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Review

A path to reduce variability of the environmental footprint results of photovoltaic systems

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ABSTRACT

With the ecological transition, there is a rapid growing interest in better understanding the environmental profile of photovoltaic (PV) systems, seen today as clean renewable energy. Nevertheless, published Life Cycle Assessment (LCA) of PV systems exhibit significant differences in their assumptions and methodological choices, as well as their resulting outcomes. Such variability makes it difficult to take energy policy decisions. The goal of this study is to identify factors promoting this variability in order to reduce it. To this end, studies, methodological choices, data quality and defined assumptions were analyzed from 30 published crystalline LCA PV to recognize critical PV parameters (solar irradiation, efficiency, etc.) in an LCA study. As a result of this analysis, a big variability was identified in the choice of the system boundary, functional unit and impact categories, which may influence the interpretation of the obtained results. Through a criticality analysis, the solar irradiation was the main critical parameter in a PV LCA study with 41% of criticality rate followed by the lifetime and the module efficiency with 20% and 17% respectively. Concerning the data quality to model the system, the results showed a significant impact of the electricity mix: carbon footprint of a PV system is twice higher with Chinese mix than with the European mix. In conclusion, the variability of LCA PV studies is essentially due to dynamic parameters previously mentioned that evolve continuously with the evolution of PV. Then, for reliable LCA results in the future, these paper uncovered recommendations helping to define the appropriate assumptions taking into account the dynamic aspect of the PV systems parameters.

Contents

1. Introduction . . . 1608
2. Literature survey . . . 1609
3. Methodology . . . 1609
4. Variability in the implementation of LCA method . . . 1610
   4.1. System boundary . . . 1610
   4.2. Impacts categories . . . 1610
   4.3. Functional unit . . . 1611
5. Variability in PV parameters . . . 1611
   5.1. Efficiency of the PV modules . . . 1611
   5.2. Solar irradiation . . . 1612
   5.3. Performance ratio . . . 1612
   5.4. Life time . . . 1613
   5.5. Degradation rate . . . 1614
   5.6. Criticality analysis . . . 1614

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0959-6526/

6. Data quality: variability in materials, components and processes 1614
6.1. PV materials and manufacturing processes 1614
6.2. Electricity mix 1615
7. Summary of the analysis 1616
8. Conclusion 1616
Acknowledgements 1617
References 1617

1. Introduction

With the growing of the environmental concerns, the generation of electricity from solar energy is positioned today as a renewable “clean” energy. This positive effect explains the significant growth of photovoltaic (PV) energy during the last ten years. The PV modules global production is estimated to be about 108 GWp at the end of 2017 (JRC, 2017). This exponential growth is dominated by the crystalline silicon technology which represent 94% of the PV market in 2017 (ISE, 2017). This market covers the use of both monocrystalline (mono-Si) and multicrystalline (multi-Si) silicon material.

Regardless of the technology, the PV system is a set of by-products interacting between each other (Fig. 1). Each part of the value chain is defined by specific characteristics and manufacturing processes. Although PV electricity generation is generally seen as an improvement over fossil fuel technologies from environmental point of view, the implementation of PV systems may also causes environmental changes. Hence, life cycle assessment (LCA) is nowadays considered as one of the main relevant tool to study the environmental impact of a product. The field of LCA is already covered by several standards and guidelines as the ones provided by the International Organization for Standardization (ISO, 2006a, 2006b) or the Life Cycle Data System Handbook (EC-JRC, 2010).

However, as shown by the literature survey reported in section 2 of this paper, the assumptions and the methodological choices as well as the resulting outcomes of the published PV LCA studies exhibit large discrepancies. Thus decision makers have to deal with the wide variety of modelling choices and assumptions. Several papers attempt to clarify the assumptions and the results of these PV LCAs. Hsu et al. (2012) conducted a meta-analysis of existing studies, harmonized key performance characteristics to produce more comparable and consistently derived results. Koppelaar (2017) carried out a meta-analysis of quality aspects of existing energy studies for PV systems then reproduced and harmonized twenty-nine studies with a focus on the data quality. Bhandari et al. (2015) conducted a systematic review and meta-analysis of embedded energy of crystalline and thin film PV systems. PV parameters were harmonized to calculate the less disturbed energy metrics values and compared them before harmonization. Pacca et al. (2007) looked at the way that the PV parameters such as efficiency and solar irradiation affect the results of a specific LCA. However, they did not take into account the previously published LCAs. Almost all these published works were focused on the harmonization of the PV parameters to reduce the variability of the results. But none of them has attempted to understand and analyze:

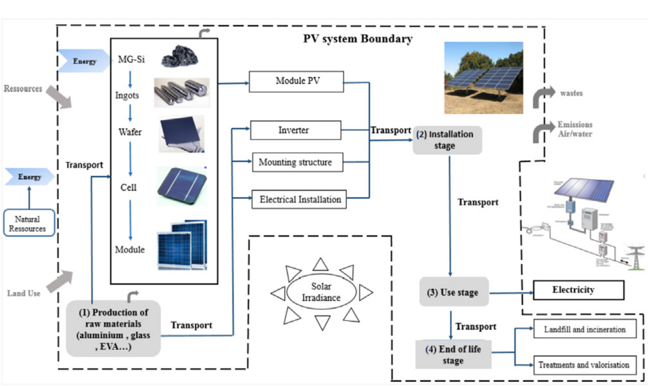

Fig. 1. The system boundary of PV system from the extraction of the raw materials to the end of life.

- The variability of the PV parameters and the implemented LCA method in the different studies,
- The rate of the criticality of each parameter,
- The appropriate values of the parameters to ensure reliability in future analysis.

The present paper seeks to understand and to analyze the variability of the assumptions and to identify the critical PV parameters from the 30 PV LCA studies of mono-Si and multi-Si PV systems of the literature survey (section 2). In this work we have used the so-called impact categories identified according to the different kind of resource uses and pollutant emissions. section 3 of this paper deals with these impact categories. They are often expressed per unit of electricity generated (kWh). For the PV systems, the electricity generated Epv over the life time of a PV system depends on technical PV parameters and may be expressed as follow:

$$Epv = I \times A \times \eta \times T \times PRi \times \sum_{y=1}^{T} (1 - (y\ X\ DR)) \quad (1)$$

where I is the average annual solar irradiation (kWh/m^2/yr) which is specific to the location, A is the total surface area of the PV modules (m^2), η is the module efficiency that is the percentage of solar radiation energy that can be converted into electrical energy, PRi is the initial performance ratio which represents the ratio of the electricity generated to the electricity that would have been generated if the plant consistently converted sunlight to electricity at the level expected from the DC nameplate rating, T is the life Time corresponding to the service time of the system (years), and DR is the degradation rate corresponding to the mean annual degradation of the systems efficiency during its service time. The PV parameters that are analyzed are the solar irradiation, the module efficiency, the performance ratio, the life time and the degradation rate. Indeed the environmental results depend indirectly on these parameters.

The LCA methods implemented in the analyzed studies are identified and analyzed in terms of (i) system boundaries, functional units and impact categories in section 4 of the paper, (ii) PV parameters in section 5 and (iii) the data quality in section 6. The methodological choices made by the LCA experts to assess the environmental impact of the PV systems are carefully discussed from the point of view of their impact on the LCA results. The way that the PV parameters affect the specific results of a given LCA are also evaluated. Further, this paper makes recommendations summarized in section 7 that are based on the feedback of the installed PV systems and the today PV market. They are expected to support the choice of the most appropriate assumptions for a better reliability of the results of future PV LCA analysis. Hence they could inform decision makers and future LCA practitioners about critical factors for a PV LCA study and they could also induce more transparent and comparable results of the PV energy system.

2. Literature survey

The 30 PV LCA studies treated in this work are listed in Table 1with the key performance characteristics and the Greenhouse Gas (GHG) emissions results. All of them are quantitative studies; 19 are academic, and 11 are industrial. The analysis of each defined parameters is detailed in section 5.

It is worthy to mention that the year 2005 was chosen as a threshold in this work because, on one hand, the world production of PV cells exceeded 1 GWp that year according to (EurObserv''ER, 2011) and on the other hand, the methodology of the PV LCA was structured by some major studies in this period.

3. Methodology

The methodology adopted in this work is described in Fig. 2. It was consisted on (i) the identification of the assumptions and methodological choices defined in the 30 PV LCA studies, (ii) the analysis of their variability and their limits then (iii) the proposition of recommendations.

The analysis of the LCA method was based on a comparison between what have been defined in the 30 studies and what is recommended by LCA experts to assess environmental impact of the PV systems (in particular, the IEA (2016) guidelines). Such

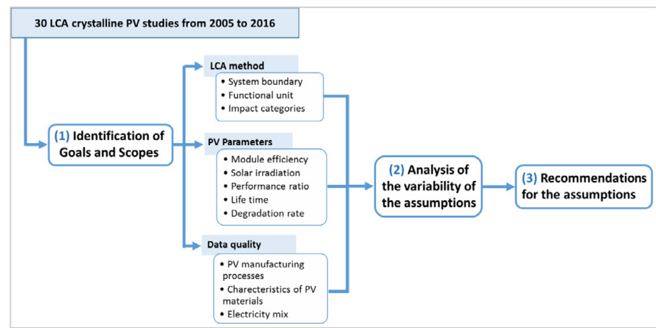

Fig. 2. Different steps of the methodology of analysis proposed in this paper with details of the assumptions extracted from the 30 PV LCA studies.

Table 1
Variability in carbon footprint results of mono-Si and multi-Si PV systems in the 30 PV LCA studies between 2005 and 2016 with parameter values and characteristics defined in those studies.

Studies	Location	Carbon Footprint (gCO2eq/kWh)	Technology	η (%)	I (kWh/m^2/yr)	PR	LT (years)	DR (%)
Hondo (2005)	Asia	53	multi-Si	14	1314	0.75	30	-
Battisti and Corrado (2005)	Europe	–	multi-Si	10.8	1530	-	30	-
De Wild-scholten and Alsema (2005)	Europe	35	multi-Si	13.2	1700	0.75	30	-
Jungbluth (2005)	Europe		multi-Si	13.2	1117	–	30	-
		79	mono-Si	16.5				
Fthenakis et al. (2012)	Europe	–	mono-Si	20.1	1800	0.8	30	-
Pehnt (2006)	Europe	72	multi-Si	13.4	1100	0.85	25	-
Muneer et al. (2006)	America	44	mono-Si	11.4	800	-	30	-
Kannan et al. (2006)	Asia	217	mono-Si	11.8	1635	-	25	-
Alsema et al. (2006)	Europe	32	multi-Si	13.2	1700	0.75	30	-
		35	mono-Si	14				
Raugei et al. (2007)	Europe	72	multi-Si	14	1700	0.75	20	-
Pacca et al. (2007)	America	72	multi-Si	12.9	1359	0.95	30	-
Lenzen (2008)	Australia	106	multi-Si	13	1750	0.85	25	-
Stoppato (2008)	Europe	61	multi-Si	16	1697	0.83	28	-
Fthenakis et al. (2008)	Europe	43	mono-Si	14	1700	0.8	30	-
		41	multi-Si	13.2				
Ito et al. (2008)	Europe	12	multi-Si	12.8	1702	0.78	30	-
De Wild-Scholten et al. (2008)	Europe	23	mono-Si	13.2	1700	0.75	30	-
Jungbluth et al. (2009)	Europe	–	mono-Si	14	1117	0.75	30	-
		–	multi-Si	13.2				
Zhai and Williams (2010)	Europe	24	multi-Si	13.2	1700	0.75	30	-
Ito et al. (2010)	Asia	50	mono-Si	–	1702	0.78	–	-
		43	multi-Si					
Sumper et al. (2011)	Europe	–	multi-Si	16.8	1614	-	-	-
Desideri and Yan (2012)	Asia	89	multi-Si	14.4	1552	0.8	25	0.5
Fthenakis and Kim (2011)	Europe	64	multi-Si	13.2	1800	0.8	30	–
De Wild-Scholten (2013)	Europe	38	mono-Si	14.8	1700	0.75	30	0.67
		27	multi-Si	14.1				
Yue et al. (2014)	Europe	38	mono-Si	14.2	1700	0.75	30	-
		32	multi-Si	13.2				
Kim et al. (2014)	Asia	42	mono-Si	15.9	1310	0.8	30	-
		32	multi-Si	14.9				
Palanov (2014)	Europe	53	mono-Si	14.2	1150	0.8	30	0.5
Frischknecht et al. (2015)	Europe	35	multi-Si	13	1700	0.75	30	-
Fu et al. (2015)	Asia	50	multi-Si	13.6	772 - 2100	0.75	25	–
Wyss et al. (2015)	Europe	88	mono-Si	15.1	1331	0.75	30	0.8
		59	multi-Si	14.7				
Hong et al. (2016)	Asia	56	multi-Si	12.7	1300	-	25	–

comparison can help beginners to choose the best alternatives to adopt in the implementation of the LCA method for the PV system. The PV parameters were extracted from the 30 treated studies LCA. Based on the FMECA method, the criticality rating of each parameters was determined. As well, PV manufacturing processes, defined characteristics of PV materials and the electricity mix employed were analyzed. Following this analysis, recommendations to define the appropriate assumptions were proposed.

4. Variability in the implementation of LCA method

4.1. System boundary

An LCA study has to include tdifferent stages of the life cycle of the system in the system boundary. For the PV system, it was recommended in the (IEA, 2016) to include the different parts of the PV life cycle mentioned above. For the end of life stage, it is recommended to perform several analysis on material recycling using the recycled content allocation approach (cut-off) as default and the end-of-life recycling approach (avoided burden) in a sensitivity analysis.

As shown in Fig. 3, the system boundary defined in the 30 treated studies varies from one study to another. In some PV LCA studies, the system boundary was limited to the manufacturing stage only (13%). The installation of the system, called Balance Of System (BOS), composed by the mounting structure, the electrical installation and the inverter, was considered in 23% of the studies. PV modules can be installed on roof top, open ground, or facade, and each type of installation has its own BOS.

This boundary was extended in other studies to include the transport, which connects these different stages, and the end of life of the PV, taking into account waste treatment and recycling of some materials. The end of life was taken into account by 30% of the studies treated. Different scenarios were put in place to model this phase. Some studies adopted scenarios to recycle the PV panels (Wyss et al., 2015), (Desideri and Yan, 2012), others considered that the end-of-life panels are landfilled without material or energy recovery (Battisti and Corrado, 2005), or excluded this stage from the system boundary justified by the lack of data.

It is necessary to mention that the recycling stage was rarely the subject of PV LCA papers and although studies exist, few of them specify the type of allocation or justify their methodological choices.

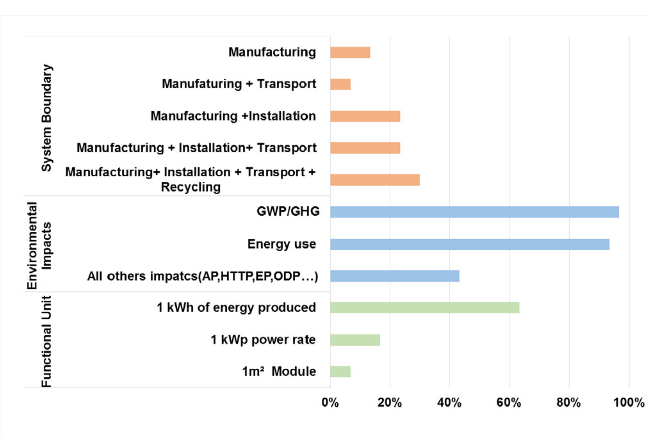

Fig. 3. Distribution of the studies including the different types of system boundary, impacts categories, which contains the environmental impacts, the emissions and the resources, and functional unit. In total 30 LCA PV studies were taken into account.

This variability on the choice of the stages to include in the system boundary had an impact on the LCA results. Wyss et al. (2015) evaluated the environmental impact per life cycle stage for the same PV system (Fig. 4). Considering the full life cycle, the carbon footprint reaches 53.8 gCO2eq/kWh compared to a minimum of 45.9 gCO2eq/kWh for only manufacturing stage. Fig. 4 highlights the benefits of the recycling process (about 6% decrease) and shows the contribution of the BOS for a multi-Si PV system mounted on roof (about 21% increase).

In order to show the influence of some stages on results, some studies conducted a sensitivity analysis. Raugei et al. (2007) have studied changes in the results by including the BOS components. Results showed an increase of about 35% in the cumulative energy demand (CED) and about 13% in the carbon footprint. Pacca et al. (2007) studied the impact of the BOS element and assume that the BOS contributed to 13.8% of the cumulative energy demand of the entire PV system. Wyss et al. (2015) conducted a sensitivity analysis of the inclusion of the inverter to the mounting system. It was shown that depending on the impact categories, the inclusion of these components add an impact between 0% and 84%.

Considering the entire life cycle of a PV system ensures the reliability of LCA results. Lack of data of some stages such as the installation and the end of life can be filled by scenario from other relevant studies with caution on data quality as well as study assumptions.

4.2. Impacts categories

A wide range of impact categories can be studied in order to determine the environmental profile of PV system. They are generally related to resource depletion, environmental damages, climate change and effects on human health. Depending on the system studied, results can be significant for some impacts and negligible for others. To evaluate these impacts, the method is based on models, which quantify the relationships between the material, the energy inputs and the associated emissions.

As reported in (PEF, 2012), it was recommended to start the LCA by evaluating all the impact categories. Then, a selection of the most relevant impact categories is done to offer more credibility. Based on this selection, the most relevant life cycle stage, process and elementary flows can be analyzed.

The majority of the studies treated in this work assessed the carbon footprint and the CED (Fig. 3). However, only 43% assessed other impacts such as acidification, ozone depletion, human toxicity, and resources depletion. Since LCA results vary depending on the impact categories, it is worthy to mention that the carbon footprint and the energy use are not the only arguments to consider

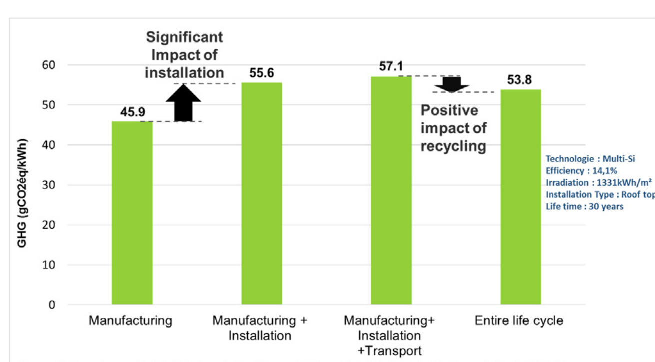

Fig. 4. Contribution of different life cycle stages of a multi-Si PV system in the carbon footprint depending on the assumptions defined in (Wyss et al., 2015).

when making decision about the environmental profile of a PV system. A risk exists that the results of some other impacts could be high and ignored in that case.

Selecting the important impact categories, where the PV system has a high contribution, can be a good solution to make decision about the environmental profile of the PV system but the fact that indicators are expressed in different units makes choice of priority difficult. One way to solve the problem and select the significant impact categories is to normalize them. Therefore, the proposed approach was to normalize results of the environmental impact of a PV system comparing to other sources of energy (Coal, Gas, Nuclear, Oil, Wind, and Biomass). The environmental impact of all sources of energy cited above were assessed. For each impact, the minimum and the maximum of obtained results were extracted. Then, PV LCA results (Gazbour et al., 2016) were normalized by these extracted values. Based on this normalization, the 17 impact categories were ranked by order of importance (Fig. 5).

As shown in Fig. 5, the resource depletion, the land use, the water consumption and human toxicity are the significant impact categories to take into consideration when conducting a PV LCA study.

4.3. Functional unit

The functional unit (FU) is a key element of the LCA study; it is a measure of the function of the studied system and it provides a reference flow to which the inventory will be related. For a PV system, the functional unit can be defined as the energy produced (kWh), rated power (kWp) or the module's area (m^2).

Three functional units are proposed in (IEA, 2016) depending on the objectives of the PV LCA study:

- “Energy produced by the PV system” is adapted to compare one PV technology to another or to a different mode of energy generation.
- “Power rate delivered by the PV system” is adapted to assess the manufacturing stage of a technology PV
- “The module area” is interesting when the surface is an important factor in the LCA study, such as quantifying the environmental impact of a building equipped by PV panels.

The “1 kWh produced by the PV system” was served as the FU in the majority of LCA PV studies as shown in Fig. 3, which is not surprising since the majority of the studies compare one PV technology to another mode of energy generation. Only Yue et al. (2014) and Fthenakis et al. (2008) chose “1 m^2 of the panel's area” for their LCA.

In order to be able to compare to not only other PV systems but also other sources of energy, the 1 kWh produced by the PV system is recommended as a functional unit.

5. Variability in PV parameters

The second category of variability refers to the PV parameters detailed above and which are shared by most of LCA PV studies treated in this paper. In this section, the PV parameters defined in the 30 studies were analyzed. Furthermore, an analysis of criticality (Section 5.6) was carried out to figure out critical parameters to pay attention to when conducting a PV LCA study. This analysis were followed by recommendations to define the appropriate value for each parameter.

5.1. Efficiency of the PV modules

The PV manufacturing processes become more efficient in recent years (ITRPV, 2017). The implementation of advanced cell technologies and the use of improved materials resulted in higher module efficiency. As shown in Fig. 6, module efficiency is rapidly evolving and expected to continue to increase with the progress in the development of PV systems. Consequently, this improvement would directly affect the environmental results.

Table 2 shows efficiencies defined in LCA studies, cited in Table 1, within their date of publication. Based on values extracted from the 30 studies, average efficiencies were 13.18% for multi-Si modules and 13.80% for mono-Si modules. Efficiency values over time are very low regarding significant improvements that has seen the PV industry since 2008 (Fu et al., 2017). Thus, estimated averages for publications on 2013–2016 (13.64% for the multi-Si and 14.37% for the mono-Si) are very low compared with the reality of the PV industry, about 16.28% for the multi-Si and 17.19% for the mono-Si for the year 2017 based on estimations detailed later in this section.

Some studies carried out sensitivity analysis by the variation of the efficiency value to identify environmental profile changes with improvement of PV modules efficiency ((Lenzen, 2008), (Ito et al., 2010)). Modules efficiency is almost inversely proportional to the

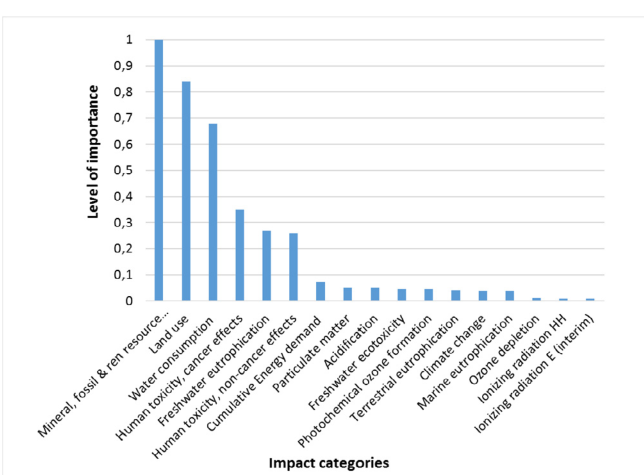

Fig. 5. The impact categories by order of importance to help selecting the significant impacts where the PV has a high contribution comparing to other sources of energy.

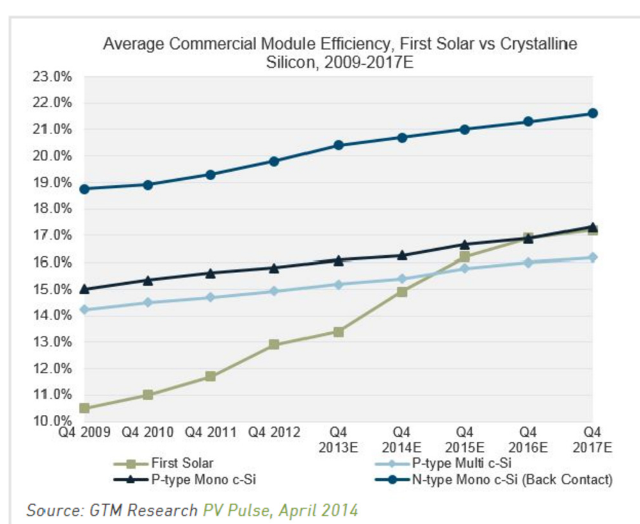

Fig. 6. Evolution of module efficiencies by technology from 2009 to 2017.

Table 2
Average efficiencies of PV panels in the 30 PV LCA studies.

	2005–2008	2009–2012	2013–2016	Average 2005–2016
Studies Number	15	7	8	30
Multi-Si	12.37%	13.54%	13.64%	13.18%
Mono-Si	12.84%	14.20%	14.37%	13.80%

environmental footprint. That is why updating this parameter with recent trends should be taken into consideration. Therefore, the proposed method is to define an efficiency representative of the PV market consisting on calculating the average of the modules efficiencies sold by of the top 10 modules producers in the world. For example, from the list of the top 10 of crystalline silicon modules producers on 2017, reported on the JRC (2017), average efficiencies of 17.19% and 16.28% respectively for mono-Si and multi-Si modules for the year 2017 were estimated.

5.2. *Solar irradiation*

All PV LCA studies should define an average annual irradiation, specific to the geographical area studied. Depending on the location, the irradiation values can be concluded from the information system called PVGIS (Photovoltaic Geographical Information System) of the Joint Research Center (JRC), which characterizes the level of photovoltaic average irradiation for Europe and Africa. In a PV LCA study, this parameter has a direct impact since it is inversely proportional to the environmental footprint.

Some works defined specific irradiation values corresponding to specific geographical locations, such as Fthenakis and Kim (2011) who choose 1800 kWh/m^2/yr as average value of the United States, or Kim et al. (2014) who took 1310 kWh/m^2/yr for their study in Korea based on estimation of the Korea Institute of Energy Research. Wyss et al. (2015) estimated 1331 kWh/m^2/yr as an average value of irradiation representative of Europe at an optimal angle, weighted by the place of installation of the PV.

It was deduced from the analysis that about 60% of the irradiation values defined in the 30 LCA studies vary between 1400 and 1900 kWh/m^2/yr (Fig. 7), where 12 studies assumed 1700 kWh/m^2/yr to represent south of Europe. However, the solar irradiation value in the south of Europe can be extended up to 2400 kWh/m^2/yr (Fig. 8).

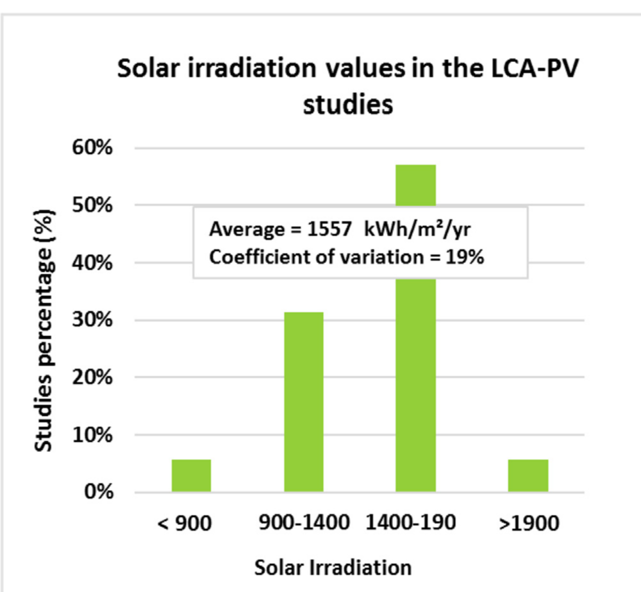

Fig. 7. Distribution of the 30 PV LCA studies including different values of solar irradiance.

Sensitivity analysis were carried out by modifying the value of the irradiation in each case. Stoppato (2008) studied the influence of this parameter on the Energy Pay Back Time (EPBT). For the same type of PV, the EPBT varies from 1.7 years for 2200 KWh/m^2/yr to 3 years for 1100 kWh/m^2/yr. Sumper et al. (2011) plotted EPBT curves in order to derive a relation between the solar radiation and the EPBT. A linear equation was obtained which highlighted the impact of this parameter on LCA results.

As the choice of the solar irradiation affect the choice of other PV parameters such as the PR, recommendation for this parameter is given in section 4.3.

5.3. *Performance ratio*

The PR defines the system losses. This ratio is affected by many factors such as inverter efficiency, operating temperature of the modules and the module efficiency under various irradiances.

Since this factor is difficult to estimate, a value of 0.75 for roof installations and 0.8 for ground installations were recommended (IEA, 2016). The PR values estimated in the majority of the studies were between 0.75 and 0.79 (Fig. 9). However, it is important to mention that the PR is increased with the recent inverters improvements and the predominance of the open ground installations, which have higher PR related to lower modules temperatures.

Others authors defined specific values such as Ito et al. (2010) who studied the environmental performance of a large scale PV system in the Gobi desert and defined a PR around 0.78 where the desert conditions and the temperature coefficient of PV modules were considered. Lenzen (2008) estimated 0.85 as a based value for large-scale PV systems then bounced between 0.8 and 0.9 as a low and high values for the PR. On the other hand, 30% of the studies didn't mention the PR value chosen even though this

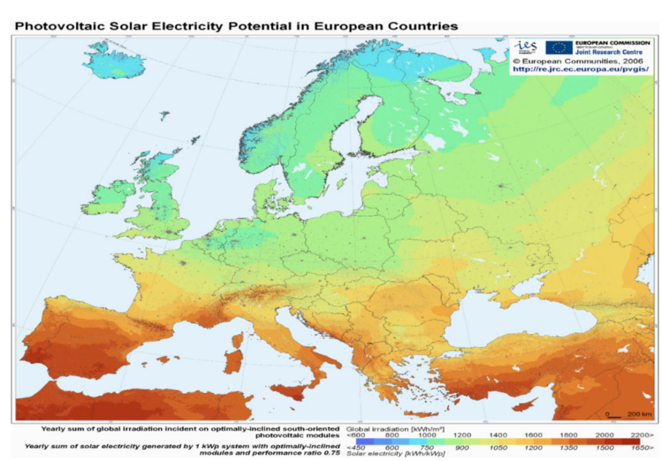

Fig. 8. Average values of global irradiance (kWh/m^2/yr) for the different European countries estimated by the information system PVGIS.

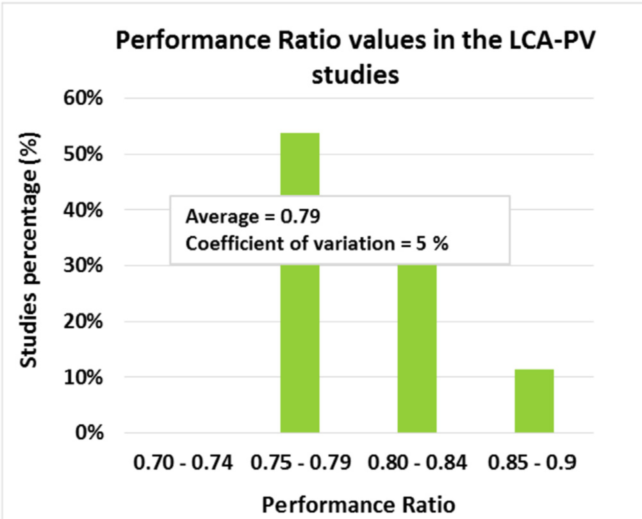

Fig. 9. Distribution of the 30 PV LCA studies defining different values of performance ratio.

parameter has significant consequences on the estimation of the annual electricity produced and therefore the results of the environmental impact.

Many the LCA studies neither indicated in their choice whether the PR value was considered as initial or average value along the life time. However, such precision is mandatory in order to use properly the PR values in calculations, since it avoids double counting of the degradation of the PV system along the life time.

The appropriate value to choose for the PR is related to solar irradiation and the type of installation.

As mentioned in section 5.2, many studies assumed a solar irradiation of 1700 kWh/m^2/yr for the South of Europe but not for the rest of Europe. In Table 3, different relevant scenarios for Europe depending on location, installation type, orientation type and solar irradiance value, as well as the PR associated to each case, are recommended.

These values were calculated based on PVGIS data and the data from (Huld et al., 2012), where he carried out the yearly global irradiance and PV energy output for horizontal, optimum and vertical angle of the PV module and for regions in Europe. Then, they were weighted by location and type of installation (rooftop and open ground plants). The loss of non-optimal orientation of rooftops was considered. The distribution of the types of installations was extracted from (EPIA, 2017).

From the solar irradiation values described in Table 3, a PR for each scenario taking into account the influencing factors (temperature and installation types) was estimated.

Such high PR values are legitimated by other sources than the considered LCA studies. For example, estimated that the PR around the world is 83.3%, based on annual yields (GWh/GWp) and total operating capacities (GWp). In (Wiki solar database, 2014), it was estimated 85.9% as global initial PR for the year 2014; their results are based on global projects of photovoltaic on utility scale around the world. The initial PR on open ground in Germany was estimated to be around 85%, as shown in (ISE, 2017).

So if the aim of an LCA study is to evaluate the environmental profile of the PV system in Europe, the first scenario in Table 2 where the PV plants were weighted by real location, real installation types and real orientation, 1425 kWh/m^2/yr as solar irradiance and 81.8 as initial PR are recommended.

5.4. Life time

The life time assessment of PV systems is not standardized. A reference value of 30 years is proposed for crystalline modules (IEA, 2016). From the 30 LCA studies, almost all studies defined 30 years, but few choose 25 years or 20 years (Fig. 10) which brought an average value of the life time to 28 years.

Indeed, for instance Stoppato (2008) choose 28 years as an average value reported by many authors, Pehnt (2006) estimated 25 years as life service for the multi-Si modules and expect an increase of this value to reach 30 years by 2030 with the increase of improvements in the PV manufacturing. Pacca et al. (2007) considered that the life service of the module depends on the PV technology and they assumed 25–30 years for the crystalline modules.

From feedback of PV systems monitored at CEA Cadarache since 1978, it is recommended to use 30 years as the adequate value to represent life time of crystalline PV systems today.

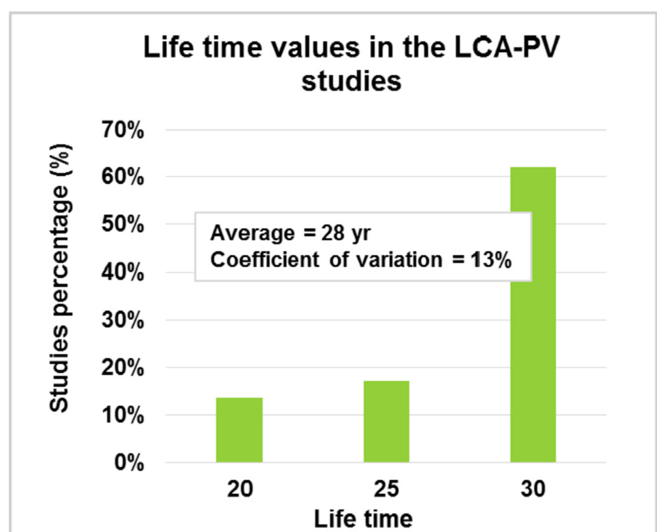

Fig. 10. Distribution of the 30 PV LCA studies defining different values of life time of the PV system.

Table 3
Different estimation of solar irradiation and initial PR values representative of the Europe and adapted for different PV system positions.

Different scenarios of PV plants	Solar irradiation value (kWh/m^2/yr)	Initial Performance Ratio (%)
European PV plants weighted by location, installation types and orientation	1425	81.8
European PV plants installed on roof with the adequate angle	1402	80.6
European PV plants installed on open grounds with an optimum angle	1496	85.0
European geographical average with optimal orientation	1463	82.2
European average weighted by installation sites in 10 countries	1511	77.0
French geographical average with optimal orientation	1520	80.0

5.5. Degradation rate

The DR is the mean annual degradation of the systems efficiency during its service time. As modules and systems components age, they gradually lose some performance. A linear decrease of 0.7% per year for the crystalline modules systems was estimated (IEA, 2016).

From the analysis of the 30 studies, few studies considered this parameter (Fig. 11); de Wild-Scholten (2013) estimated a DR of 0.67% per year. According to Frischknecht and Itten (2014), when a degradation of 0.7% per year is applied, the panel performance is reduced by 21% in the 30th year of operation. Based on (Jordan and Kurtz, 2013), Palanov (2014) assumed a DR factor of 0.5% per year for mono-Si modules. Literature rarely mention system the DR factor, which makes comparison between studies difficult and reduce therefore reliability of LCA results.

From published literature throughout the last decade years, Jordan et al. (2017) assembled 10 572 reported DR, measured on individual crystalline modules or entire systems, and resulted in a mean value of 0.91% per year and then they applied filters of database on many factors such as the quality of data and climate effect: the selection of only high quality studies of crystalline systems (384 degradation rates), showed 0.81% per year as a mean value. The DR in zones with moderate climate (European countries) was 0.57% per year.

Therefore, based on this feedback from real fields, 0.91% per year is recommended as an appropriate value of DR of crystalline PV systems.

Depending on the objectives of the study, the results resumed in Table 4 can help the LCA practitioners to choose the appropriate values.

In order to have a global view of the PV trends, the average of the electricity produced around the world is presented in this table. This value was extracted from (IEA, 2017) and represents the ratio of the average electricity production in many countries weighted by the PV cumulative installed capacity on 2016. Such value can be employed to assess the environmental profile of PV system representative of the world.

The different values of the electricity produced the first year in Europe depending on the position of PV plants are also presented in Table 4. For each of these scenarios, the electricity produced over the 30 years with different degradation rate; 0.57%, 0.81%, and 0.91% per year were calculated.

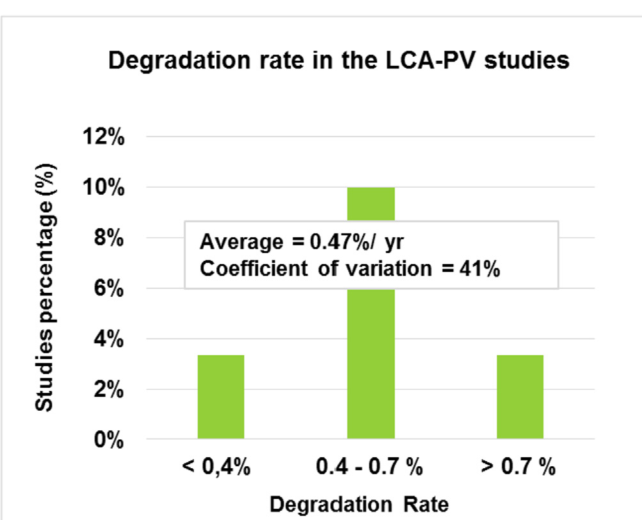

Fig. 11. Distribution of the 30 PV LCA studies defining different values of degradation rate.

5.6. Criticality analysis

In order to identify the impact of the parameters cited in section 5 (efficiency, irradiance, PR, life time, degradation), a sensitivity analysis was carried out. Based on the results of the carbon footprint of the mono-Si modules (Gazbour et al., 2016), each parameter was modified by ±10%. The results, plotted in Fig. 12, represent the "severity" of each parameter.

The carbon footprint results are almost linearly affected by the solar irradiance, the PR, the efficiency and the life time. Such conclusion is justified as the multiplication of all these parameters is close to the electricity produced by the PV system during its life time, as detailed in Eq.(2). However, the effect of a DR, below 1% per year, is much lower, as the impact on the electricity produced of the PV systems lifetime is small.

This sensitivity analysis showed that almost all of the PV parameters had a significant impact on the environmental footprint. Therefore, it is worthy to go further and propose a classification of these parameters by order of criticality (Fig. 12).

In the industrial world, methods are already used to analyze the reliability, as for example the FMECA that expressed the criticality as the adequacy of the severity and the probability.

The severity of Fig. 12 is re-expressed in Fig. 13 a. Based on the parameter values defined in the 30 LCA studies, the coefficient of variation was calculated for each parameter. It represents the ratio of the standard deviation to the mean and shows the extent of the variability of the data. This variability is summarized in Fig. 13 b and represents the "probability" to have a variation. The severity of a parameter multiplied by its probability gives an idea of its criticality. The normalization of this criticality is represented in Fig. 13 c.

Results showed that the solar irradiation is the main critical parameter that need to be considered in the PV LCA study. The choice of the life time and the efficiency is two time less critical but it is significant comparing to the choice of the PR and the DR which is four time less critical.

6. Data quality: variability in materials, components and processes

6.1. PV materials and manufacturing processes

To fully understand variability in PV LCA studies, another aspect which has to be analyzed is the collected data to model the panel. The PV system is a complex system that requires a huge amount of data to be modeled which can bring uncertainty if data are not well referenced.

Each part of the value chain (feedstock, ingot, wafer, cell, module and system) is a final product; each product has its specific characteristics and own manufacturing process. In the studies treated here, the characteristics of the PV components were not detailed. For example, concerning the wafer, some studies defined its characteristics with dated data, such as (Kim et al., 2014) and (Fthenakis and Kim, 2011) where they considered 240 μm and 270–300 μm as wafer thickness respectively, while this value was reported to be 180 μm since 2012 (ITRPV, 2017).

Manufacturing processes were also based, in the majority of the studies, on aged processes such as the Slurry Wire Sawing (SWS), which was applied for a long time and was increasingly replaced today by the Diamond Wire Sawing (DWS) (ITRPV, 2017). Such changes leaded to significant improvements in terms of wafering process costs and performances.

In order to ensure coherence between the LCA study and improvements in the PV system, it is recommended to include new manufacturing processes adopted by the PV industry today as well as the characteristics of the different components of the value

Table 4
Estimation of the electricity produced and the average over the life time depending on the degradation rates values for different scenario of location and type of installations.

Degradation rate (%)	Initial electricity production	Average electricity production over the life time (kWh/kWp/yr)		
		0.57	0.81	0.91
Global average weighted by cumulative PV installation capacity	1250	1152	1114	1098
European average weighted by location, installation types and orientation of PV plants	1165	1074	1038	1024
European average of open ground PV plants with optimal orientation	1272	1172	1133	1118
European average of PV plants installed on rooftop	1131	1042	1008	994

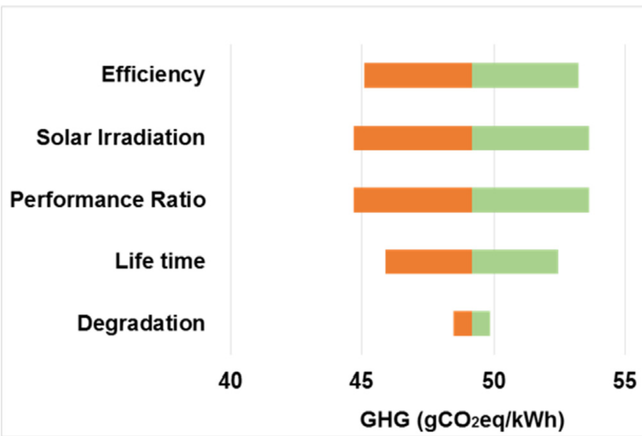

Fig. 12. Impact of the variation by ±10% of the PV parameters values on the carbon footprint results of mono-Si modules.

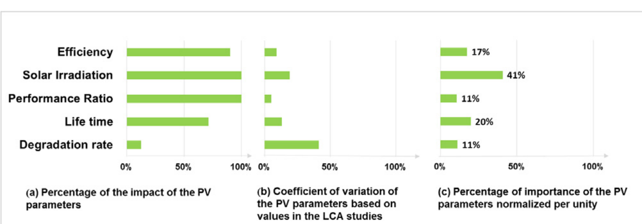

Fig. 13. Classification of the PV parameters by their importance based on the coefficient of variation and on the impact of each parameters on the environmental footprint to determine the main critical parameters to pay attention to in a PV LCA study.

chain. In Table 5, this update was assembled based on recent published data and on information reported in the datasheet of the top 10 of the PV producers in the world.

6.2. Electricity mix

The environmental footprint of the PV panels arise largely from the manufacturing stage. This bulk of contribution is explained by the substantial electrical energy required in this stage. The global electricity generation is dominated by fossil fuels. 61% of the production on 2014 was coal and gas generated, followed by hydro at 17%, nuclear at 11% and barely 7% of renewable energies such as wind, PV solar and geothermal (RN21, 2017). This share of the sources of electricity vary between countries, which leads as consequence to different environmental footprint results. For example, the fossil fuels emit significant amount of GHGs and acidification gases, which is about 100 times higher than hydroelectricity or nuclear electricity. That is why the electricity mix is an important aspect to consider when examining the environmental impacts of a PV system.

Several electricity mixes were defined in the LCA studies treated in this work. The choice of the electricity mix of Frischknecht et al. (2015) was based on the market share for the production of the different components of the module (ingots, wafers, cells, modules) on 2011. For example, it was assumed that modules installed in Europe are produced at 78% in China, 14% in Europe and 6% in Asia & Pacific. Desideri and Yan (2012) assessed one specific system installed in Italy and choose the Chinese electricity for the modules manufacturing. Palanov (2014) choose the European electricity mix to model different parts and processes of the PV system expected for the assembly stage. de Wild-Scholten (2013) assumed feedstock production with hydropower, ingots, wafers cells and module production with UCTE electricity which represents a mix of the

Table 5
Recommendations of PV modules components characteristics and manufacturing processes along the value chain of PV system (ITRPV, 2017), (JRC, 2017).

Manufacturing step	Parameter	Mono-Si modules	Multi-Si modules
Feedstock	Process	Modified Siemens Process	Modified Siemens Process
Ingot	Process	CZ process	Directional Solidification
Wafer	Process	Diamond Wire Sawing (DWS)	Slurry Wire Sawing (SW)
	Wafer size	0.0243 m^2	0.0244 m^2
	Wafer thickness	180 μm	180 μm
	Wafer loss	157 μm	157 μm
Cell	Process	AL-BSF process	AL-BSF process
	Cell size	0.0239 m^2	0.0244 m^2
	Cell efficiency	19.10%	18.70%
	Cell weight	14.53 g	14.53 g
Module	Process	Laminate process	Laminate process
	Module size	1.63 m^2	1.63 m^2
	Module weight	18.43 kg	18.35 kg
	Module power	280 Wp	265 Wp
	Cells number	60	60
	Module frame	Aluminum	Aluminum
	Module composition	Glass- EVA-Back sheet	Glass- EVA-Back sheet
	Glass thickness	3.2 mm	3.2 mm

European countries. It is important to emphasize that many authors did not mention the source of electricity used in their studies.

Considering the impact of this parameter on LCA results, Fthenakis et al. (2012) added three scenarios in their study using electricity from Europe, Korea, and Malaysia. Results showed variability depending on the country: carbon footprint results were lowest in Europe due to the lowest percent share of the fossil fuels in the electricity generation. However, CED results were important because of the nuclear energy in Europe, which represents 25% of the global production on 2012.

de Wild-Scholten (2013) carried out a sensitivity analysis where the modelling was done by the UTCE European mix and the Chinese one. The results showed a carbon footprint twice time higher (around 80 gCO2eq/kWh) than with a European mix (around 40 gCO2eq/kWh) which highlight the impact of this parameter.

In Fig. 14, the market share of the PV components on 2008 and 2017 are assembled based on data published on (IEA, 2009), (IEA, 2017) reports, respectively. An important change can be observed since 2008. The recent predominance of Eastern Asia in the manufacturing of PV materials and its associated coal share requires as a consequence to take caution when adapting assumptions from previous studies. Because of the spread change of the manufacturing locations and the impact of the electricity source on LCA results, updating the source with recent data is highly recommended.

Based on Fig. 14, a distribution of the electricity sources by the industry involved in the production of all PV materials (feedstock, ingots, blocks, wafers, cells, modules, and balance of system components) during the year 2017 is detailed. This distribution is recommended to be adopted to define the electricity mix in a PV LCA study. For example, the electricity mix suggested to be employed to model the feedstock would be 50% of Chinese mix, 4% of Japanese mix, 15% of south Korea mix, 6% of Malaysia mix, 15% of German mix, 8% of United States mix and 2% of the Norwegian mix.

7. Summary of the analysis

In order to provide a clear vision of the goal of the presented work in a way intended to be useful for policymakers and analysts in future studies, the main results, which have to be deducted, are summarized in Table 6.

Table 6 comprises average values of PV parameters from 30 LCA studies treated in this work, and the recommendations proposed throughout this paper, to help with choice of the appropriate assumption. Therefore, the rationale for choosing each of the proposed recommendations, which are detailed in section 5, is summarized in this table. It is necessary to mention that some of the parameters such as the module efficiency and the electricity mix are always evolving. It is therefore worthy that these parameters would be continuously update with PV market trends and improvements, following the methods suggested in this work.

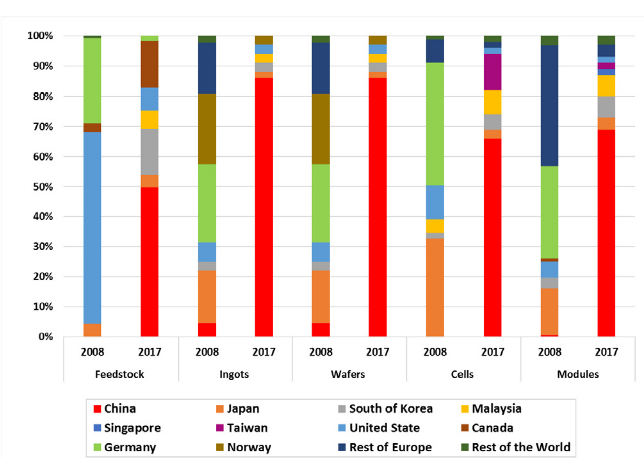

Fig. 14. Comparison of the market share of countries on feedstock, ingots, wafer production, crystalline silicon cells and modules manufacturing on 2008 and 2016. Data were assembled from the IEA (2009) and IEA (2017) PV trends reports.

8. Conclusion

PV technology is one of the renewable technologies, which has a potential to generate clean and decarbonized electricity systems. It is therefore worthy to study the different assumptions that affect the environmental profile of a PV system. By the analysis of 30 LCA studies of crystalline PV systems, this article demonstrated that the variability in the definition of assumptions was relatively high.

27 of the 30 studies evaluated the carbon footprint and the energy demand, while only 43% studied other important impacts categories. To assess PV technologies, the main impacts to pay attention to were the resource depletion, the land use, the water consumption and the human toxicity.

The analysis of the variability PV parameters in the 30 LCA studies showed that the solar irradiation is the main critical parameter that need to be considered in the PV LCA study. The majority of the studies assumed a solar irradiation for South of Europe but not for the rest of Europe. Therefore, it has been recommended 1425 kWh/m^2/yr for solar irradiation which correspond to the European average of the PV weighted by real location, real orientation, and installation type based on estimation from PVGIS data, BDPV data and Solar Power Europe data. Another important parameter was the module efficiency, an average of around 14% was assumed from published studies on 2013–2016 while the efficiency of crystalline modules attained around 16% at that period. Therefore, it has been suggested to update this parameter with the status of PV modules. For the year 2017, the average of the efficiencies of the top 10 modules producers are 17.2% for mono-crystalline modules and 16.3% for the multi-crystalline. As well, analysis showed that the choice of electricity mix has been a significant impact on the LCA results; with a Chinese mix the carbon footprint is twice time higher that with European mix. In addition, the geographical shift in PV materials production to Eastern Asia requires to take caution when adopting assumptions from previous PV LCA studies.

The choice of the life time was less critical but significant comparing to the choice of the PR and the degradation rate. It has been proposed 30 years for the life time, largely assumed in the community, based on the observation of the operation of old PV plant and on the degradation rate throughout the last decades. 0.91% per year has been proposed as a mean degradation rate, based on the 10 572 reported degradation rates, measured on individual crystalline modules or entire systems throughout the last decades, and 81.77% of PR was calculated for European average weighted by location and installation type.

Lastly in this work, an identification of the sources of variability was done over the PV parameters, limited to the carbon footprint. It would be interesting to analyze LCA studies that consider all the impact categories including energy and water consumption, toxicity and chemical substances. On the other hand, as the volume of solar installations in the world is growing, PV industry is oriented today to pay more attention on the recycling stage by creating recycling projects and developing new processes. Therefore, analyzing the variability of assumptions in studies which take into account the entire life cycle of the PV system may change the assumptions choice. Increasing the number of analyzed LCA studies

Table 6
Synthetic table of average values extracted from 30 PV LCA studies and proposed recommendations to help with the choice to define the goal and scope in a PV LCA study.

	unit	Average in Literature in 30 PV LCA studies	Recommendations proposed in this paper	Justifications of the recommendations
Period		2005–2016	2017	Great technical and industrial evolutions
PV parameters				
Solar Irradiation	$kWh/m^2/yr$	1557	1425	European average based on PVGIS data, real location, real type, and rooftop losses.
Performance Ratio	%	79.0	81.8	Based on PVGIS data and published papers
Degradation rate	%	0.47	0.91	Based on the feedback of 10 572 measurements on crystalline systems (NREL study)
Life time	years	28	30	Feedback of installed systems
Efficiency Mono-Si	%	14.2	17.2	Calculations based on the datasheets of the top 10 producers in the world
Efficiency Multi-Si	%	13.4	16.3	
Electricity Mix		Mainly European	GLO (65% China)	Based on PV market on 2017

with fixed criteria of selection such as quality, transparency, date of publication may change the interpretation of published LCA results and the analysis of variability.

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