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RESEARCH ARTICLE

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An open-source parameterized life cycle model to assess the environmental performance of silicon-based photovoltaic systems

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Abstract

Despite being renewable, photovoltaic energy is not burden-free, since energy and materials are necessary to manufacture, maintain, dismantle, and recycle photovoltaic systems. Over its life cycle, the assessed carbon footprint of silicon-based photovoltaic energy published in the literature often ranges from 40 to 110 gCO_2eq/kWh. However, most of these estimations rely on life cycle inventory (LCI) data that represent the early-stage performance of the photovoltaic industry. Indeed, collecting LCI data is time-consuming and practitioners often reuse existing outdated data, which becomes problematic as the photovoltaic industry has been rapidly and significantly evolving. This analysis relies on the parametrization of existing LCI data to better account for the progress already accomplished by the photovoltaic industry. A Life Cycle Assessment (LCA) model, called PARASOL_LCA, is thus developed. The results of the analysis highlight that the use of outdated LCI data leads to an overestimation of environmental impacts of photovoltaic energy by a factor of 2 or even more for the best current available technologies. The analysis also shows that PARASOL_LCA, with its numerous parameters, can also serve to assess the environmental performance of prospective photovoltaic technologies and to identify impact reduction levers through sensitivity analysis.

KEYWORDS

crystalline silicon photovoltaics, environmental footprint, life cycle assessment, life cycle inventory, parameterized model, photovoltaic energy, updated environmental performance

Highlights

- PARASOL_LCA is a model for tailor-made LCA of silicon-based PV systems.

Abbreviations: EPD, Environmental Product Declaration; IEA, International Energy Agency; ILCD, International Reference Life Cycle Data System; IPCC, Intergovernmental Panel on Climate Change; IRENA, International Renewable Energy Agency; LCA, Life Cycle Assessment; LCI, Life Cycle Inventories; PV, Photovoltaic.

- A generic method to develop parameterized LCA models is presented.
- A strong reduction trend of the environmental impacts of PV electricity is highlighted.
- A considerable update for the carbon footprint of PV electricity is observed: from 70 to 15–30 gCO2eq/kWh.
- A multicriteria sensitivity analysis is performed to identify levers to improve PV environmental performance.

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1 | INTRODUCTION

The solar photovoltaic (PV) industry has considerably improved over the last 20 years as evidenced by the PV price drop. This spectacular cost decrease, which is due to economies of scale and technological improvements,[1] has led to the installation of almost 140 GW_p in 2020.[2] This is 18% more capacity in comparison with 2019. Initially, first PV systems were deployed to provide electricity in remote areas: to power satellites onboard electronic, relay masts or buildings located far from national electricity grid such as in mountain huts.[3] At that time, such systems were not specifically aiming at reducing the environmental impacts of electricity production but rather at providing electricity in off-grid and specific environments. Nowadays, the situation is different as grid-connected PV systems are promoted as a technological solution, among others, to reduce fossil fuel dependency and mitigate greenhouse gas emissions and more generally environmental impacts related to their use. However, this increase in PV capacity is also justified, in an increasing number of regions, by economic considerations independently of the environmental concerns.[1] It is also worth to highlight that PV energy is expected to play an increasing role in the world energy mixes as the share of PV in the electricity production is rising, as well as the share of electricity in the world's final energy consumption.[4]

Despite relying on solar radiation, a renewable energy source, PV systems are not environmentally burden free as energy and materials are necessary to manufacture, maintain, and dismantle those systems.[5] For technologies that do not require fuel, such as PV systems, environmental impacts mainly occur during their construction rather than in the electricity generation phase. Quantifying these environmental impacts over the life cycle of PV systems becomes necessary to ensure that their installation within the energy transition context presents environmental benefits compared with their fossil-fuel based alternatives and are compatible with energy transition goals.[5] These impacts can be assessed using Life Cycle Assessment (LCA).

Life Cycle Assessment is a systemic and multicriteria method to assess environmental impacts over the whole life cycle of a product or a system.[2] Many LCA of PV systems have been published in the literature, including a meta-analysis published in the IPCC special report based on a review of 400 studies of PV systems.[6] Most of these studies concern crystalline silicon-based PV systems that represent more than 90% of the PV market.[7] The assessed carbon footprint, representing the life cycle impact on climate change, of photovoltaic energy varies between 5 and 217 gCO_2eq/kWh.[6] Results of the meta-analysis indicate carbon footprint quartile ranging from 45 to 110 gCO_2eq/kWh for single-crystal silicon and 40 to 85 gCO_2eq/kWh for multicrystalline silicon. It is important to note that the meta-analysis was published in 2012, meaning that the underlying studies were published even before. Data harmonization was performed by the NREL following the IEA PVPS task 12 recommendations.[8] The analysis highlighted that once the solar irradiation level, the operating lifetime, the module efficiency, and performance ratio are harmonized, the interquartile dispersion is reduced by 65%.[9] Other factors such as the electricity mix used for PV panel manufacturing, the type of installation, and, to a lesser extent, its size can influence the carbon footprint of photovoltaic energy production. System boundaries, data quality, and methodological choices can also explain the remaining variability.[10,11] With harmonized values corresponding to an average Southern Europe solar irradiation level and PV system performance in 2012, the median value obtained is around 50 gCO2eq/kWh.[9] Higher carbon footprints are expected for locations with a lower solar irradiation. Moreover, other environmental impact categories are relatively less addressed by the scientific literature compared with the clear focus of the latter on the climate change impact category.

The PV industry has considerably evolved and improved over the last decade, as evidenced by the cost reduction by a factor 10 within the last 10 years.[1] The cost decrease is multifactorial, but among the factors explaining it, we can cite the increase of the panel efficiency, meaning that for a given surface of PV systems, more energy is produced. The environmental impacts per kilowatt hour are therefore lower since more energy is produced with the same amount of material. Besides, a study published in 2016 by Gorig et. al showed that the energy learning curve follows a trend similar to the cost learning curve.[12] The two main factors are the panel efficiency increase and the improvement of the silicon production process. A recently published study confirmed the environmental impact reduction trends of crystalline silicon-based photovoltaic systems.[13] The study concludes that considering past improvement results in an increase in the energy return on investment ranging between 20 and 50, depending on solar irradiation. This study also addressed another impact category with the acidification potential, but, to the knowledge of the authors, there is no LCA addressing the impact evolution on a wider set of impact categories.[14] LCA addressing multiple impact categories is, however, essential to allow the identification of potential burden shifting from an impact category to another and enable a comprehensive life cycle impact analysis.

Previously published studies highlighted the need to consider updated data in the LCA of photovoltaic systems to avoid a misrepresentation of its environmental impacts.[10,15] Indeed, past eco-design considerations have already improved the environmental performance of PV energy.[16,17] In addition to past or present environmental footprints, prospective environmental footprints should be assessed and used to know if the expected evolution of photovoltaic industry will contribute to enhancing the environmental performance of PV. This would confirm or infirm the potential of this technological solution to mitigate greenhouse gas emission and justify to be promoted as such.[14] However, most PV-related life cycle inventories (LCI) present in the widely used ecoinvent database[18] are representative of the PV performance in 2005, which, as previously explained, may misrepresent the technological improvement in the sector. An obstacle to the use of up-to-date data is the time-consuming aspect of LCI data collection. In addition, access to such updated data is also often limited by confidentiality consideration: Industrials are often reluctant to share the updated data necessary to build LCI.

To overcome those challenges, the study proposes to rely on the parametrization of existing LCI data resulting in tailored-made inventories of PV systems that can easily be adapted to changes in the chosen parameters. A parametric approach was proposed by Miller et al. in 2019 to assess the life cycle greenhouse gas emissions from photovoltaic power.[19] However, except the electricity mix used for manufacturing, all the parameters considered are related to the assessment of the electricity production of the PV system. The consequence is that, despite being published relatively recently (2019), the study overestimated greenhouse gas emissions with typical carbon footprint of 60–70 gCO_2eq/kWh. To overcome this issue, which is the objective of the present article, the proposed approach is to parameterize the LCI based on a comprehensive set of input parameters, rather than only focusing on parameters related to the electricity production. Indeed, the parametric approach was first applied to PV panels by Bracquene et al. in 2018.[20] The present work proposes to go further by (i) formalizing the method to identify parameters, (ii) introducing in the model a comprehensive selection of parameters to account for identified sources of improvement of the PV sector not included in Bracquene et al.,[18] (iii) providing a method and the associated tool to analyze the influence of parameters on a multicriteria basis, and (iv) providing the code as an open source LCA model. As a result, the user is provided with an open-source model that allows the environmental performance to be automatically assessed for many configurations, including prospective configurations, without the need to build a new LCI through a conventional time-consuming approach. Therefore, an LCA model called PARASOL_LCA is developed in this study to assess crystalline silicon-based PV systems. This parameterized model enables to account for improvements already accomplished by the PV industry and to explore the prospective environmental performance of PV systems with a multicriteria perspective by varying the large set of parameters defined, which can be of interest to PV stakeholders in an eco-design perspective.

This paper contains four sections. Section 1 introduces and sets the context for the study. Section 2 describes the parameterized model development in this analysis. This method is general and can be applied to any energy technology or other products or services. In Section 3, the environmental performance of past, present, and near-future crystalline silicon PV systems is assessed and discussed. Section 4 concludes and summarizes the main implications of the findings of this analysis.

2 | MATERIAL AND METHODS

LCA is a method for evaluating the potential environmental impacts of products or systems from the extraction of raw materials to the treatment of waste at the end of life. It is also a multicriteria method that allows the evaluation of the impacts on climate change, depletion of fossil resources, mineral resources, and impacts on human health and ecosystems. Thus, LCA allows, by its holistic nature, the identification of potential burden shifting. It is why LCA is the most commonly used method for environmental assessment.[21] Its use also allows the different actors of an industrial sector to better know and understand the impacts they cause, which is an essential step before taking rational and effective measure to mitigate them.[22] It also constitutes a valuable decision-making tool for governmental authorities in the context of environmental impact limiting policies.[22]

LCA is standardized by ISO 14040 and ISO 14044 which describe the good practices to adopt when conducting an LCA consistent with its initial objective. It follows a four-step approach:

1. the goal and scope definition where the underlying problematic, the system boundaries, and the functional unit are defined ultimately aiming for comparable studies;
2. the inventory analysis where the flow of resources, materials, and pollutants are modeled to represent the studied system;
3. the impact assessment where the impact categories are selected to translate the inventories into environmental impacts; and
4. the interpretation where the results are analyzed to provide recommendations.

Parameterized LCA models are designed to account for the technological, spatial, and temporal variabilities of systems. In this study, the method is applied to PV systems but it is not specific to energy system and could be applied to other types of systems. These parameterized models rely on a set of input parameters ranging from very few up to several dozens to describe the inventory flows of the studied system. Building a parameterized LCA model for a given energy sector aligns with the same four steps of the general LCA framework. First, in the goal and scope definition, the foreseen use of the model,

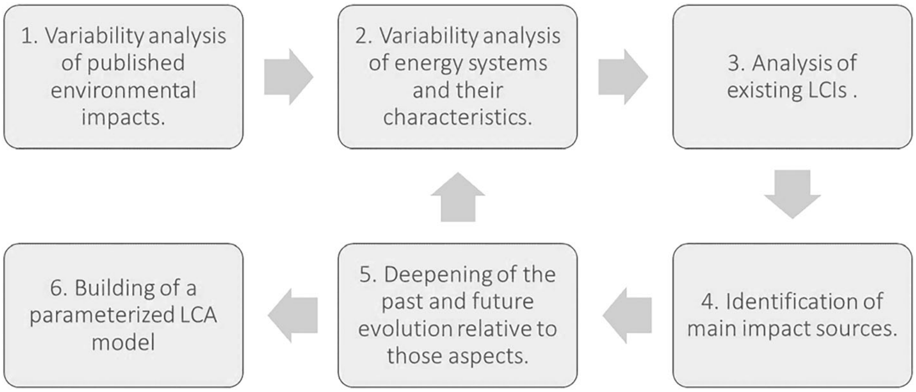

FIGURE 1 Iterative six-steps method to develop parameterized LCA models.

its functional unit, and system boundaries are defined. Second, in the inventory analysis, a parameterized LCI is built from the following iterative approach, depicted in Figure 1:

1. analysis of the variability of the environmental impact results published in the scientific literature;
2. analysis of the characteristics of the studied energy systems, which will then constitute the set of input parameters, and their variability;
3. analysis of existing LCIs and the systems they represent. Sources of inventories can be
   a. the ecoinvent database,
   b. inventories published in the scientific literature, and
   c. environmental declarations of various products (EPD);
4. identification of the main contributors to the environmental impacts, both in terms of life cycle stages and individual components, of the studied energy systems by exploring the tree structure of existing LCIs;
5. in-depth analysis of the past and future evolutions of the processes identified as nonnegligible sources of impacts; and
6. building of a parameterized LCI model from the comparison and fusion of existing LCIs including parameters for the processes with most environmental impacts or expected to evolve a lot with time.

Third, the potential environmental impacts of the parameterized model are quantified, and finally, in the interpretation phase, the results are analyzed for consistency and compared with available literature.

2.1 | PARASOL_LCA: A parameterized LCA model for crystalline silicon-based PV systems

PARASOL_LCA is developed to assess the environmental performance of crystalline silicon-based PV systems including both monocrystalline silicon and the multicrystalline silicon systems, whether roof or ground mounted. The final functional unit considered is 1 kWh of electricity generated. In some particular cases, an intermediate functional unit of 1 kWp of nominal capacity of the PV system can be used. PARASOL_LCA includes the following life cycle stages: raw material extraction, manufacturing, assembly, use phase, and end of life. In addition, the system boundary of this study includes the transport of equipment and workers considered for the installation of the power plant, its maintenance, and decommissioning. A recycling end-of-life scenario is included based on the available data, even though these are very scarce, thus limiting the accuracy of the assessment for this particular life cycle stage. The PV system consists of the PV modules but also the mounting system, the inverter, and the components of the electrical installation such as cables or circuit breaker, which were accounted for in the study. No additional storage system is considered.

The ecoinvent cut-off version of the database is used. This version is based on the "polluter pays" principle. The impacts of recycling are attributed to the first user of the material not the user of the recycled product. Other approaches to allocate impact recycling exist that deduce impacts of the producing system when materials are recycled at their end of life, but the cut-off approach was preferred as it supports the so-called strong sustainability principle.[23] The model was initially developed with ecoinvent 3.4 and has been updated to the most recent version to date: ecoinvent 3.7.[18]

As LCI data of PV-related datasets were collected typically more than 15 years ago, those data are analyzed to identify values that could have evolved over that period. The identification of those parameters is achieved following the method presented in Section 2.2 and based on secondary data from an in-depth review of the reports elaborated by the experts of task 12 of IEA PVPS along with other studies and industrial data.[20,24–27] Aside from Task 12 reports, Bracquene et al.[20] represent the main advancements and challenge for the c-Si technology based on the expertise of 55 leading international panels and systems' producers and suppliers.

Environmental impact assessment is conducted using the open-source LCA framework *Brightway2*. Life cycle inventories are parameterized using *lca_algebraic*,[28] a Python library specifically developed to build parameterized LCA models and perform sensitivity analysis in a very efficient manner by relying on symbolic calculus. Environmental impacts are calculated for the ILCD 2.02018 midpoint impact categories recommended by the European Commission in the International Reference Life Cycle Data System (ILCD).[17,29] The set of impact categories enables to address the environmental impacts related to climate change, ecosystems, human health, and resource depletion.

The last step of the LCA, the interpretation, can be found directly in Section 3. This step includes the assessment of the evolution of the environmental performance of PV systems with technological improvements, as well as the realization of sensitivity analysis. Indeed, sensitivity analysis can be used to identify the influence of parameters on the studied environmental impact categories and thus help to identify impact reduction levers. Such results can be used to inform decision-making regarding the potential and prioritization of research and development efforts to efficiently reduce the environmental footprint of PV electricity. Sensitivity analysis is particularly relevant in our case due to the important number of parameters. Performing multicriteria sensitivity analysis is an important step to interpret the weight of the various parameters considered, for the various impact categories.

2.2 | PARASOL_LCA: Description of the model and its parameters

The following paragraphs detail the modelling of the LCI of the PV system from the mounting systems, inverter, PV modules, and so forth, to the transport of equipment. The ecoinvent database, as the most exhaustive and widely used LCA database,[18] is the starting point for the LCI.

The ecoinvent database contains two datasets for photovoltaic mounting systems. One of them describes open ground installations (photovoltaic mounting system production, for 570-kWp open ground module), and the other one corresponds to slanted-roof installations (photovoltaic mounting system production, for slanted-roof installation). These systems have a total weight of 11.5 and 4.5 kg/m^2, respectively, with 4 and 2.8 kg/m^2 being aluminum. However, current systems can be considerably lighter and contain much less aluminum, which has a nonnegligible environmental impact when sourced from primary production. For example, a system for steel roofing can weigh only 3 kg/m^2[30] and is composed of 80% aluminum (corresponding to 2.4 kg/m^2). Regarding the open ground mounting system, the global weight is coherent with the value orally communicated by mounting system manufacturers, but the aluminum content can be much lower than the 4 kg/m^2 indicated in the inventory. The Helios RC3 system,[31] which only accounts for the interface between panels and the structure, weights between 3.5 and 5.5 kg/m^2 and is composed of only 15% aluminum corresponding to less than 1 kg/m^2. No precise data were found for the total weight of the structures that are mainly made of galvanized steel. Following these observations, the aluminum content is defined as a parameter ('*Mounting_system_weight_alu*'). Further, a parameter is added to allow considering a wood-based mounting system ('*Mounting_system_weight_wood*'). The amount of steel is calculated from the subtraction of the total mounting system weight ('*Mounting_system_weight_total*') and the amount of aluminum and wood.

As the ground-mounted dataset was more exhaustive than the rooftop one, it was also used to model the rooftop system after removing the unnecessary flows related to the use of cement. The PARASOL_LCA model therefore relies on this inventory parameterized with the weight of steel, aluminum, and potentially wood. In addition, the land footprint was adapted since the one considered in the ecoinvent inventory was overestimated. The ground coverage ratio considered was 21%, while current practices are closer to 45%. In fact, when PV panels were more expensive, they were more spread out to maximize the production per panel. Since nowadays, the price of PV panels has dropped, it is often more economical to orient panels not to maximize their power output per panel but rather the power output per land square meter.

In ecoinvent, two datasets describe the photovoltaic electrical installation for (1) a small 3-kWp power plant (photovoltaics, electric installation for 3kWp module, at building) and (2) an open ground 570-kWp power plant (photovoltaics, electric installation for 570-kWp module, open ground). Once divided by their total weight, the two datasets reflect very similar material compositions. Consequently, one of the two datasets was copied and expressed per kilogram of material.

While the material composition was kept as expressed in ecoinvent, the mass-to-power ratios were modified depending on the nominal power of the installation. In fact, the weight of the electrical installation calculated for the 3 and 570 kWp lead to 10.7 and 2.7 kg/kWp, respectively. Those values are not in line with current practices. Current components' weight communicated by a small PV cooperative[32] and the associated PV engineering office[33] are as follows:

- around 13 m/kWc for PV array cables (DC) corresponding to less than 1 kg/kWc with a weight of 75 kg/km;
- around 1 kg/kWc for the grid injection cable (AC), considering a hypothesis of 50 m between the inverter and the grid injection point; and
- 10 kg for a 9 kWc, 20 kg for a 36 kWc, and 30 kg for a 100 kWc for the general low voltage panel.

Those data lead to mass-to-power ratios ranging between 2.2 and 5 kg/kWp depending on the installation size. As a result, the PARASOL_LCA model uses the material composition per kilogram ('*Electrical_installation_specific_weight*') of the ecoinvent datasets, while the total mass of the equipment is expressed using a parameter for the mass-to-power ratio. Three datasets for PV inverters, namely, of 0.5, 2.5, and 500 kW, are listed in ecoinvent. These datasets, respectively, correspond to weights of 3 kg, 18.5 kg, and 3 t. Divided per nominal capacity, it, respectively, corresponds to 6, 7.4, and 6 kg/kW.

Figure 2 compares the normalized weights, calculated from the ecoinvent inventories, to the ones extracted from the technical data sheet of the SMA product portfolio. Current inverters are considerably lighter, leading to a reduction of the amount of material per unit of power. By default, a value of 2 kg/kW is considered in

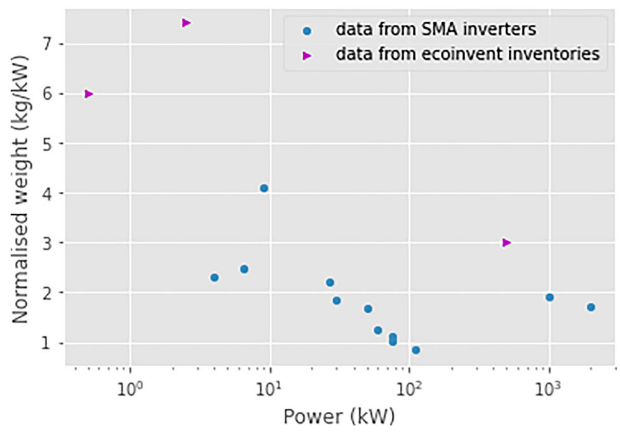

FIGURE 2 Comparison of the inverter weight normalized per power capacity. [Colour figure can be viewed at wileyonlinelibrary.com]

PARASOL_LCA. This value is still a bit conservative as modern products are even lighter inverters such as the new sunny tripower core 2 weighing as low as 0.85 kg/kW.

The material composition of ecoinvent inventories for the inverters varies significantly between the 2.5- and 500-kW inverter. The inverter dataset modeled in PARASOL_LCA therefore includes a parameter describing the weight per power capacity ('*Inverter_weight_per_kW*') discussed above multiplied by the shares of the different materials linearly interpolated between the 2.5- and 500-kW ecoinvent inventories.

Crystalline silicon has photovoltaic properties that are exploited in PV systems. Silicon, which represents 27% of earth crust, is abundant but a high amount of energy is required to produce crystalline silicon that is pure enough to be used for PV applications. The ecoinvent database indicates 110 kWh/kg of electricity and 185 MJ/kg of heat to transform metallurgical grade silicon into solar grade silicon. On top of that, 85 kWh/kg of electricity are necessary to turn the solar grade silicon into a crystalline making this production especially energy—and electrically intensive. However, with the development of the PV industry, the energy efficiency of those processes has dramatically improved leading to the spectacular cost decrease of solar grade silicon. Modern fluidized process reactors limit energy consumption to 30–40 kWh/kg,[34] and some companies, such as REC Solar, announced a certified value as low as 11 kWh/kg.[35]

PARASOL_LCA accounts for this development by including parameters describing the electricity ('*Silicon_production_electricity_intensity*') and heat consumption ('*Silicon_production_heat_intensity*') of the silicon cell. Processes related to the cutting of silicon ingots have also improved with, among others, the recycling of some products involved in the cutting process and the development of diamond wiring processes. With the traditional cutting process, a cutting liquid, also called the slurry, is used. It consists of a mixture of poly (ethylene glycol) (PEG) and silicon carbide (SiC) particles solution that circulate while the cutting is happening.[36] The inventories, developed by Stolz et al.,[24] have served as a basis to create the LCI model for the recycling of silicon carbide. The silicon carbide recycling is related to the advancements of the traditional cutting process (loose abrasive slurry). The progress of their recycling has resulted in the use of their recycled material recovered. A parameter ('SiC_*recycled_share*') was introduced in PARASOL_LCA to specify the amount of recycled silicon carbide used.

Nevertheless, the diamond wiring cutting method has almost replaced the slurry-based technology to cut the silicon panels due to its promising results at different levels especially the economic savings.[37] Despite its benefits, the main limitation is the lack of industrial and scientific data to be able to integrate its full inventory. In this case, an estimation based on Bianco et al.[38] was used, first, to highlight the importance to include this process and, second, to determine the influence on the environmental impacts of eliminating the silicon carbide (SiC) and the triethylene glycol (TEG), replacing the TEG by water used for slicing, and adding the diamond wire required. It should be noted that Bianco et al.[38] addressed the supply chain of stone technologies, for which the diamond wiring cutting process plays an important role. A Boolean parameter ('*Diamond_wiring_cutting*') is used to consider either a diamond wire cutting process or a conventional hard steel wire process.

To account for these improvements related to cutting/kerf losses and thinner wafers, both the thickness of the wafer ('*Wafer_thickness*') and the kerf loss ('*Kerf_loss*') are parameterized. The kerf loss corresponds to the share of material that is lost in the form of powder during the cutting process.

As for silicon production, the necessary amount of energy is likely lower today than at the time of data collection of the inventory. A parameter called manufacturing efficiency gains has been introduced in PARASOL_LCA to consider the effect of a potential improvement. This parameter also serves to adjust the amount of energy for cell production and panel production. However, no sourced data have been found to justify a reduction. As a consequence, this parameter was set by default to the original value, but it remains useful to explore the effect of such an improvement.

A metallization paste is used to electrically connect PV cells and collect electron–hole couple created by the photovoltaic effect. This paste often contains silver due to its excellent conductivity. The high conductivity minimizes the size of the electrical contact and maximizes the production per surface area. In absence of a reduction trend in the use of silver in metallization paste, silver has been identified as a potential factor limiting a massive PV deployment. Silver production dedicated to PV represented in 2020 around 10% of the global silver supply.[39] Silver alone also accounts for 10% of a PV module cost. For those reasons, alternative solutions, especially based on copper, are developed[40] and already commercialized.[41] To model this evolution, a parameter ('*Silver_content*') is introduced in PARASOL_LCA to adapt the amount of silver used in the paste, by substituting it with copper. The amount of each metal is calculated based on this parameter and considering the conductivity ratio between both metals.

The design of PV panels has also improved over time. For instance, the weight of the aluminum frame is lower today than some years ago. The ecoinvent inventory model assumes 2.6 kg aluminum/

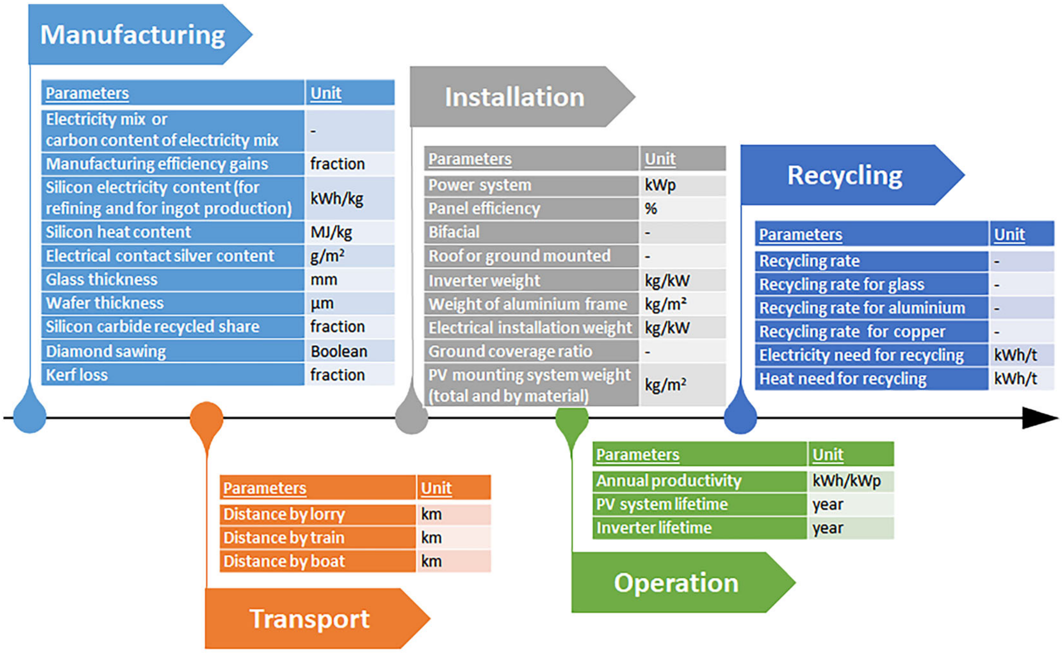

FIGURE 3 Graphical representation of PARASOL_LCA parameters. [Colour figure can be viewed at wileyonlinelibrary.com]

m^2 of module, whereas more recent studies indicate 1.5 kg/m^2.[42] Some PV panels are even frameless. Besides, there is an increasing trend to use thinner glass on PV panels.[43] A parameter corresponding to the weight per surface area of the aluminum frame ('*Aluminium_frame_surfacic_weight*') and another one describing the glass thickness ('*Glass_thickness*') were therefore introduced in PARASOL_LCA.

Another evolution is the existence of bifacial modules. In such modules, the tedlar backsheet is replaced by glass, which has the benefit to be transparent. Such modules, for which the market share is rapidly increasing, produce more energy for a given PV panel surface taking advantage of both panel's sides. A Boolean parameter ('*Bifaciale_modules*') was implemented in PARASOL_LCA to consider a backsheet PV panel or a glass–glass PV panel.

PV panel's efficiency has also remarkably evolved over time. The ecoinvent datasets consider around 12% efficiency, whereas recent commercialized PV panels can reach 20% efficiency, with a maximum of 22.8% for already commercialized products.[44] PARASOL_LCA therefore includes the PV panel's efficiency ('*PV_module_efficiency*') as additional parameter.

In PARASOL_LCA, the recycling rates per material are parameterized as well as the amount of electricity ('*Electricity_consumption_for_recycling*') and heat ('Heat_*consumption_for_recycling*') necessary to recycle the PV panels based on the IEA task 12.[45]

Parameters describing the transport distance by boat ('*Transport_distance_boat*'), train ('*Transport_distance_train*'), and lorries ('*Transport_distance_lorry*') are included in PARASOL_LCA. Additional transport of 300 km by car and van is considered for transport of workers for the installation, maintenance, and dismantlement of the power plant.[33]

Finally, the annual electricity production of the PV system, which strongly depends on the location, and to a lower extent, on the orientation of the panel, was parameterized. The lifetime of the PV system was also parameterized, as well as that of the inverter, which might need to be replaced over the PV system's lifetime. The parameters are summarized in Figure 3.

3 | RESULTS AND DISCUSSION

The parameterized LCA model enables the assessment of the life cycle environmental impacts of a crystalline silicon-based PV system defined according to 35 input parameters (Figure 3). The model was validated by applying the same assumptions as those of the original ecoinvent dataset and comparing both results.

3.1 | Evolution of the PV environmental performance

Figure 4 shows the evolution of the climate change potential of photovoltaic energy accounting stepwise for the different technological improvements. Based on ecoinvent data, the climate change impact is around 70 gCO_2eq/kWh for an installation producing 1200 kWh/kWp annually for over 30 years. The assumption of 1200 kWh/kWp corresponds to a typical annual production of an installation in France.[33] The successive and cumulative improvements leading the considerable decrease of the PV carbon footprint are analyzed in details.

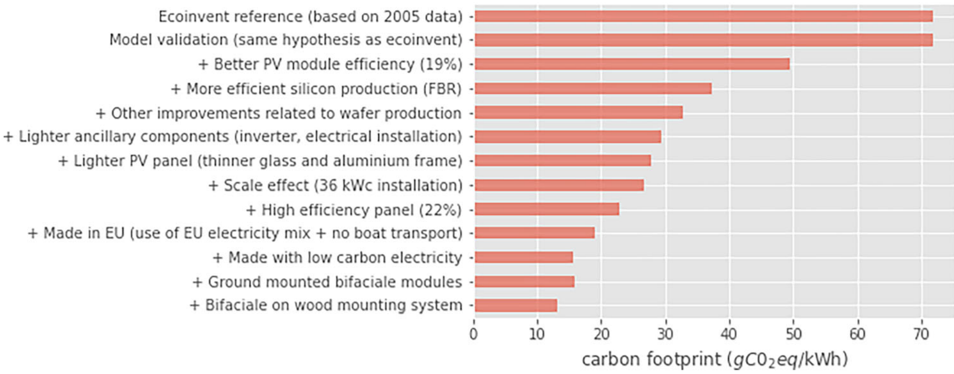

FIGURE 4 Estimation of photovoltaic carbon footprint with technological improvements (considering an annual productivity of 1200 kWh/kWp and a 30-year lifetime). [Colour figure can be viewed at wileyonlinelibrary.com]

When considering the same efficiency for the PV module and silicon production and the same mass for the various components of a PV system, PARASOL_LCA estimates a similar climate change impact. When considering the large increase of PV panels' efficiency ('*PV_module_efficiency*'), the assessed climate change impact drops to around 50 gCO_2eq/kWh. It is worth highlighting that a higher efficiency leads to, per capacity installed or energy generated, material savings not only for the panel but also for the mounting system.

The assessed climate change impact drops to 35 gCO_2eq/kWh when considering a more efficient Fluidized Bed Reactor for silicon production ('*Silicon_production_electricity_intensity*'). Additional improvements such as the use of recycled silicon carbide and diamond wiring lead to further reductions of the assessed climate change impact. The reduction of the weight of ancillary equipment such as the inverter ('*Inverter_weight_per_kW*') or the electrical installation weight ('*Electrical_installation_specific_weight*') leads to a climate change impact of 30 gCO_2eq/kWh.

The fact that less aluminum is used for the frame of the PV panels ('*Aluminium_frame_surfacic_weight*') or that the glass thickness is reduced ('*Glass_thickness*') leads to an even lower value. We can also observe some benefits of scale considering a bigger PV installation compared with the previous installation size ('*Power_plant_capacity*'), which corresponded to a small residential installation of 3 kWp. Such a carbon footprint is in line with the recent assessment from the work of Fthenakis et al.[13] that highlight a reduction of the carbon footprint of PV energy as well as its energy payback time. Fthenakis et al.'s work[13] is also consistent with the result obtained by the Fraunhofer Institute showing in February 2022 confirming a strong reduction of the embodied energy of PV energy.[7]

The use of a highly efficient panel that currently corresponds to the top-of-the-range of PV modules, but is expected to become increasingly common in coming years, leads to a climate change impact below 25 gCO_2eq/kWh. Even lower climate change impacts can be reached for locations with higher irradiance than the one considered here. It is possible to reduce the carbon footprint further by producing the PV panel in Europe. The reduction is mainly due to the use of electricity with a lower climate change impact than the world's average one. The absence of impacts from the boat transport is a plus, but the benefit is low compared with using low-carbon energy. The consequence is that a PV system with lower climate change impact is not necessarily a locally produced one but rather the one produced with an electricity mix with low climate change impact, even if the panels have to travel over thousands of kilometers by boat. An analogous reasoning applies to other environmental impact categories.

Finally, the climate change impact of bifacial PV modules is also assessed. An increase in the annual production of 15% was considered for the bifacial module.[46] The production increase can be higher or lower depending on the local albedo. Despite a higher electricity production, the impact remains similar as the previous configuration. The ground mounting system is heavier and has a higher impact counterbalancing the benefits of a higher production. Since the climate change impact of PV modules decrease, the share of impact coming from ancillary components of the system increase, an additional opportunity to reduce the climate change impact even further can be the use of a wood-based mounting system. In the configuration of a very efficient PV system, manufactured with low carbon electricity, the climate change impact can almost drop to 10 gCO_2eq/kWh, for a relatively modest annual productivity of 1200 kWh/kWp. It is worth noting that the panel efficiency considered corresponds to products already available in the market, though situated on the top of range. A system manufactured with low carbon electricity, with an even higher efficiency, or installed in a location with higher irradiance, can present an even lower carbon footprint.

Figure 5 presents similar trends, for the 16 considered impact categories, to the one presented for the carbon footprint in Figure 4. There were initially 19 impact categories, which included several indicators for the climate change impact corresponding to the contribution of land use and biogenic and fossil greenhouse gases. Only the total indicator for climate change is represented in Figure 5. The reduction trend observed for the climate change impact is similar for most of the other impact categories, although the proportion is different depending on the incremental evolution considered for each parameter. For example, the reduction is lower for the freshwater ecotoxicity impact category than for climate change. Another point to notice is the increase of impact for land use, but it is due to the change from a roof installation to an open ground installation. If we compare with the ecoinvent ground installation, the impact is lower because the assumed ground coverage ratio is higher than it was in the past as previously discussed. As the direct land use impact of PV

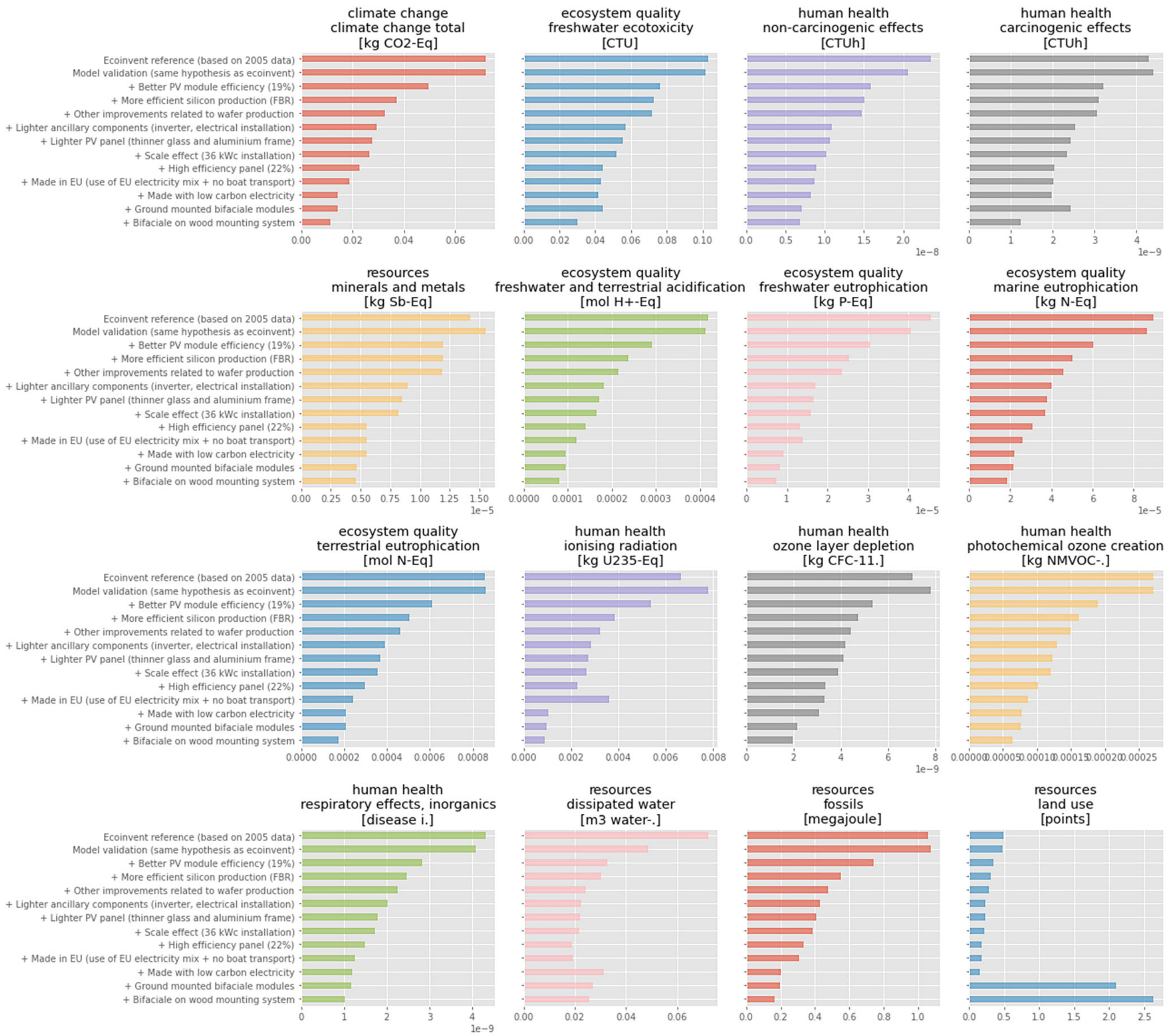

FIGURE 5 Multicriteria LCA of photovoltaic energy with technological improvements. [Colour figure can be viewed at wileyonlinelibrary.com]

system dominates its land use impact, this reduction is mainly due to the increase of panel efficiency.

3.2 | Sensitivity analysis

Given the uncertainty and variability on the many parameters of the model, it is interesting to perform sensitivity analysis to identify the most influential ones. The tools used to build the model, namely, *Brightway2*,[47] and the additional layer, *lca_algebraic*, ease the implementation of such analyses.[28]

Figure 6 presents a sensitivity matrix based on a one-at-a-time sensitivity approach, that is, when each parameter is varied separately while keeping all others in their default values. For each parameter, the variability range is established based on an analysis of the scientific literature as well as industrial data. Those data with the associated references can be found in supplementary information. The *x*-axis corresponds to the 16-impact categories and the *y*-axis to the parameters of PARASOL_LCA. The colors of the cells represent the extents of the variability of the impact for the considered impact categories when the considered parameter varies from a lower limit to a higher limit divided by the mean value. Thus, parameters with a high coefficient of variation are represented in dark red, whereas those with a low coefficient appear in light orange. It is a synthetic way to represent and identify the influential parameters. We can see that the annual production ('*Normalised annual PV production kWh per kWp*') of the installation and its lifetime ('*Power plant lifetime*') are the most important parameters for all impact categories. However, some parameters are influential for a limited number of impact categories or even a single one. For example, the parameters defining whether the

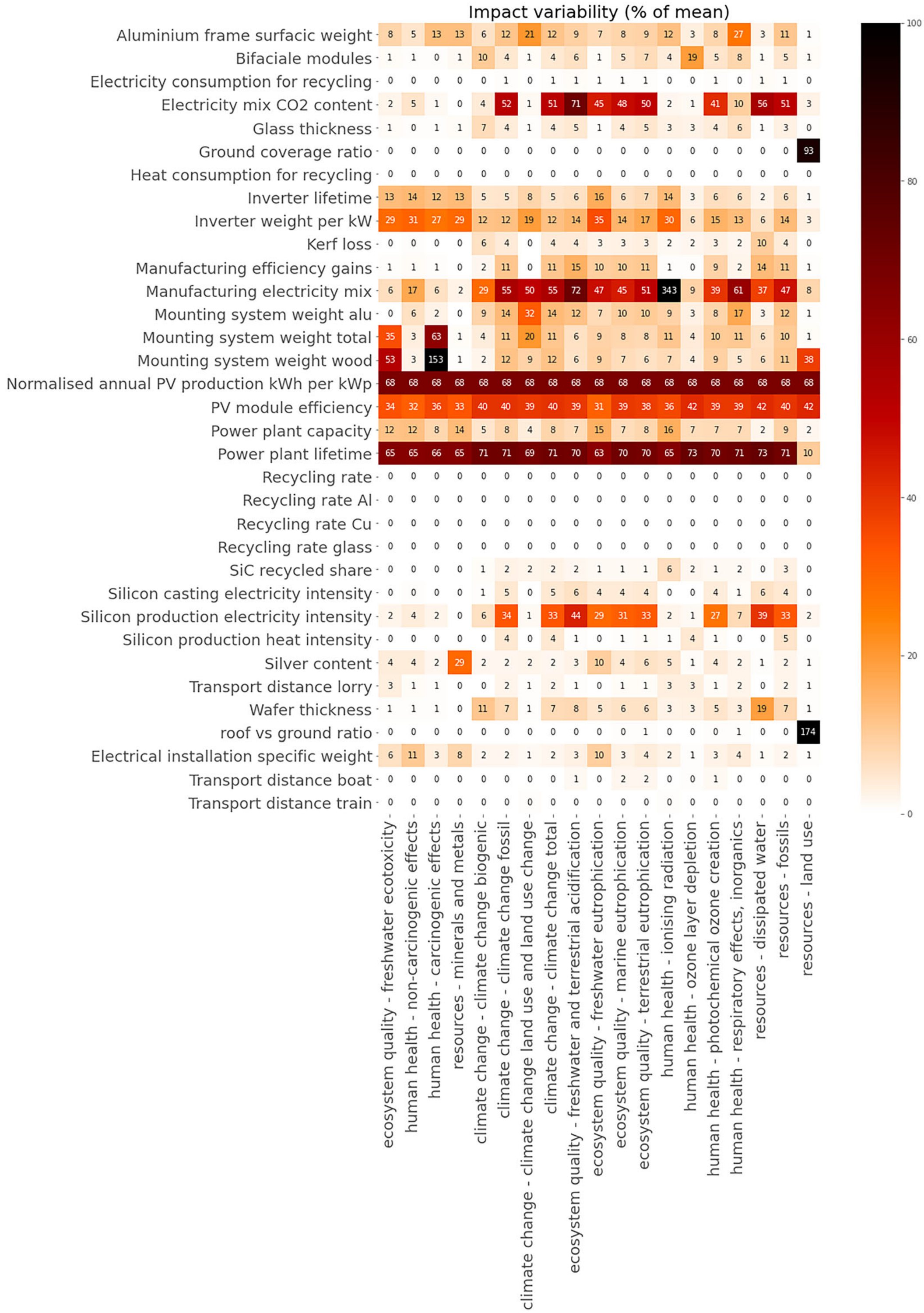

FIGURE 6 Multicriteria sensitivity analysis matrix. [Colour figure can be viewed at wileyonlinelibrary.com]

installation is ground mounted or not and the ground coverage ratio are key for the land use impact category but not for the others. The use of wood ('*Mounting system weight wood*') for the support is also influential for this impact category.

Focusing on the impact of PV panels on mineral depletion, it seems that the reduction of silver content in the PV panel, the increase of module efficiency, and the reduction of inverter weight are the three most influential parameters. Parameters related to the recycling have low to no influence. This is due to the use of a cut-off approach for the LCA modeling, as no impacts are deduced when materials are recycled. However, it remains highly relevant to recycle such resources whose reserves are limited and extractions are particularly harmful to the environment. Regarding the climate change impact, apart from the parameters determining the amount of electricity produced over the lifetime of the PV panel, the amount of electricity used to produce the silicon wafer ('*Silicon production electricity intensity*') and the carbon content of the electricity mix used ('*Electricity mix CO2 content*') throughout the systems' lifecycle are also key parameters.

It is important to note that some parameters present dependencies to each other. For instance, the sensitivity, in terms of environmental impacts, of parameters determining the amount of energy consumed will increase when the environmental impacts of the energy used increase. To consider those aspects, one-at-a-time sensitivity analyses are insufficient and global sensitivity methods become necessary. Functions were introduced in the *lca_algebraic* library to perform such analyses as detailed in the publication of Jolivet et al.[28] This work was achieved in the dedicated project INCER-ACV. In addition to the global sensitivity method, an interactive online platform has been developed and provides a friendly-user access to the PARASOL_LCA model (http://viewer.webservice-energy.org/incer-acv/app/). Otherwise, the model written in Python and relying on *Brightway2* and *lca_algebraic* can be found in supplementary information.

4 | CONCLUSION

Despite being renewable, PV energy is not environmental impact-free over its whole life cycle. An LCA study is therefore necessary to properly assess its potential environmental impacts. Many LCAs of PV panels exist in the literature, but they often rely on outdated LCI data, which can be found in widely used databases. As the PV industry has considerably improved over the last decade, the use of outdated data leads to a remarkable overestimation of the PV environmental performance and hinders the accurate assessment of the environmental performance of current or prospective PV systems.

In this study, a new approach is proposed to update the existing but outdated life cycle inventories of PV systems with the elaboration of a parameterized LCA model. This update relies on the collection of the most recent data by interacting with PV stakeholders. The application of the proposed iterative six-step approach to the crystalline silicon-based PV system led to the development of a parameterized LCA model named PARASOL_LCA. With more than 30 parameters, this proposed model enables the assessment of the environmental performance of current PV systems and could be further applied to explore prospective PV systems.

Results highlight a reduction by a factor 2 or more of the climate change impact for a modern PV system compared with the assessment made from the default LCI in existing databases. The latter implicitly corresponds to a PV system manufactured in 2005. This important reduction of environmental impacts is largely linked to the increase of the PV system efficiency as well as the enhancement of the efficiency of processes involved in the production of silicon cells, other factors contributes but to a lesser extent. When the PV panels are manufactured with low carbon electricity, the carbon footprint can be as low as 15 gCO_2eq/kWh (with a moderate irradiance corresponding to an annual production of 1200 kWh/kWp).

The considerable reduction of the climate change impact of photovoltaic energy is also observed for all the other environmental impact categories considered, although the extent can be higher or lower. A sensitivity analysis matrix was represented to describe, in a synthetic way, the influence of all the input parameters of the model for all the impact categories considered. This analysis and representation enable, for a given impact category, the identification of the most influential parameters and, consequently, the levers to improve the environmental footprint of PV energy. Therefore, the results of this study could be particularly useful to support the decision-making process and the research and development strategies for the advancement of the PV industry stakeholders.

As a perspective, the PARASOL_LCA model could be extended to allow the environmental impact assessment of tandem cells PV panel or other thin-film technologies. The associated python code relying on *Brightway2* and *lca_algebraic* is transparently published. The method developed in this study and, thus, applied to a crystalline silicon-based PV system is generic and can be applied to other energy systems, renewable or not, and even to systems that are not related to the energy sector.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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