technology and site location.

2.1.3.3. Parameters used in power calculation

The uncertainty on the estimation of the module power calculation depends on the following steps: plane of array (POA) irradiance estimation, effective irradiance estimation, cell temperature estimation, temperature coefficients, PV module degradation and mismatch.

Module shading and module coverage by soiling or snow can be a notable yield-reducing factor as well. Finally, the AC power calculation depends on the PV inverter model where typical uncertainty values are in the order of 0.2-0.5% [25].

Another important parameter in yield assessment is PV system availability. Failures as listed in PVPS Assessment of PV Module Failures in the Field [26] , i.e. EVA browning, delamination, detached junction boxes, defective by-pass diodes, glass breakage, cell cracking, and corrosion can strongly reduce the PV plant availability and, consequently, the energy yield. The failure risk can be reduced by quality assurance measures in component procurement and appropriate handling.

2.2. Procurement

In order to reduce risks of failure during operation, both suppliers and modules need to be qualified. As an example of such a qualification process one could list the following steps:

1. Qualifying a supplier for a certain time period is done in a multiple step validation process:
   - Analysis of a supplier's eligibility, followed by a first go/no go decision
   - Financial and technical analysis, followed by a second go/no go decision
   - Factory inspections/audits and module tests followed by a decision to qualify the supplier, or not.
2. IEC qualification tests (61215:2016, 61646:2008, 61730-2:2016) presently prescribe up to 160 days field-equivalent AM 1.5G UV dose which is much less than 25 years of expected deployment [27]. Further quality control is thus necessary.
3. Quality Control Process of modules, on randomly selected samples may include
   - Indoor tests
     - Initial power evaluation, light induced degradation behavior;
     - Degradation evaluation, enhanced test sequences based on IEC standards, combined stresses with UV, dynamic load tests, PID tests;
   - Outdoor tests
     - System degradation on a small plant, typically 3 to 15 kW;
     - Module degradation tests, with individually monitored modules;

This leads to an agreement with the supplier, including specifications on how to measure power, on packaging and on module sorting, and what type of microcracks and other flaws are acceptable or rejected.

So far, little attention has been paid to all other system components, as their durability has rarely been questioned. Precisely these system components (connectors, cables, generator junction boxes, DC switches, circuit breakers, fuses) are often the cause of system malfunctions, along with yield losses. Their quality and reliability are of major importance since they are highly relevant for safety.

2.2.1. Factory inspection

One prerequisite for the issuance and maintenance of a module certificate is the performance of periodical factory inspections. Factory inspections include the verification of all raw materials used for the certified products, inspection of the complete production process and review of general quality-related issues. In Technical Assumptions in Financial PV Models: Review of Current Practices and Recommendations [21], TÜV Rheinland systematically categorized and evaluated all deviations encountered during several years of factory inspections (2012-2016). Flasher related deficiencies refers to correction procedures to Standard test Conditions (STC) (both irradiance and temperature), calibration of equipment, general maintenance and flasher classification and sum up to 16% of all the deviations. This can lead to uncertainties in the estimation of the module power with differences up to 10% in $P_{mpp,STC}$ by comparing laboratory measurements with datasheet values. Other deviations are related to safety tests in production (9%), calibration of measurement equipment (7%), production traceability (9%) or standard quality tests.

Published in 2016, IEC 62941 contains the guidelines for increased confidence in PV module design qualification and type approval. Since its publication various PV module manufacturers received the IEC TS 62941 technical specification certification leading to the expectation that this certification should lead to a reduction of technical risks during manufacturing [27].

2.2.2 Module service life and annual failure rates

The degradation rate of a solar PV module is defined as the rate of performance reduction over time and is dependent on a large number of factors including cell and module technology, materials and production methods [28]. The degradation types can be divided into different categories depending on the timeframe of their occurrence as shown in Figure 3 [29]. All the degradation mechanisms are initiated through a combination of environmental factors such as solar irradiance, very high or very low temperature, temperature oscillations, humidity, precipitation, dust, snow and ice, mechanical loads from wind and hail or nearby lightning strikes [30].

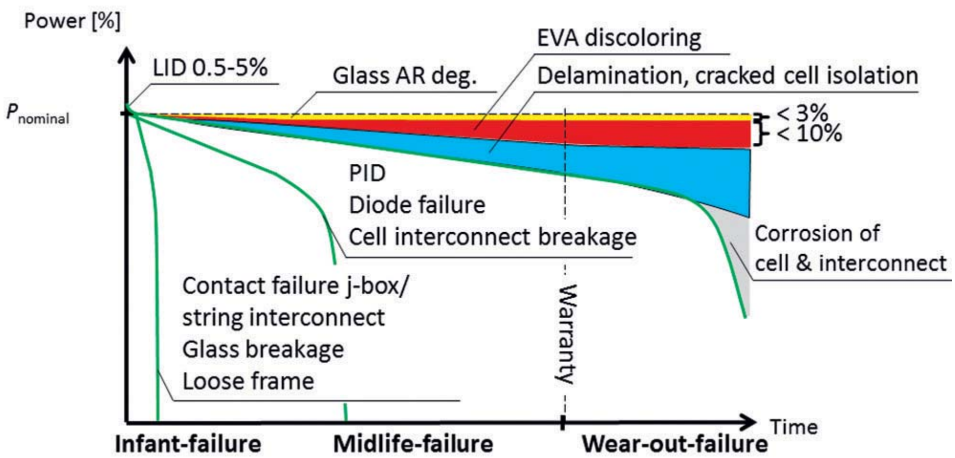


Figure 3: Typical failure scenarios for wafer based crystalline photovoltaic modules [29]

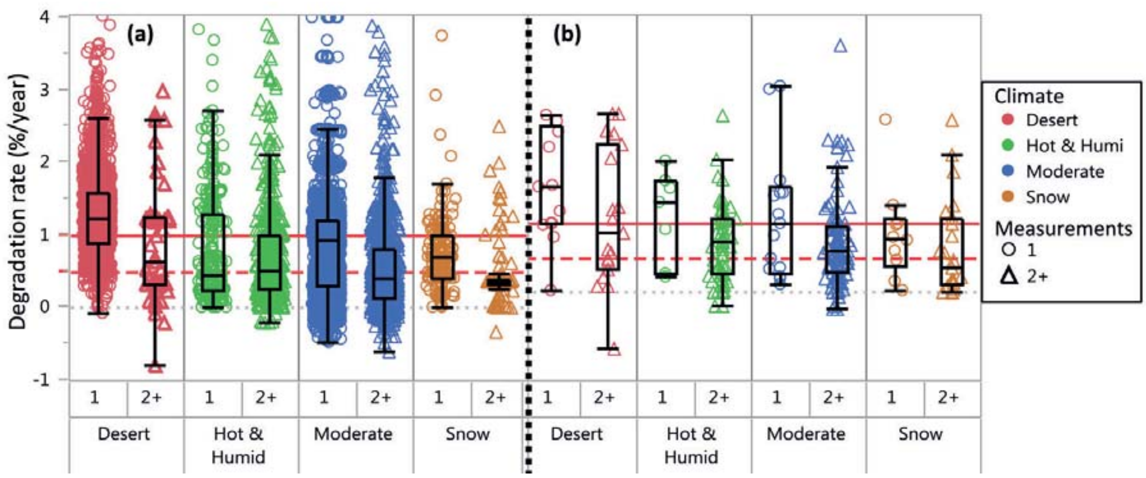


Figure 4: Degradation rate for x-Si PV module depending on climate (Jordan 2016)

The median degradation rate of about 0.5-0.6 % annually for c-Si PV modules is calculated from long-term fielded samples [31]. These values have been extracted from over 10.000 data points from PV systems, investigated for different durations, silicon technology generations and climates. In this study the most common degradation modes for PV modules were found to be hot spots, internal circuitry discoloration, glass breakage and encapsulant discoloration [32].

Another study cited the following mechanisms: laminate internal electrical circuit defect, glass damage, J-box and cell damage [29]. Differences between these studies are strongly linked to the age of the installation. Other elements that explain the difference in conclusions are the climate condition and differences in interpretation of the observed power loss. In the last 5-10 years the progress in PV module materials reduced the frequency of common degradation modes such as delamination, fractured cells and encapsulant discoloration. Notably the frequency of certain degradation modes varies depending on the duration of installation [26]. Next to occurrence one must also consider the severity of the various degradation modes, in term of downtime or financial impact. Based on this classification the four most critical mechanisms that contributes to power loss is shading, EVA discoloration and glass breakage and potential induced degradation [33].

2.2.3 Inverter performance and reliability

The effect of inverters on the overall quality of a PV plant is determined by their energy efficiency in normal operation and by their technical reliability.

2.2.3.1 Inverter Efficiency

The energy overall efficiency of a PV inverter in normal operation depends on the inverter’s energy conversion efficiency and on its energy maximum power point (MPP) tracking efficiency. An inverter’s conversion efficiency and its MPP are defined and can be determined in the lab according to EN50530. Both immediately affect the specific yield of a PV plant and, hence, its LCOE. One percentage point difference in inverter efficiency means approximately one percent relative difference in specific yield throughout the lifetime of the inverter, hence, 1% lower revenues from the PV project.

2.2.3.1.1 Energy Conversion Efficiency

As an indication of the energy conversion efficiency for long-term operation in the field, the European efficiency is commonly used. The European efficiency is a weighted average of inverter efficiency in the laboratory at different operating points. The European efficiency may only be considered representative for the moderate climate in central and Western Europe. Other weighted average efficiencies in the field have been proposed for other climates. Nevertheless, European efficiency is the measure for inverter efficiency in the field that is most widely used in Europe and commonly supplied with the inverter’s data sheet. Today’s PV inverters show European efficiency values of around 96% and above, depending on size and electrical topology.

Beyond nameplate European efficiency, the energy conversion efficiency of PV inverters depends on the inverters' input voltage. Particularly when operating often at relatively low input voltage, the conversion efficiency may be smaller than the nameplate European efficiency. For today's PV inverters, the voltage dependency of the conversion efficiency should count for variations below 1% When the long-term energy yield is estimated with common modelling tools, PV plant designers typically assume uncertainty values in the order of ±1% to ±2% to account for voltage deviations and environmental influences [21].

2.2.3.1.2 MPP Tracking Efficiency

The MPP tracker of a PV inverter is the control system that makes the DC voltage of the PV array follow up on variable irradiance and temperature. [34] It should ensure that the PV array can always generate the maximum power available for the given environmental conditions.

Independent measurements show that that the MPP efficiency for most inverters is in accordance with the manufacturer's data sheet [34]. However, there are currently products available with insufficient MPP tracking, leading to unexpected losses and accordingly lower specific yield.

2.2.3.2 Inverter Reliability

The inverter reliability affects the LCOE of a PV plant through specific yield and OPEX. In practice, low reliability implies that the equipment fails sooner or more often than expected. The event of failure can be catastrophic or non-catastrophic [21]. Catastrophic failures are characterized by an entire shut-down of the inverter during a period that can clearly be observed through the monitoring system. Non-catastrophic failures imply operation at a reduced conversion or MPP tracking efficiency.

2.2.3.2.1 Impact of Catastrophic Inverter Failures on Specific Yield

Catastrophic failures cause a reduction of specific yield. When there is a monitoring system followed up upon by an operator, catastrophic failures are detected fast when systems are monitored, and operators respond to monitoring. The yield reduction will then mainly depend on the time to repair. Moreover, for a PV plant with multiple inverters, it also depends on the size of the PV generator connected to the failing inverter compared to the overall PV array size.

2.2.3.2.2 Impact of Non-Catastrophic Inverter Failures on Specific Yield

Non-catastrophic failures also cause a reduction of specific yield; unfortunately, they are detected less easily than a catastrophic failure. With a non-catastrophic failure the yield reduction is partial, depending on the severity and frequency of the underlying fault. The most common fault causing non-catastrophic failure is inverter overheating, i.e. due to improper installation, a broken fan or a clogged filter [35] These situations may cause inverters to curtail their output power far below the rated value or to shut down intermittently.

Other common non-catastrophic failures include curtailment or intermittent shutdown triggered by the grid monitoring functions or intermittent shutdown due to fault currents on the DC side. These faults are detected by the inverter, but their root causes mostly lie outside, on the grid or PV array side, respectively, or in the system design. These failure modes are therefore discussed in Section 2.2 Engineering.

As for a catastrophic failure, the yield reduction also depends on the time to repair. Time to repair is often dominated by the time needed to detect the failure, isolate the fault, and diagnose the underlying root cause. In comparison, the time between diagnosis and repair is less significant. Even for monitored plants with an operations team, it may take several weeks to months to detect, isolate and diagnose a non-catastrophic failure. For residential and small commercial plants, such failures regularly go undetected.

2.2.3.2.3 Impact of Inverter Failures on OPEX

The OPEX contribution of both catastrophic and non-catastrophic failures consists primarily of the cost of the spare part plus the labor costs for repair.

For maintenance and repair, there are generally two strategies: inverter replacement and on-site repair. Tendentially, inverter replacement is applied for smaller inverters (up to several tens of kilowatt) while on-site repair is applied for medium to large inverters (starting from several tens of kilowatt). However, we also see kilowatt range inverters designed for on-site repair.

As a minimum requirement with a given inverter type, PV plant owners and their O&M contractors may want to control OPEX by consciously choosing an O&M strategy that goes beyond the maintenance actions recommended by the manufacturer, including active management of the stock of spare parts and ensuring the availability of qualified staff to replace or repair the devices.

2.2.3.3 Quality and Risk over the Product Life Cycle

The product life cycle of a PV inverter model can be illustrated by a bathtub curve (Figure 5).

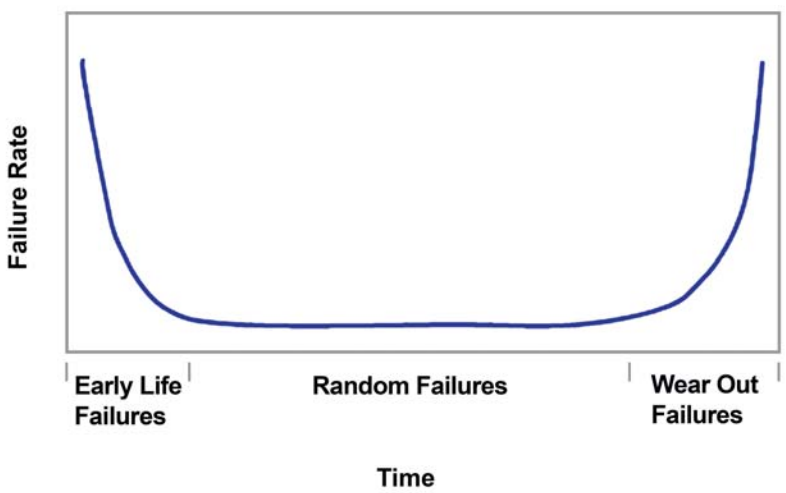


Figure 5: Bathtub curve showing probability of failures over the technical lifetime of a product or project [21]

The bathtub curve in Figure 5 illustrates the product life cycle as seen by a reliability engineer. The bathtub curve has three characteristic segments, each of which has a particular meaning for a PV inverter in the field:

Early life failures are covered by warranties. This holds for inverters and PV modules as well as for the entire installation, where the EPC contractor or installer is liable for any installation fault until final acceptance.

Random Failures (Failure after burn-in): for inverters and plants as a whole, the interesting question is the "failure rate" that may statistically be expected for the given inverter, plant, etc. of this model/manufacturer or EPC contractor. For inverters (specific types, or generations from one manufacturer) this is in principle possible. However, now such comprehensive statistical analyses have been published yet. The lower the failure rate after burn in, the lower the O&M costs.

End of life: An expectancy for the time to fail is commonly modelled with Weibull distributions, allowing to compare the lifetime for different inverters.

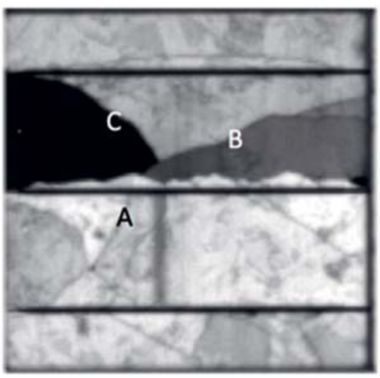
2.3. Construction

Transportation, installation, operation and maintenance are included under the construction phase of a PV project. The new standard IEC TS 63049:2017, available since January 2018, provides guidelines for effective quality assurance in PV system installation, operation and maintenance.

2.3.1. Transportation

Transportation begins when a solar panel is stacked onto a pallet and continues until the PV module is installed in the field. This process may include such diverse steps as manual handling of PV modules, transportation by ship in large containers, movement of pallets employing a forklift and truck transport of individual pallets, among others. During transportation, solar modules undergo mechanical stress that can lead to cracks that affect both their short and long-term performance.

Common reasons behind PV module damage due to transportation include shocks and vibrations occurring during transport. These shocks and vibrations can cause cell cracks due to deflection of the modules. Cell cracks can be of three types, A, B and C, in which cracks of Type A do not imply any loss in current generation, Type B induce electrical losses, and Type C are electrical isolating cracks. These cracks are depicted in Figure 6. Notably, although cell cracks of Type A do not mean immediate power output loss, these cracks can develop into cell cracks of Type B due to outdoor exposure.



An adequate packing system of the PV modules that is able to withstand mechanical stress is key in order to transport the PV modules safely from the manufacturing to the installation site. Test revealed that no cell cracks occurred for vertical transport stacks while up to two Type A cracks per module were observed for the horizontal stacks. PV modules should hence be packed into vertical stacks to avoid damages during transport.

Figure 6: Single cell region of a module with 0,1 x Isc applied showing crack types, as labelled. labelled. [37].

2.3.2. Installation and Commissioning

PV plants should be constructed by experienced EPC contractors and installers. In commercial PV projects the installation quality is verified through the commissioning process. It "basically covers the handover of the plant from the EPC contractor to the future owner by verifying the achievement of several essential milestones in technical, financial and legal terms." [37]

The commissioning process is split into three subsequent acceptance tests [37]

- Acceptance of mechanical completion, where the proper installation is verified before the system is set into operation;
- Provisional acceptance, where the responsibility for the plant is transferred to the owner (excluding any contractual warranties), after few weeks of operation;
- Final acceptance, where any remaining liabilities are transferred from the EPC contractor to the owner, typically after several years, in line with the EPC contract.

The commissioning process should be carried out by an independent party.

Errors occurring during the construction of the PV plant may result in damage that affects plant availability, if these errors remain undetected over long periods. Installation errors can be caused by time pressure in the construction, lack of quality control, lack of expertise, or by willful acts. Such errors remain undetected as a result of missing or insufficient technical inspection after installation of the system.

On-site inspection is a demanding task during the construction phase. The site manager is responsible for the correct execution of the construction and installation measures. Monitoring and examination of the services to be provided by the executing companies, review and comparison of documents must be coordinated. Through regular quality checks, construction and installation defects can be detected and eliminated at an early stage.

The final technical inspection provides reliable information on the quality of the PV system. An extensive inspection as well as measurement and evaluation of the main components and installation takes place on site. All verified items are noted in a commissioning report. The aim of commissioning is to prove the functionality of the photovoltaic system. The tests to be performed are described in EN 62446-1 [38]. As part of the technical due diligence, all technical aspects that are relevant for the economic success of the project are examined. This includes:

- Examination of the planning documents with regard to a yield-optimized system design;
- Examination of a standard-compliant implementation;
- Extensive measurements that go beyond the initial tests (IV curve measurements, thermographic investigations, electroluminescence analysis, PID test, insulation and grounding measurements, functional test of the monitoring system);
- Review of the system documentation and the assessment of technical contracts for plant monitoring and for maintenance and other services;

2.4. Operation and Maintenance

The quality of the O&M services plays a vital role for the reduction of the Levelized Cost of Electricity (LCOE) within the entire lifecycle of a PV project [18] [39].

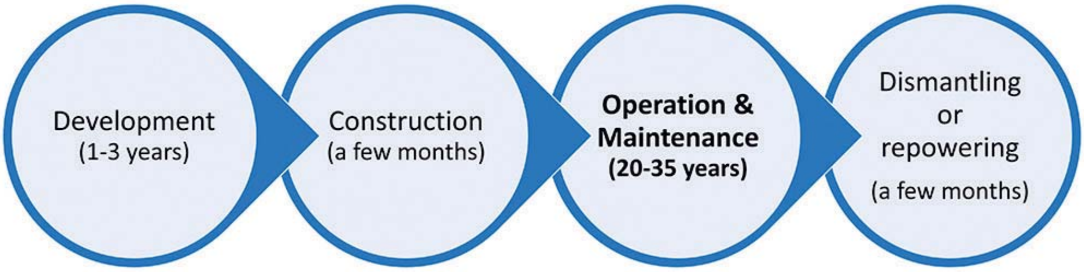


Figure 7: PV Plant Life Cycle

After final acceptance, when a PV plant has been running for several years, O&M duties are often passed from the EPC to a dedicated O&M contractor. This is typically a different party than the asset owner and the EPC contractor. The O&M contractor, on behalf of the asset owner, has to make decisions about plant performance and life time versus operational costs.

Recently, the solar industry has successfully formulated a number of good and best O&M practices. Organizations such as the ETIP-PV, SolarPower Europe [40] IEA-PVPS [41] and NREL/SANDIA just to name the most active, [42] have published technical guidelines, minimum requirements and recommendations, and whitepapers for non-technical stakeholders that cover the full spectrum of activities of the O&M ecosystem.

One of the main challenges facing the O&M industry are the discrepancies between the quality of services provided by different O&M Contractors. Reasons for this include increasing price pressure, lack of standardisation and minimum requirements, inadequate management processes, poorly qualified staff and insufficient use of digital data analytics. Responding to these discrepancies, SolarPower Europe first published in 2016 a set of O&M Best Practices Guidelines that, by 2018, have become a living document with an active community behind, today already consisting of nearly one hundred top experts from nearly 50 companies. In its newest release (version 3.0) [40] a variety of important new chapters were added, where topics such as aerial thermographic inspections and advanced data analytics are included.

Additionally, based on these guidelines, the Solar O&M Best Practices Mark was launched in June 2018, which is a self-certification-based label aimed at creating more transparency in the O&M market and allowing leading companies to demonstrate their excellence and increase the level of quality and consistency of their services.

The International Electrotechnical Commission (IEC) has published an extensive framework of international standards and technical specifications related to O&M [43] [44] [45] [46] [38] just which are verified through a Conformity Assessment (CA) Scheme put into place by the IECRE [47]. Ongoing efforts towards the standardisation of O&M contracts are being led by the Solar Energy Standardisation Initiative (SESI) [48].

The key O&M activities [18] [39] are summarised in the following sections.

2.4.1. Operations

Operations include remote monitoring, supervision and control of the PV power plant and involves the coordination of maintenance activities by a qualified management team. It includes proper documentation management and data analysis capabilities.

After commissioning, error sources can be subdivided into factors that can be eliminated easily, and those that can be eliminated to a limited extent only. The factors that can be eliminated to a limited extent include the aging and wear-out of main components or subcomponents, environmental influences (in particular lightning strikes), external influences, vandalism and network faults. Factors such as incorrect operation of the system as well as the lack of monitoring and maintenance of the system can be overcome with minor effort.

2.4.2. Maintenance

On-site maintenance activities include (i) Preventive Maintenance, i.e. regular visual and physical inspections and verifications activities aimed at reducing the probability of malfunctions, (ii) Corrective Maintenance, to fix malfunctions and restore the faulty PV plant, equipment or component to the required functionality, (iii) Extraordinary Maintenance, i.e. all actions that can be necessary after major unpredictable events in the plant site that require substantial repair works, and (iv) Additional Services such as module cleaning, vegetation control or IR inspections.

2.4.3. Spare Parts Management

Spare Parts Management is an inherent and substantial part of O&M aimed at ensuring that spare parts are available in a timely manner to minimise the downtime of a solar PV plant.

2.4.4. Monitoring and Data Management

Plant operation is supported by a remote monitoring system that allows supervision of the energy flow in a PV plant. Plant monitoring includes dataloggers capable of collecting data (such as energy generated, irradiance, module temperature, etc.) of all relevant components (such as inverters, strings, energy meters, pyranometers, temperature sensors, etc.) and storing all historical data, as well as a reliable Monitoring Portal (interface) for the visualisation of the collected data and the calculation of KPIs. For proper monitoring, detection of failures and performance calculations, data acquisition and recording should be close to real time with 5–15 min time resolution [37].

2.4.5. Field inspections

Field inspections for failure detection and performance measurement are part of advanced O&M activities. In recent years, Unmanned Aerial Vehicles (UAVs), commonly known as drones, have proven to be a cost-effective tool for conducting infrared (IR) thermographic inspections of large-scale PV plants [49] [50]. If deployed properly, they could become a cornerstone technology for effective O&M and they would not only be an activity performed just to comply with contractual obligations.

Aerial thermography might seem a trivial activity, but when not conducted following a set of minimum technical requirements, it is almost of no use for effective plant maintenance. In that context, high-quality IR images captured by a drone and their proper post-processing allow for a detailed PV module failure analysis that could trigger conclusive maintenance decisions. Furthermore, other field interventions like IV curve tracing or EL imaging could be optimized and PV plant underperformance could also be better understood and addressed. For example, faulty modules that need to be replaced can be identified with precision and high-quality IR images can be used as proof in warranty claiming processes.

The demand for IR inspections is growing fast, and so is the range of post-processing services offered by new players in the market, who are now pushing this stage beyond basic reporting.

Figure 8: Post Processing Stage

Aerial inspections and their associated post-processing activities are evolving rapidly and the quick adoption of new technologies and fully automated solutions is of strategic importance in today's highly competitive O&M market.

Copyright: BayWa r.e.

3. Suggested measures

3.1. Practical measures

A few percent of underperformance in a plant may severely reduce the investor's return, while it will usually not affect an involved lender. For this reason, it is the investor who should pay most attention to quality. Due to the technical, economical and legal complexity of large PV power plant projects, competent main contractors are essential for the plant's profitability. They need to smoothly coordinate the interaction of numerous suppliers and stakeholders. As a counterpart to the main contractor, a third party should be assigned by the investor for independent quality assurance through all project phases from development to engineering, procurement, construction and operation.

3.1.1. Components

Independent quality assurance is required to avert risks from the enormous cost pressure in the entire PV value chain. PV Module test certificates following international standards prove a basic qualification. For further reduction of performance risks, extended type testing and continuous conformity supervision in production is strongly advised. With regard to large batches of PV modules supplied to PV projects, the off-taker should check quality on representative samples.

PV plant designers should choose for inverters with confirmed high energy and MPP tracking efficiency. For large shipments, particularly when new inverter models are concerned, investors should commission tests of efficiency and MPP tracking efficiency by an independent test lab.

3.1.2. Yield prediction

Annual insolation variability represents a main source of uncertainty for annual yields and needs to be considered in short term financial modelling. In the long term, trends in annual irradiation should be observed when simulating power plant yield from historical irradiation data. Irradiation data derived from satellite measurements requires validation based on data from ground stations. Depending on the site, yield losses due to module coverage by soiling of up to 0.5-1%/day and associated cleaning cost may require a soiling risk assessment.

3.1.3. Data Analytics for Enhanced Monitoring

3.1.3.1. Industrial & Utility scale systems

Diagnostic tools for predictive maintenance and 'smart' software solutions can contribute to further increase quality and reduce LCOE of PV plants.

The main target is to move from pure visualization tools to automatic diagnosis and decision-making solutions. O&M contractors are starting to adopt machine learning and data-driven solutions, as well as innovative diagnostic instruments, to keep up with the market requirements, without jeopardizing the quality of their services.

Innovations in O&M services can potentially reduce the LCOE by 0.8% to 1.4% between 2015 and 2030. The savings are dominated by improvements in OPEX and power plant availability, and hence net Annual Energy Production [51]. According to preliminary estimations made by BayWa r.e. based on confidential information collected from third parties the effective implementation of diagnostic software based on Artificial Intelligence ("AI") algorithms could lead to an energy yield increase of existing assets of up to 5%, and to more than 10% savings in O&M costs, with positive impact on the LCOE. Interoperable monitoring system components that can talk to each other through the internet of things and autonomously configure their parameters would facilitate such diagnostic functions.

3.1.3.2. Residential & Commercial Systems

Residential and small commercial PV plants are often not monitored or the owners do not actively follow up on monitoring even when it is in place. In such cases, the owners may only detect the fault after several weeks to months, depending on the billing frequency.

Monitoring systems in this segment should include an irradiation reference, e.g., an irradiance sensor or irradiation data from a satellite service. Regional environmental agencies or R&D centers could provide maps of year to year differences in yield, and grid operators could report yield difference with neighbor PV plants.

Moreover, energy suppliers and PV installers in the business-to-consumer segment may consider offering simple and standardized PV O&M services based on monitoring with automatic fault detection.

3.1.4. Active Participation in Power Markets

The integration of PV plants into the grid with an active participation to the balancing markets is a further option to improve revenues and reduce LCOE of PV. Consequently, the prediction of PV production is becoming essential to capture economies in a market with large penetration of variable sources (solar and wind). Algorithms that can match weather forecasts with PV plant characteristics are going to be integrated in the monitoring software.
As a result, PV plants could also take part in Virtual Power Plants (VPP), which are the aggregation of different predictable and non-predictable energy production plants and storage systems. This would allow the VPP operators to manage them as a unit for better dispatching them into the grid and to participate to the most remunerative opportunities of the electricity market.

3.2. R&D Challenges

Experience from the field clearly shows that wafer-based silicon PV modules can, in principle, be operated for 30 years and potentially more. Some more recent thin film technologies also display a service life exceeding 25 years. These findings are not self-evident for all current or future product designs. Ongoing innovation in solar cell and module materials often introduce novel degradation mechanisms observed in the field, but not detected in current type testing procedures. The adjustment of qualification procedures, service life prediction and yield prediction remain an ongoing challenge in the fast moving PV sector. This challenge is diversified with increasing PV deployment in demanding climates which require adaptations of test procedures.

Comprehensive testing sequences under combined and varying loads with conservative acceleration factors are able to reveal unknown failure mechanisms. R&D effort is then required to translate expensive procedures into cost and time effective, simplified and highly accelerated sequences still relevant for field operation.

Since many PV module types still contain hazardous materials like lead, the reduction of the use of these materials and their replacement becomes an increasing challenge with growing deployment. Module designs that facilitate cost-effective material separation and recycling need to be developed.

The financial sector requires precise, probabilistic translation of technical risks into cash-flow and LCOE risks. This would allow less conservative assumptions and eventually lower LCOE.

Early life failures of inverters are covered by the product warranty of typically five years. However, for the failure rate during operation and the expected service life of recent PV inverters, there is now evidence available. There is an opportunity for the manufacturers of top tier inverters to proactively document their track records and the reliability of their products.

The important relation between quality (assurance) and economy of PV systems is now recognized worldwide and has led to publications dedicated to emerging markets (see for example "Boosting solar PV markets: the role of quality infrastructure" published by IRENA in 2017) [52] and to the establishment of international tasks e.g. the IEA PVPS Task 13: Performance and Reliability of Photovoltaic Systems (***http://www.iea-pvps.org/index.php?id=57***) [41] and the International Photovoltaic Quality Assurance Task Force (PVQAT: ***http://www.pvqat.org/index.html***) [53]. These tasks provide a platform whereby quality aspects are elaborated and they lead global efforts to craft quality and reliability standards for solar energy technologies. These standards will allow stakeholders to quickly assess a PV module's performance and ability to withstand local weather stresses, thereby reducing risk and adding confidence for those developing products, designing incentive programs, and determining private investments.

3.3. Suggested regulatory actions

3.3.1. Reduction of carbon footprint

Mainly because a large amount of the PV components installed in Europe today are produced far away and shipped around the globe, measures like the EU emission trading system or national carbon taxes have hardly any effect.

To increase the pressure on carbon emissions, a carbon footprint certificate for PV components needs to be established. The footprint value should become part of product nameplate information. Publicly regulated tenders, feed-in-tariffs, taxes or levies can set up incentives for low carbon footprints, also raising awareness for private investment decisions.

In France, the current regulation for tenders (2017-2019) gives an important weight to the CO_2 footprint of a PV power plant. 20-30% of the evaluation of a tender is related to the carbon impact in terms of kg eqCO_2/kWp. Each component of the system must be evaluated according to its "Global Warming Potential" GWP which is based on many factors, like the weight of raw materials and the country of transformation. In that way, the price of the system weighs only for 70% in the final decision. Depending on the size of the power plant, other criteria are evaluated like environmental suitability, non-clearing of forest land and possession of an urbanization agreement.

The rating of the carbon content can either come from a country specific rating per material or from a supplier specific LCA calculation validated by a French independent certification body. For more details, see link below to the website of the national energy regulation commission.

This unique low carbon footprint regulation has led to the development of a specific supply chain. Ingots and wafers are sourced mainly in Norway, Korea or France because of the low carbon content of the electricity production there. These choices lead to an extra module cost of about 0.05€/Wp, compared to the cheapest sources, however the carbon footprint is many times lower.

The current production capacity of low carbon wafers can be estimated to 2-3 GW, to be compared with the total word capacity of over 100 GW.

3.3.2. Reduction of use of hazardous materials

Like other electrical and electronic products used for electricity generation, many PV modules contain certain hazardous substances. PV Modules are not included in the "Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment" (RoHS) scope at present. Recycling regulations in place reduce the risk of uncontrolled waste deposition. Yet, with the upcoming deployment of a few billions of PV modules in Europe, even a few percent of non-recycled products become relevant. It should be ensured that high value recycling captures and de-pollutes the end-of-life PV panel waste stream. To enable that, manufacturers shall list the presence of IEC 62474 declarable substance groups and declarable substances in the product at or above the reporting threshold amounts stated in the IEC 62474 Standard, using the version of IEC 62474 which is current at the time the product is put on the market. A certificate disclosing the type and amount of IEC 62474 declarable substances is required and should be incentivized, for example through the introduction of an Eco-Label or Green Public Procurement criteria. The international NSF457 Sustainability Leadership Standard for Photovoltaic Modules [54] provides a template for eco-label requirements. The declaration should become part of product nameplate information. Publicly regulated tenders, feed-in-tariffs or taxes can set up incentives for the reduction and omission of declarable substances, also raising awareness for private investment decisions.

3.3.3. Ecolabel

A conscious eco-design should focus on addressing those hotspots through use of lower-carbon grid mixes, renewable energy supply for manufacturing, increased use of recycled material in manufacturing and system construction, including Balance of System components, and of course, the increase of conversion efficiencies and lifetime, which increases the denominator for the net energy production of the system. As the PEF Screening study points out, increasing the lifetime of the system by 5 years, leads to a reduction of approximately 15% across all impact categories. Increase of high value recycling and the allocation of recycling benefits through the use of recycled materials leads to significant improvements on a number of impact categories for the average PV system. The impact category "mineral, fossil and renewable resource consumption" could be reduced by up to 67%, the impact on the human toxicity impact category could also be up to 28% lower if recycling approaches are applied. [55]

Currently, the Ecolabel initiative is undergoing the preparatory study of the European Commission, which evaluates potential sustainability policy measures for Photovoltaic Modules, Inverters and systems. The results of the preparatory study are expected in Summer 2019, and will include policy recommendations regarding potential eco-labels, green public procurement criteria, energy labels and eco-design requirements for the European Union.

3.3.4. Performance monitoring for small PV systems

While the performance of PV power plants in the industrial and utility segment is usually monitored and referenced to the expected yields on an hourly or daily base, many smaller systems in the home and commercial segment are not properly monitored and serviced due to cost reasons. This could be solved by enforcing monitoring of data in those PV plants that receive public support (tender systems, net billing, net metering, feed-in tariffs) to ensure that they are properly working.

4. Annex

Table 3: List of life cycle assessment indicators relevant for a product environmental footprint.

Impact category	Indicator	Reference
Indicators required according to the PEF guide		
Climate change	Radiative forcing as Global Warming Potential (GWP100) [kg CO_2 eq.]	[56]
Ozone depletion	Ozone Depletion Potential (ODP) [kg CFC-11 eq.]	[57]
Human toxicity, cancer effects	Comparative Toxic Unit for humans [CTUh, c]	[58]
Human toxicity, non-cancer effects	Comparative Toxic Unit for humans [CTUh, n c]	[58]
Particulate matter / respiratory effects	Intake fraction for fine particles [kg PM2.5 eq.]	[59]; [60]; [61]
Ionizing radiation, human health	Human exposure efficiency relative to U^{235} [kBq U^{235} eq.]	[62]
Photochemical ozone formation	Tropospheric ozone concentration increase [kg NMVOC eq.]	[63] as applied in ReCiPe
Acidification	Accumulated Exceedance (AE) [mol H^+ eq.]	[64]; [65]
Eutrophication, terrestrial	Accumulated Exceedance (AE) [mol N eq.]	[64]; [65]
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P) [kg P eq.]	[66] as implemented in ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N) [kg N eq.]	[66] as implemented in ReCiPe
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems [CTUe]	[58]
Land use	Soil Organic Matter [kg C deficit]	[67]
Resource depletion, water	Water abstraction related to local scarcity of water [m^3 water eq.]	[68]
Resource depletion, mineral, fossil, renewable	Scarcity [kg Sb eq.]	[69]

Impact category	Indicator	Reference
Additional indicators		
Cumulative energy demand, renewable	Gross energy content of renewable primary energy resources [MJ oil eq.]	[70]
Cumulative energy demand, non-renewable	Gross energy content of non-renewable primary energy resources [MJ oil eq.]	[70]
Nuclear waste	Radiotoxicity index, RTI [m^3 HAA eq.]	[71] [72]

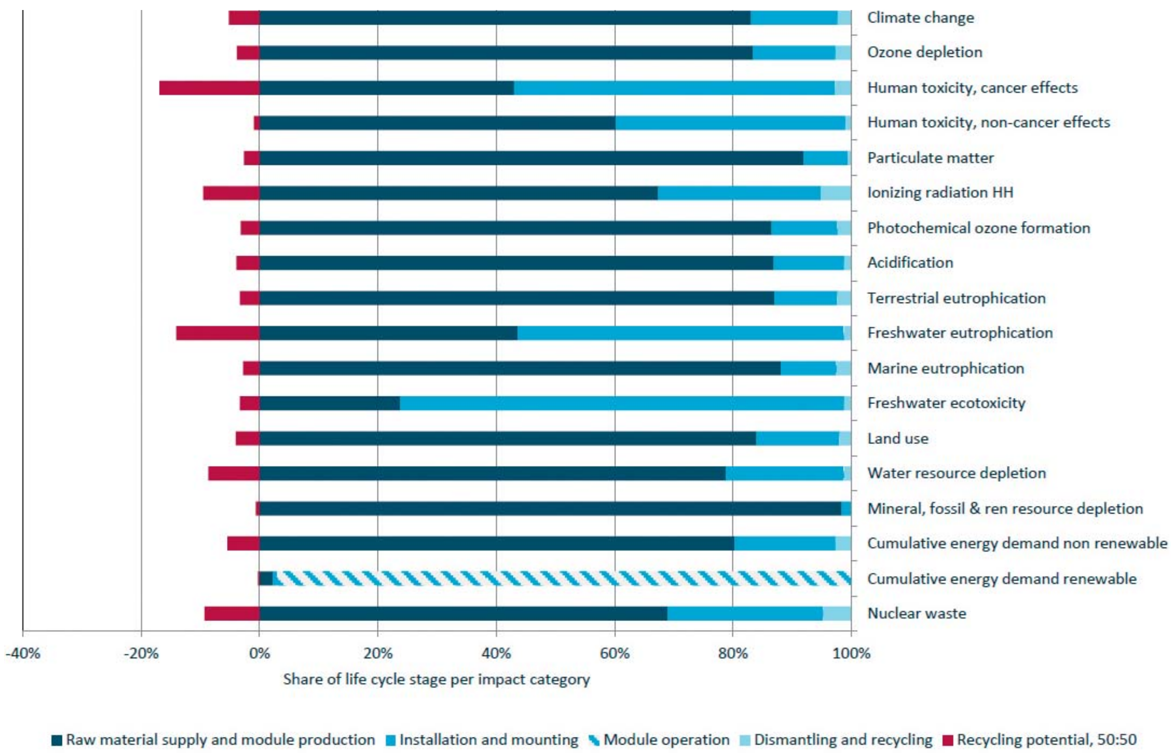


Figure 9: Environmental impact (characterized, indexed to 100%) of 1 kWh of DC electricity produced with a 3 kWp residential system composed of the average EU PV module [17]. All impact categories are normalized to the functional unit of 1 kWh, in order to establish comparability.

5. References

[1] Breyer et al. , «On the Role of Solar Photovoltaics in Global Energy Transition Scenarios,» 2016.

[2] «Fact Sheet About Photovoltaics,» ETIP PV.

[3] A. Wade et al., «Beyond waste – the fate of end-of-life photovoltaic panels from large scale PV installations in the EU the socio-economic benefits of high value recycling compared to re-use.,» chez 33rd EU PVSEC, 2017.

[4] CENELEC, «Collection, logistics & treatment requirements for WEEE - Part 2-4: Treatment requirements for photovoltaic panels and Collection, logistics & Treatment requirements for WEEE - Part 3-5: Technical specification for depollution - Photovoltaic panels,» 2017.

[5] V. Fthenakis et al., «Environmental life-cycle assessment of photovoltaic systems,» chez The Performance of Photovoltaic (PV) Systems, Modelling, Measurement and Assessment, Elsevier Ltd, 2017, pp. 209-232.

[6] D. Moser et al., «Technical Assumptions in Financial PV Models: Review of Current Practices and Recommendations,» IEA PVPS, 2016.

[7] K.P. Bhandari et al. , «Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis,» Renewable and Sustainable Energy Reviews 47, p. 133–141, 2015.

[8] «Life Cycle Assessment of Future Photovoltaic Electricity Production from Residential-scale Systems Operated in Europe,» IEA PVPS, 2015.

[9] R. Koppelaar, «Solar-PV energy payback and net energy: Meta-assessment of study quality, reproducibility, and results harmonization,» Renewable and Sustainable Energy Reviews, pp. 1241-1255, 2017.

[10] A. Louwen et al. , «Re-assessment of net energy production and greenhouse gas emissions avoidance after 40 years of photovoltaics development,» Nature Communications 7, 2016.

[11] F.Ferroni et al, «Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation,,» Energy Policy 94, p. 336–344, 2016.

[12] M. Rauge et al., «Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation: A comprehensive response,» Energy Policy 102, p. 377–384, 2017.

[13] 2. [FhG ISE.

[14] R. Frischknecht, P. Stolz, G.Heath, A. Wade, L. Francke, I. Theologitis, J. Tian, «Product Environmental Footprint Category Rules, Photovoltaic Modules used in Photovoltaic Power Systems for Electricity Generation,» (NACE/CPA class 27.90, 2017.

[15] A. Wade, P. Stolz, R. Frischknecht, G. Heath, P. Sinha, «Photovoltaic (PV) balance of system components,» The Performance of Photovoltaic (PV) Systems, p. 135–181, 2017.

[16] A.Wade et al., «The Product Environmental Footprint (PEF) of photovoltaic modules-Lessons learned from the environmental footprint pilot phase on the way to a single market for green products in the European Union“».Progress in Photovoltaics: Research and Applications.

[17] Wyss et al., «PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules,» (PEFCR) Pilots v.2.0, 2016.

[18] «Solar Bankability - PV Investment-Technical Risk Management. Best Practice Guidelines for Risk Identification, Assessment and Mitigation».

[19] «HERA-VPP - High Efficiency, Reliability, Availability of Virtual Power Plants,» Fraunhofer-Institut für Windenergie und Energiesystemtechnik, 2016.

[20] «Bewertung des Brandrisikos in Photovoltaik-Anlagen und Erstellung von Sicherheitskonzepten zur Risikominimierung, TÜV Rheinland Energie und Umwelt GmbH Fraunhofer - Institut für Solare Energiesysteme ISE.».

[21] M. Richter et al., «Technical Assumptions Used in PV Financial Models - Review of Current Practices and Recommendations,» IEA PVPS, Report IEA-PVPS T13, 2017.

[22] M. Suri, «Uncertainties in solar electricity yield prediction from fluctuation of solar radiation 2007,» chez 22nd EU PVSEC, 2007.

[23] B. Müller et al, «Rethinking solar resource assessments in the context of global dimming and brightening,» Sol. Energy 99, p. 272–282, 2014.

[24] Belluardo et al., «Novel method for the improvement in the evaluation of outdoor performance loss rate in different PV technologies and comparison with two other methods,» Solar Energy, pp. 139-152, 2015.

[25] M.Richter, «Uncertainties in PV modelling and Monitoring,,» chez 31st EU PVSEC, 2015.

[26] M. Köntges et al., «PVPS Assessment of PV Module Failures in the Field,» IEA–PVPS T13, 2017.

[27] I.Repins, «PV QAT – A global effort to craft quality and reliability standards,» chez Quality and Sustainability of PV Systems Conference, 2018.

[28] A.Phinikarides et al. , «Review of photovoltaic degradation rate methodologies,» Renewable and Sustainable Energy Reviews 40, pp. 143-152, 2014.

[29] M. Köntges et al., «Review of Failures of Photovoltaic Modules,» IEA-PVPS T13, 2014.

[30] P. Sachez-Friera, «Analysis of degradation mechanisms of crystalline silicon PV modules after 12 years of operation in Southern Europe,» 2011.

[31] C.Jordan et al., «Compendium of photovoltaic degradation rates,» pp. 978-989, 2016.

[32] D. C. Jordan et al., «Photovoltaic failure and degradation modes,» pp. 318-326, 2017.

[33] D.Moser et al, «Identification of technical risks in the photovoltaic value chain and quantification of the economic impact,» Prog. Photovolt: Res. Appl., vol. 25, p. 592–604, 2017.

[34] F. Baumgartner, «Photovoltaic (PV) balance of system components,» The Performance of Photovoltaic (PV) Systems , p. 135–181, 2016.

[35] D. Moser et al., Technical Assumptions in Financial PV Models: Review of Current Practices and Recommendations, 2016.

[36] «Photovoltaic (PV) devices - Part 13: Electroluminescence of photovoltaic modules,» EC TS 60904-13, 2018.

[37] A. Woyte, S. Goy,, «Best practices for the design and operation of large photovoltaic power plants,» chez The Performance of Photovoltaic (PV) Systems, 2017.

[38] « Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 1: Grid connected systems - Documentation, commissioning tests and inspection, » IEC 62446-1, 2016.

[39] O. &. M. B. P. Guidelines, SolarPower Europe, 2017.

[40] «www.solarpowereurope.org,» [En ligne].

[41] «Performance and Reliability of Photovoltaic Systems,» IEA PVPS Task 13, (http://www.iea-pvps.org/index.php?id=57).

[42] «Best Practices in Photovoltaic System Operations and Maintenance,» 2nd Edition, NREL/Sandia/Sunspec Alliance SuNLaMP, 2016.

[43] «Photovoltaic system performance - Part 2: Capacity evaluation method,» IEC TS 61724-2, 2016.

[44] «Photovoltaic system performance - Part 1: Monitoring,» IEC 61724-1, 2017.

[45] «Photovoltaic system performance - Part 3: Energy evaluation method,» IEC TS 61724-3, 2016.

[46] «Terrestrial photovoltaic (PV) systems - Guidelines for effective quality assurance in PV systems installation, operation and maintenance,» IEC TS 63049, 2017.

[47] IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE System).

[48] Global Solar Energy Standardisation Initiative (sesi.terrawatt.org).

[49] Buerhop-Lutz, Inspecting PV plants using aerial, drone-mounted infrared thermography systems, 2015.

[50] «Utilizing Unmanned Aircraft Systems as a Solar Photovoltaics Operations and Maintenance Tool,» Electric Power Research Institute, 2015.

[51] «Future renewable energy costs: solar photovoltaics,» KIC InnoEnergy, 2015.

[52] «Boosting solar PV markets: the role of quality infrastructure,» IRENA, 2017.

[53] «The International Photovoltaic Quality Assurance Task Force,» http://www.pvqat.org/index.html.

[54] «https://webstore.ansi.org/Standards/NSF/NSFANSI4572017,» [En ligne].

[55] Wyss et al., PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots v.2.0, 2016.

[56] IPCC, «The IPCC fourth Assessment Report - Technical Summary,» Cambridge University Press, 2007.

[57] WMO, «Scientific Assessment of Ozone Depletion,» World Meteorological Organisation, 1998.

[58] R. Rosenbaum, T. Bachmann, L. Gold, A. Huijbregts, O. Jolliet, R. Juraske, A. Koehler, H. F. Larsen, M. MacLeod, M. Margni, E. McKone, ;J. Payet, ; M. Schuhmacher; D. van de Meent ; M. Z. Hauschild, «USEtox - the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle assessment,» International Journal of Life Cycle Assessment, vol. 13, n° %17, pp. 532-546, 2008.

[59] S. Greco, A. Wilson, D. Spengler, J. Levy, «Spatial patterns of mobile source particulate matter emissions-to-exposure relationships across the United States,» Atmospheric Environment, n° %141, pp. 1011-1025, 2007.

[60] S.Humbert, «Geographically Differentiated Life-cycle Impact Assessment of Human Health. PhD Thesis.,» University of California, Berkeley, California, USA, 2009.

[61] A. Rabl, J. V.Spadaro, «The RiskPoll software,» 2004.

[62] R. Frischknecht, A. Braunschweig, P. Hofstetter, P.Suter, «Modelling human health effects of radioactive releases in Life Cycle Impact Assessment,» Environmental Impact Assessment Review, vol. 20, n° %12, pp. 159-189, 2000.

[63] R. Van Zelm, A. Huijbregts, A. Den Hollander, A. Van Jaarsveld, J Sauter, J. Stuijs, J. Van Wijnen, D.Van de Meent, «European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment,» Atmos Environ, pp. 441-453, 2008.

[64] M.Posch, J. Seppälä, J. P. Hettelingh, M. Johansson, M. Margni, O. Jolliet, «The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA,» Int J LCA, pp. 477-486, 2008.

[65] J. Seppälä, M. Posch, M. Johansson, P. Hettelingh, «Country-dependent Characterization Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator,» Int J LCA, pp. 403-416, 2006.

[66] J. Struijs, A Beusen, H. van Jaarsveld, A. Huijbregts, «A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level,» 2008.

[67] L. Milá i Canals, J. Romanyà, J. Cowell, «Method for assessing impacts on life support functions (LSF) related to the use of 'fertile land' in Life Cycle Assessment (LCA),» Journal of Cleaner Production, vol. 15, n° %115, pp. 1426-1440, 2007.

[68] R. Frischknecht, R. Steiner, N. Jungbluth, «Methode der ökologischen Knappheit-Ökofaktoren 2006,» Bundesamt für Umwelt (BAFU), 2008.

[69] B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, A. Udo de Haes, H. de Bruijn, R. van Duin, A. Huijbregts, E. Lindeijer, A.Roorda, P. Weidema, «Life cycle assessment; An operational guide to the ISO standards; Parts 1 and 2,» Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), 2001.

[70] R. Frischknecht, F. Wyss, S. Buesser, T. Lützkendorf, M. Baloutktsi, «Cumulative energy demand in LCA: the energy harvested approach,» Int J LCA, vol. 20, n° %17, pp. 957-969, 2015.

[71] R. Frischknecht, S. Büsser Knöpfel, «Swiss Eco-Factors 2013 according to the Ecological Scarcity Method. Methodological Fundamentals and their application in Switzerland. Environmental Studies n. 1330,» Federal Office for the Environment, 2013.

[72] R. Frischknecht, S. Büsser Knöpfel, «Ecological scarcity 2013- new features and its application in industry and administration- 54th LCA forum,» Int J LCA, pp. 1361-1366, 2014.

[73] «Photovoltaic (PV) systems- Requirements for testing, documentation and maintenance- Part 1: Grid connected systems- Documentation, commissioning tests and inspection,» IEC 62446, 2016 .

[74] «Photovoltaic (PV) systems- Requirements for testing, documentation and maintenance - Part 3: Photovoltaic modules and plants- Outdoor infrared thermography,» IEC TS 62446-3, 2017.

[75] M. Suri, «Uncertainties in solar electricity yield prediction from fluctuation of solar radiation,» chez 22nd EU PVSEC , 2007.

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