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An agile life cycle assessment for the deployment of photovoltaic energy systems in the built environment

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Abstract

Background In the context of urban energy transition, photovoltaic (PV) systems play an important role in electricity generation. However, PV technology has some environmental drawbacks that also need to be acknowledged and managed. Life cycle assessment (LCA) is widely used to assess the environmental impacts of systems, but LCA is very complex to perform. Therefore, this research work presents a proof of concept for a parameterized LCA tool for grid-tied photovoltaic systems in urban areas that allows non-experts in LCA to obtain LCA results reliably and quickly.

Results The resulting methodology is an integration of three preexisting tools: PVGIS, Brightway and Ecoinvent, plus a Breakeven point analysis. The first step of the approach consists of identifying the main parameters of photovoltaic systems: geographical, technological, and temporal. Once the non-expert practitioner sets the influential parameters, the tool assesses the greenhouse gas emissions over the life cycle of the PV panels per unit of supplied electricity, allocates the emissions per component, and calculates the point at which the avoided emissions compensate for those produced by the power system. The algorithm strives to find the optimal PV system configuration to reduce the environmental impact, providing decision-making support for promoters and policymakers in the context of the urban energy transition. Two case studies are presented to illustrate the proposed method's applicability and benefits.

Conclusions The production of PV panels was confirmed as the main source of emissions in this kind of installation. The reasons are analyzed, allowing for improved design. Furthermore, the estimated break-even point where savings of conventional electricity offset emissions shows the influence of the parameters on the system's environmental performance.

Keywords Photovoltaic systems, Urban electricity production, Life cycle assessment (LCA), Environmental break-even point, Greenhouse gases

Background

In the last decades, population growth and technological advancements have increased global electricity demand [1]. In 2020, 74% of the worldwide electricity demand was covered by non-renewable energy sources associated with greenhouse gas (GHG) emissions, contributing to climate change [1].

In this context, an ever-increasing population lives in cities, currently up to 55%, and is responsible for

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approximately 70% of global energy consumption and GHG emissions [2]. Cities are expected to lead an energy transition towards an emissions-free, autonomous, and inclusive energy supply [3], and some authors expect to have a 100% renewable energy-based urban system in the medium term [4]. Taking Valencia (Spain) as an example, around 30% of the city's energy consumption and (indirect) emissions correspond to electricity, and the other 60% to urban mobility, which is expected to become ever more electric [5]. Thus, photovoltaic (PV) systems represent in this process a leading renewable energy source in cities with mild weather and high solar radiation like Valencia [1].

Several studies have analyzed the rooftop and/or the facade PV potential in urban areas, among others, for example: [6]. Due to the higher annual irradiation, the solar potential of buildings in urban areas is higher on rooftops than on facades. However, facades are also considered relevant because of the large available surfaces. Freitas et al. [7] analyze a complete state-of-the-art review of modeling solar potential in the urban environment.

Although renewable energy (RE) systems significantly reduce greenhouse gas emissions, these systems also cause environmental impacts when considering the whole life cycle. The type and intensity of those impacts and, therefore, the environmental benefits vary with technology, geographic location, seasonal issues, their corresponding parameters, and further influencing factors [8]. Hence, it is necessary to assess the environmental outcomes of different PV system configurations by modeling the life cycle of their components [9]. In this access process, the PV system performance is a key factor in reducing emissions [10].

A first review of these parameters in the literature is summarized in Table 1. As expected, the installation location determines the expected solar radiation, which influences the PV panel's performance [11]. Furthermore, the type of installation (flat, slanted, or facade) and their feasible corresponding inclination and orientation highly influence the PV electricity output [11]. PV technologies have different efficiencies and widespread single- and multi-silicon PV panels and PV laminates [11]. Losses in the transformation from solar radiation to electricity are also caused by high temperatures, power inverters, wiring, and dust on the PV panels and PV laminates. Regular maintenance can diminish these negative influencing technological parameters. Finally, there are temporal influencing parameters like the installation's lifetime (operation in years) and the environmental profile of the substituted electricity.

PV systems are associated with high energy demand in the manufacturing process, especially in the energy-intensive production steps of solar-grade silicon and solar cell manufacturing [20]. In 2017, 95% of total PV production was accounted for silicon wafer-based technologies, of which 62% were multi-crystalline PV panels [21]. China as a dominant PV cell/module manufacturing country with a share of over 60% of the world's PV production in 2019, is followed by Taiwan [16]. Furthermore, 56% of global polysilicon and 72% of solar cells are typically produced in China [22]. China's electricity generation in 2020 was based on a share of 64% coal [1] and despite ambitious policy plans, the carbon intensity in 2022 of China's electricity is well above 600 g/kWh [23]. Because most of the silicon-based technologies production takes place in China, the energy-intensive silicon PV manufacturing becomes even more CO_{2e}-intensive. Therefore, PV panels may have high environmental impacts during construction. A lack of optimization of rooftop or facade PV installations, e.g., orientation, inclination, shadow times, etc., and their

Table 1 Influential parameters in a PV power system

	Influential parameter	Influence on electricity generation or GHG emissions	Source
Geographical	Radiation (W/m^2)	Different locations have different expected solar radiation	[12]
	Inclination (degrees from horizontal)	The inclination of the PV panel affects the amount of received solar radiation	[13]
	Orientation (degrees from South)	The orientation of the PV panel affects the amount of incident solar radiation	[14]
	Temperature (°C)	Module temperature; the efficiency decreases with rising temperatures	[11]
	Shadow time	To be determined by the horizon profile	[15]
Technological	Technology	Single-silicon and multi-silicon technologies have different efficiencies	[16]
	System losses	Losses by inverter, cables, dust on the PV panels, degradation rate, etc.	[17]
	Maintenance	The quality of maintenance affects the system losses	[18]
Temporal	Environmental profile of electricity grid	The cleaner the substituted grid's electricity, the fewer emissions saved to compensate for the PV panels' life cycle emissions	[19]
	Lifetime of different equipment	PV systems are complex with different components that may have longer or shorter lifespans	[16]

consideration can fail to estimate the PV performance accurately. In summary, the parameters listed in Table 1 considerably determine the environmental benefits of an urban PV installation.

Life cycle assessment of urban PV power systems

Several authors have conducted literature reviews on LCA applied to photovoltaic systems (for example [24, 25]). The study by [26] also includes an extensive literature review including various works on the LCA of roof-mounted PV systems. With differences, all of them have remarked on the contributions of LCA to the correct assessment of the environmental benefits and drawbacks of PV systems, whether roof-mounted or not. But they also conclude that LCA is too laborious and difficult to be carried out by a non-expert. In fact, the need for an accurate application of LCA to PV systems becomes clear from the following ongoing discussion: Ferroniet al. [27] analyzed the EROI of presently available PV systems in regions with moderate solar irradiation. They concluded that, for example, in Switzerland and north of the Swiss Alps, PV systems act as a net energy sink due to their material, labor, and capital-intensive energy characteristics that lead to high consumption of resources. However, the study of Raugei [28] disagreed with this fact in the same year and uncovered methodological inconsistencies and calculation errors in Ferroni's study, for instance, regarding the usage of outdated information, double-counting, and invalid assumptions on PV specifications and other key parameters.

On the other hand, by linking the results and conclusions of Sacchi et al. [29] on wind farms in Denmark with the assessment of the environmental impacts of PV systems in Spain, it is worth noting that a similar approach should be considered. Indeed, Martinopoulos [30] uses LCA to discuss whether rooftop PV systems are a sustainable solution in all parts of Europe. He concludes that this is not the case and that parameters such as those in Table 1 largely determine the environmental performance. Therefore, adding technological, temporal and geographical parameters should better reflect the actual characteristics of a PV system. More accurate LCA results and calculation of indicators such as EPBT, EROI and GHG emissions could be obtained by reflecting PV systems more accurately rather than using generic data, which would better support decision-making.

To the authors' knowledge, there is no literature review on parametric LCA methods, let alone applied to renewable energy systems. Therefore, this research also included reviewing the literature of parametric environmental assessments, preferably with a life cycle

Table 2 State of research of LCA studies with parameters of renewable energy systems

References	Topic	Region	Product system	Main findings
[16]	Parameterized life cycle inventories	Denmark	Wind turbines	Usage of parameterized inventories instead of generic data
[38]	IC-LCE, integrated computational LCE approach	N.A	Electric vehicle	LCA standardization (methodologies LCA + LCIA) hinders it from becoming a mainstream engineering tool IC-LCE helps with time-intensive tasks and enhances flexibility
[29]	Parameterized life cycle inventories	Denmark	Wind turbines	Usage of parameterized inventories instead of generic data
[18]	ENVI-PV, multicriteria LCA	Worldwide	PV systems	Key parameters: • Latest LCI • Solar irradiation
[27]	EROI on PV systems	Moderate solar irradiation	PV systems	Material and energy-intensive energy sink
[28]	EROI on PV systems	Moderate solar irradiation	PV system	Disagree with Ferroni's methodological failures
[32, 33]	LCA of the recycling process of silicon PV systems	N.A	Silicon PV systems	Key parameter: • Recycling of Si-wafers
[34]	LCA of China's multi-Si modules considering international trade	N.A	PV systems	Key parameter • Electricity mix during production
[36]	A review of LCA of PV systems	Several locations	PV systems	The main result in EPBT, EPBT CO_2, GWP Most times FU: 1 kWh Boundaries: production and use with and/or without: • Installation, BOS, EoL
[39]	Social life-cycle assessment (S-LCA) of residential rooftop solar panels	United States	PV systems	Main potential social impacts of residential rooftop solar panels with a life cycle perspective

approach. Table 2 summarizes the articles that have most inspired this proposal. As one of the results of the literature review (Table 2), the consideration of key parameters leads to more accurate results in LCA of PV systems and the discovery of environmental hot spots [31]. Key parameters are the recycling of Si-wafers [32, 33], the electricity mix in production processes [34], the discussion of LCA methodology [35] and the usage of parametrized inventories instead of generic data [29].

Most LCA on silicon panels focus on the calculation of EPBT or CO_{2e}, as can be seen in the review of LCA studies in [36]. The presented results are estimations of the environmental impacts of particular PV systems in specific contexts and scenarios. The scenarios are different panel types, from mono- (single-), poly- (multi-), amorphous crystalline to nanocrystalline, and various PV system options (roof or ground-mounted, with or without tracking system, facade, or building-integrated). The studies are also situated in different contexts as the installation locations vary from Spain, the US, Switzerland, Italy, the Netherlands, and Germany to other countries with their different solar irradiation and electricity mixes. The functional unit is usually 1 kWh, but LCA studies on silicon solar panels have also been conducted per m^2 panel, kWp, or MWh. System boundaries differ, so reaching compatibility of main results is a difficult task [36].

Anyway, PV technologies are currently associated with an EPBT of 1–4.1 years, with cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS) technologies showing the lowest EPBTs, but there is a need for more comprehensive LCA tools [37]. As an example, in the review of LCA studies in [36] on silicon PV systems, the EPBT is up to 5.5 years on a PV tracking system with single-Si panels in Italy.

As previously said, LCA studies typically demand time and resource-intensive tasks like data collection, environmental inventory development, impacts calculation, etc. [38]. Likewise, all those tasks require a high level of expert knowledge, especially during the modeling and assessing processes, leading to inherent subjective choices [37]. Product systems such as silicon PV setups are typically defined by technical complex foreground processes, diverse contexts, and immense background systems. Available software tools fail to face this complexity's modeling and analysis, either leading to extensive iterations or rough simplifications. Most LCA studies on RE systems use generic data with assumed fixed values for sensitive parameters and, due to oversimplified models, LCA loses accuracy and flexibility [29]. Therefore, an approach was developed, with which the authors claim to overcome LCA barriers such as oversimplified models—enabling the applicability of the LCA methodology. The concept is called Integrated Computational Life Cycle Engineering (IC-LCE) and is presented more in detail in [38]. Therefore, the addressed research questions are:

1. Is it possible to assess the environmental impacts over the life cycle of urban PV power systems in an easy and quick but accurate way?
2. How to test and show the influence of key parameters on the environmental impacts of urban PV power systems?

By "quick" and "accurate" in the first question, it is meant that the results are the same as those that would be obtained following the conventional procedure but with a shorter and less specialized process. That is, more similar to the experience of designers of PV systems in the urban environment, or those who evaluate, promote or use them.

Of particular interest for this research is the proposal by Pérez-López [18]. They have built a parametrized LCA model, called ENVI-PV, which allows environmental performances of PV systems to be compared at the screening level worldwide. Furthermore, it includes the environmental footprint of the corresponding country's electricity mix. However, while ENVI-PV aims to give an overview only at the screening level of rooftop PV systems, this paper seeks to deliver more site-specific data on the environmental performance of urban rooftop and facade grid-tied PV systems. Furthermore, ENVI-PV uses a life cycle inventory developed by TREEZE, relying partially on Ecoinvent 2.2—while the hereby proposed model uses the Ecoinvent database version 3.8. Finally, ENVI-PV does not assess the environmental profile of all relevant values of influential parameters, overlooking the possibility of an accurate design optimization regarding inclination, orientation, and shadow times. The presented approach considers technological, temporal and geographical parameters. Its final objective is to deliver enhanced accuracy and comparability by using site-specific solar radiation, considering the wide variability of key parameters. Finally, integrating the impact-break-even point analysis provides decision-making support for the deployment of PV systems in urban areas for the urban energy transition.

Methods

A general methodology for an LCA is described in [40]. LCA can apply to any product or service, but its effects are affected by objects, assumptions, data availability, and accuracy. Hence, LCA operators and users must adequately understand the limitations of LCA and the assumptions that can be drawn from its results. The essentials of LCA are standardized in ISO 14040:2006 and ISO 14044:2006, which stipulate the details and fundamental points of the approach. Since the process has been programmed to carry out the step in an automatic and parametrized way, the methodology allows for obtaining the results of the LCA of a PV system quicker than using a conventional procedure. Two case studies in Valencia, Spain, will be applied to illustrate the application of the methodology developed.

Goal and scope definition

The functional unit (FU) of the created parametrized LCA model of the photovoltaic operation is, "Photovoltaic energy system to be installed on a roof/facade, at geographical coordinates A, with B m2 available, an inclination of C degrees and an azimuth of D degrees, to be installed in 2022 and operated for E years". The values of the geographic coordinates: A, the characteristics of the roof: B, C and D, etc., are inputs that vary with each case. Functional flows are determined once one technology or another is chosen from those offered by the method for electricity generation, as illustrated below in the case studies.

The scope of the study is limited to the cradle-to-grave considerations of photovoltaic life cycle inventories in Ecoinvent 3.8. This is due to the Photovoltaic systems being very durable, typically more than 20 years. Therefore, the least reliable part of these LCA studies is precisely that part. In addition, Ecoinvent does not have a good set of options for the life cycle inventory of end-of-life alternatives for PV systems, nor any other that the authors know of.

The system boundaries are determined by the usage of the Ecoinvent database, which is based on the life cycle inventories of PV systems [41]. The LCA model is made for the assessment of the impact on climate change, for comparison with previous studies, but the followed approach allows for changing the environmental impact assessment method and assessing other impact categories.

This is a consequential LCA with a management perspective, thus the Foreground system is defined as those system processes that, in terms of their selection or mode of operation, are directly affected by the decisions analyzed in the study. The foreground processes are therefore the configuration of the PV system and its operation. Since the installation is not mounted when the tool is used, there are no specific measures in the foreground. However, solar radiation is estimated based on average specific data from the past (PVGIS). The orientation, inclination and azimuth are real, and the panel, inverter, etc., as well as its performance are based on the manufacturer's catalogue data. If the user does not input specific equipment data and relies on the information by default, the tool can still be used but with less rigor, and there would be a warning.

Inventory

Ecoinvent is currently the most comprehensive database available for life cycle inventories. The tool can be adapted to read other databases. However, Ecoinvent has some limitations. For example, there is only a geographical boundary to the extent of the availability of selectable locations for the required unit processes in Ecoinvent. The availability depends on the chosen PV system's configuration. In the case of a slanted rooftop, the Ecoinvent database provides many countries as locations of solar electricity production. The choice is implemented in the parameterized LCA model and the country of operation can be chosen by its country code. But in the case of solar electricity production on flat rooftops or facades, the only option is the generic geographic unit process for the rest of the world (RoW). It means the tool will consider processes with intermediate values for cases from different locations around the world. The tool, based on the Brightway2® LCA software as explained below, allows more up-to-date inventories to be included, which could be a way to overcome these boundaries, whereas another option is to edit the data already implemented.

According to [37], the inventory analysis collects information about the inputs of resources, materials, semi-products, and products and outputs of emissions, waste, and valuable products for the product system. This paper's LCA model focuses on assessing GHG emissions based on the information about the environmental consequences of the production and operation of the chosen type of PV system. The life cycle inventory (LCI) is based on generic cradle-to-grave data from the study in [41], implemented into the Ecoinvent 3.8 database.

The method used here for developing the parameterized LCA is shown in Fig. 1. Firstly, two literature reviews have, on the one hand, confirmed the key parameters of the PV power system performance (see Tables 1 and 2), and have, on the other hand, identified similar proposals and strategies to answer the research questions.

Then, within the open LCA framework Brightway2, a Python-based model has been deployed to assess the environmental impacts over the life cycle of different PV power systems. The use of Brightway2 allows for the LCA calculation tool to be interfaced with other tools. The background life cycle inventory is provided by Ecoinvent in its version 3.8. Two different case studies are used to verify the feasibility and benefits of the model.

The PV performance is estimated via the fifth version of the Photovoltaic Geographical Information System

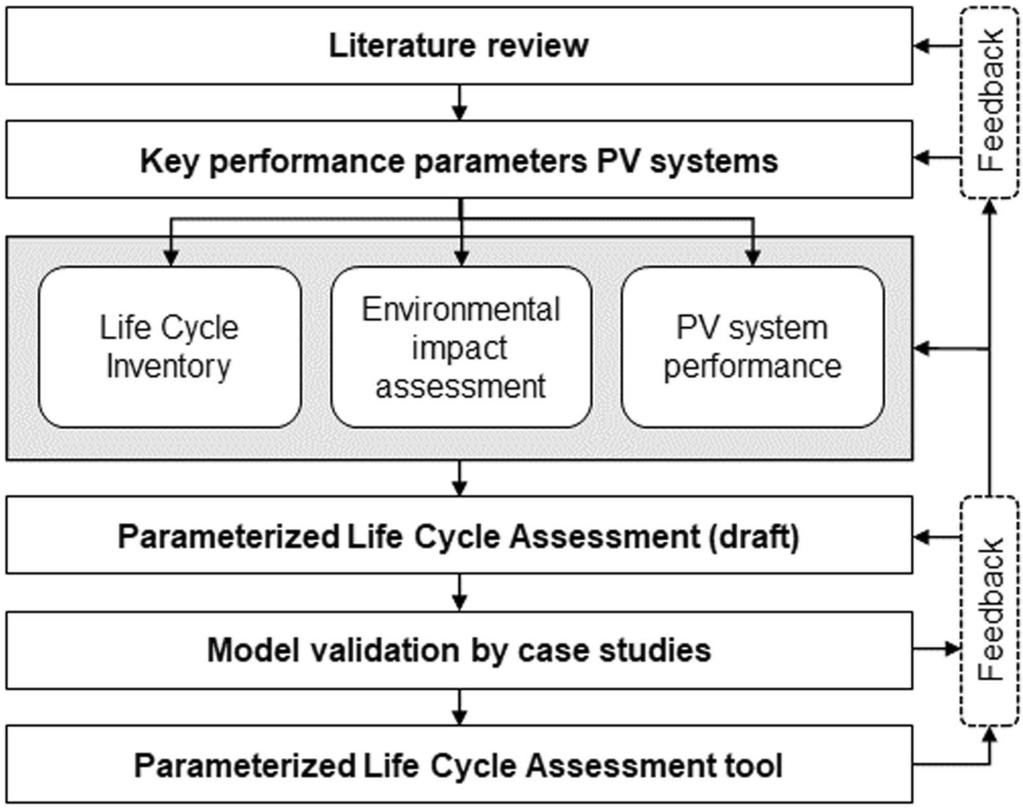

Fig. 1 Methodology for the model development

(PVGIS), developed over 10 years by the European Commission Joint Research Centre (JRC) in Ispra, Italy. For that, an application programming interface (API) has been developed in Python that interacts with PVGIS, automating this step. A key factor for PV performance is the PV module efficiency, which depends mainly on the solar radiation intensity and the module's temperature. In turn, the solar spectrum affects solar radiation intensity; the module's temperature depends on air temperature, wind speed, and solar irradiance. In addition, the research group of JRC has created models that combine these influencing parameters to achieve reliable PV module performance estimations over large geographical regions. Such models are used in the PVGIS tool [42].

Therefore, PVGIS was selected to provide solar radiation data and estimate electricity generation from PV systems. PVGIS offers, depending on the region, five solar radiation databases with hourly resolution. Thanks to PVGIS, the hereby proposed model allows the PV performance to be calculated based on the PV panel orientation and inclination, among other parameters.

Ecoinvent is the world's most consistent and complete life cycle inventory database and, in its version 3.8, it provides cradle-to-grave data on PV systems [41]. That means unit processes from raw material extraction to dismantling are included in the component's datasets. Therefore, the combination of PVGIS and Ecoinvent, made possible by Brightway2, makes it feasible to calculate the LCA as reliably as any other complex expert procedure, whose background is based on Ecoinvent.

Besides, a complementary study is added because a CO_2-break-even point analysis can be conducted. As a consequence of the operation of the PV system, expected impacts or benefits can be assessed and compared to the supply of electricity by the national electricity grid and its associated CO_2 intensity, for example. The model is intended to display the environmental impacts and show the dependency on parameters, especially on solar irradiation and the system's configuration.

Finally, what this proposal does allow is that a person with some experience in solar photovoltaic installations, but none in LCA, can optimize the design from an environmental point of view. In other words, the user only has to be able to understand the meaning of the different technical, geographical and temporal parameters that must be set, which are the basic questions for dimensioning any photovoltaic system. The procedure combines three tools with the necessary APIs. In addition, it automates the simulation of system performance, the development of the life cycle inventory, the calculation of environmental impacts, the representation of results for interpretation, etc. That is, it carries out the complete procedure according to the ISO 14040:2006 standard but the user does not need to know how it is done, just enter the requested parameters. As this is a proof of concept, the tool does not have an interface yet, rather, it is an ongoing process at the moment.

Case studies

The first case study is a household flat rooftop building, located at number 9 of José Maria Haro Street, 46022 Valencia. A picture of the plan view and its measures is shown in Fig. 2. It is planned to locate a 267 kWp flat rooftop grid-tied installation on the available surface.

The second case is a building located at the number 16 on Joan Verdeguer Street 46024, Valencia, belonging to the organization Las Naves. There is an ongoing project to set up a PV system in this location. The construction is composed of three similar buildings. A picture of one of the buildings and the dimensions of its right part are shown in Fig. 3. One half rooftop's surface is taken as a reference, and the total available surface of all three buildings is calculated by multiplying it times six, giving 2263.5 m^2. Three of the half rooftops face east (Azimuth: $-90°$) and three west (Azimuth: 90°) with an inclination of 14°. The grid-tied PV systems will be installed with the same slope. Therefore, the total Multi-Si PV peak power to be installed is 336 kWp; half is faced to the east, and the other half with the same size to the west. The building is not exposed to shadows but has rooftop windows, which avoid installing PV panels in certain parts.

Components of the PV systems

The main components of the PV system are the PV panel and the inverter. The chosen components and their characteristics are shown in Table 3. In the case of PV panels, the same brand was selected for both monocrystalline and polycrystalline: Trina Solar. Currently, the range of monocrystalline PV panels goes from 300 to 670 W. A 500 W monocrystalline panel was chosen. In the case of the polycrystalline systems, the panels for self-consumption application range from 250 to 500 W. A 350 W PV panel was selected. For the case of the laminate panel, the same polycrystalline panel is

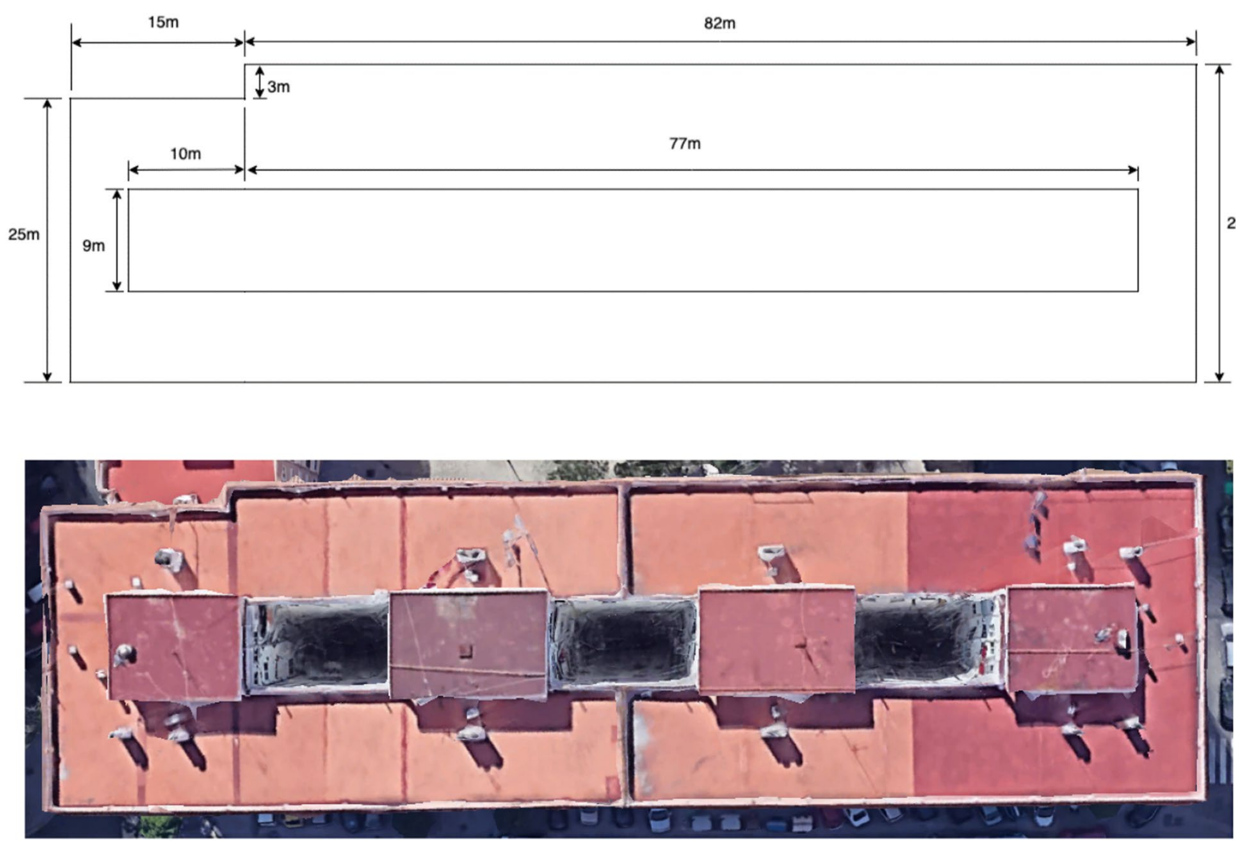

Fig. 2 Drawing and picture of the rooftop of case 1

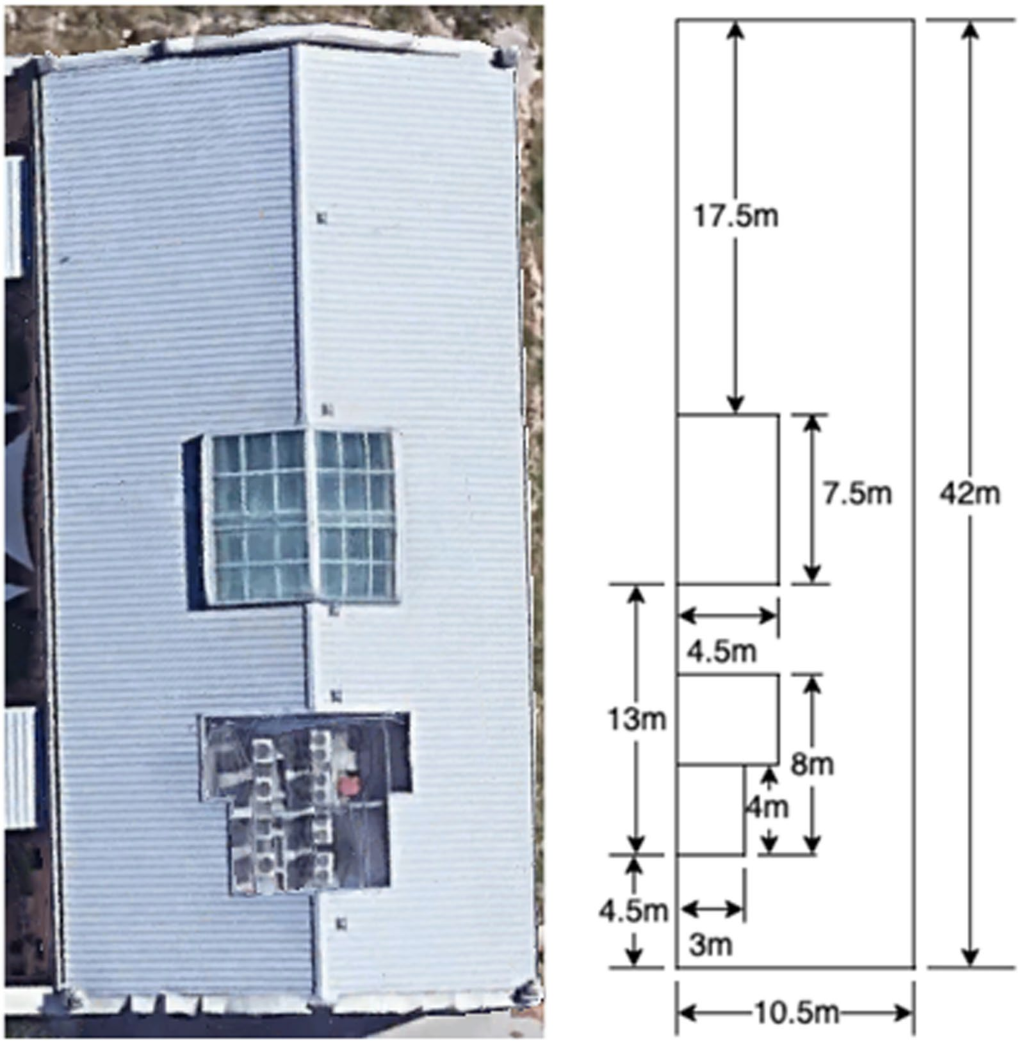

Fig. 3 Drawing and picture of the rooftop of case 2

Table 3 Datasheet of the selected PV panels for all the cases [43]

Parameter	Abbr.	1	2	Units
Brand		Trina Solar—Vertex	Trina Solar—Tallmax	
Model		TSM-DE18M (II)	TSM-PE15H	
Type		Mono	Poly	
Peak power	P_{peak}	500	350	W
Module efficiency	η	20.7	17.2	%
Module dimensions		2187×1102×35	2024×1004×35	mm
Area		2.41	2.03	m^2

considered. All equipment lasts 30 years but the inverters must be replaced after 15 years.

Results

Developed model

The modeling approach consists of three steps, which rely on different data sources (see Fig. 4) and demand several parameters to be set (see Table 1). In step 1, PVGIS estimates the PV performance for specific locations in urban areas. Step 2 allows to evaluate the initial PV configuration, and in the last step, an impact-break-even point analysis shows the user when the PV installation does environmentally pay off. While the second step relies on data provided by Ecoinvent and Brightway2, the first step only relies on solar radiation databases, whereas the last step integrates all three data sources.

The parameters that the procedure asks the user to determine have been classified as technological, temporal

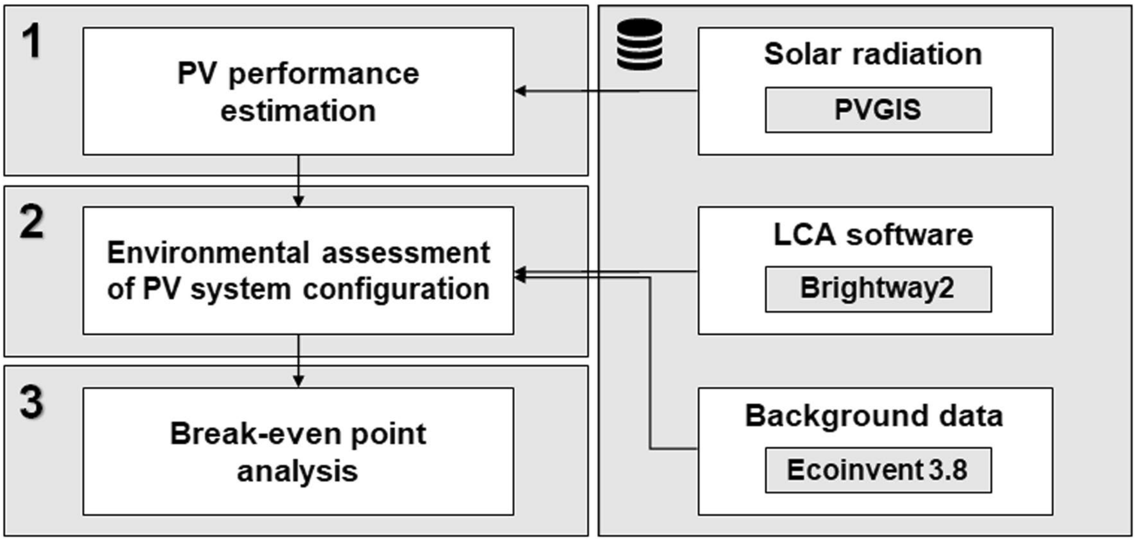

Fig. 4 The architecture of parameterized LCA model for PV systems

Table 4 List of parameters integrated into the procedure

Technological	Temporal	Geographical
Type of installation • Flat, facade, slanted… • Free mounting, integrated…	Lifetime • Operation time of each part of the PV system	Location • Geographical coordinates • Country
PV technology • Single-crystalline silicon, multi-cristalline siliscon…	Maintenance schedule Monthly, quarterly, semiannual, annual	Capacity factor (PVGIS) • Azimuth • Slope • Shadows • Combined losses
Equipment • Panels • Inverters • Other equipment • System loss		

Table 5 Datasheet of the selected grid-tied inverters for every case [43, 44]

Grid tie inverter	
Brand	Huawei
Model	SUN2000-60KTL-M0
Number of inverters	4 for case 1, 5 for case 2
OUTPUT AC	
Nominal AC power	66 KVA
Euro efficiency	98.5%

and geographical (see Table 4), based on the studies summarized in Tables 1 and 2.

According to Tables 3 and 5, monocrystalline (single-Si) panels are considered with a module efficiency of 20.7% and polycrystalline (multi-Si) of 17.2%. The inverter has a default efficiency of 98.5%. The amount of PV modules that must be exchanged during the default lifetime of 30 years is 2%, plus an additional 1% production loss. The transport of the different components (photovoltaic panels, inverter, etc.) is broken down into up to four stages, depending on the component. For example, those manufactured in China will travel: (i) from the manufacturer to the port of Shanghai by truck (about 200 km on average); (ii) from the Chinese port to the port of Valencia (Spain) by container ship (16,300 km); (iii) from the port of Valencia to the warehouse by truck (50 km) and (iv) from the local warehouse to the installation site (100 km on average by van). Other components like the mounting structure are produced locally, although its raw materials may come from other countries (and it is considered in the corresponding life cycle stage), and the tool also includes the installers' travel to and from the PV system location. As a final remark, PV laminates are considered to replace rooftop parts [41].

An LCA method and its impact category have to be chosen in advance. Here, the impact category selected is climate change, and as the LCA method, the IPCC 2021 Global Warming Potential affecting a period of 100 years (GWP 100a) is chosen [45]. In the following, the three steps of the LCA model are described.

Step 1: PV performance estimation tool (PGVIS)

In the first step, the user is automatically directed to the PVGIS website, where user requirements to estimate the PV performance are the following:

- PV technology: silicon, monocrystalline and polycrystalline.
- Installed peak PV power [kWp]: 267 for case 1 and 336 for case 2.
- Overall system loss: set to 14% for the case studies.
- Slope [degrees from horizontal]: 36° for case 1; 14° coplanar on the roof for case 2.
- Azimuth orientation [degrees from the South]: 0° for case 1; 90° and −90° for case 2.

Crystalline silicon PV technologies should be chosen to be consistent with the available PV technologies in the steps of the environmental assessment. After entering all the required information, PVGIS estimates the average daily and monthly energy production [kWh], the average daily and monthly global irradiation [kWh/m^2], and the standard deviation of the monthly energy production due to year-to-year variation [kWh]. Table 6 shows the losses taken into account by PVGIS.

Table 6 Losses considered by PVGIS [42]

AOI loss (%)	Spectral effects (%)	Temperature and low irradiance loss (%)	Combined losses (%)
2.5	0.6	7.3	21.8

Step 2: environmental assessment of PV system's configuration (Ecoinvent 3.8 + Brightway2)

The second step of the model consists of a cradle-to-grave environmental assessment of the PV system's configuration, conducted with the life cycle inventory (LCI) background data from Ecoinvent 3.8. For climate change, it would be the part of the database that counts greenhouse gas emissions, converted into CO_{2e} units. The parameterized LCA model for PV systems was created in Python code on a Jupyter Notebook with the LCA framework Brightway2. Calculations follow Eqs. 1–4:

$$\text{LCem} = \sum_i \text{SLCem}_i, \tag{1}$$

$$\text{SLCem}_i = \sum_j \text{Pem}_{i,j}, \tag{2}$$

$$\text{Pem}_{i,j} = \sum_k \text{UPem}_{i,j,k}, \tag{3}$$

$$\text{UPem}_{i,j,k} = \sum_l \text{GHG}_{i,j,k,l} \cdot \text{GWP}_l, \tag{4}$$

where LCem refers to the emissions of CO_{2e} during the life cycle of the system; SLCem_i, emissions of CO_{2e} of the life cycle stage "*i*"; $\text{Pem}_{i,j}$, emissions of CO_{2e} of the process "*j*" in the life cycle stage "*i*"; $\text{UPem}_{i,j,k}$, emissions of CO_{2e} of the unit process "*k*" of process "*i,j*"; $GHG_{i,j,k,l}$ = emissions of a greenhouse gas (GHG) "*l*", of the unit process *i,j,k* (mass CO_{2e}/unit mass GHG); GWP_k = global warming potential of the greenhouse gas "*k*".

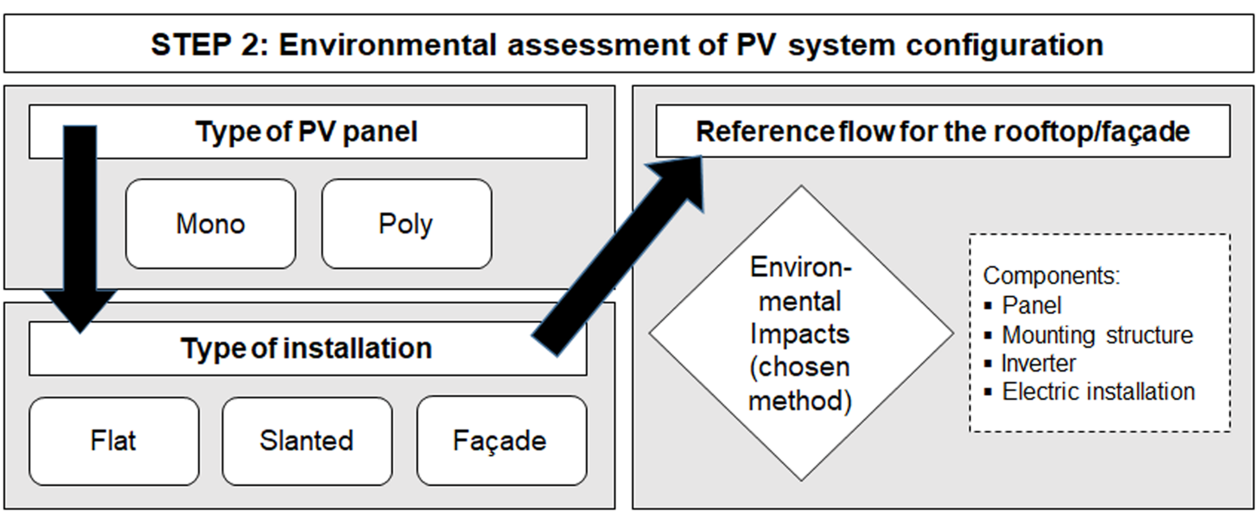

Fig. 5 Graphical representation of step 2—environmental assessment of PV system configuration

As with step 1, the user input should be equivalent to the size and type of the PV installation. The graphical representation of the third main element of the parameterized LCA model, the LCA of a PV system's construction, is depicted in Fig. 5. Then the model calculates the total contribution to the chosen impact category and the shares of PV panels, mounting structure, inverter, electric installation and "Rest". The latter stands for all other GHG emissions caused by unit processes not included in the four main elements of a PV system. The inventory of the "Rest" is supplemented with data for the transports of the PV panels, the inverter, and the electric installation. The choice of mounting structure is intended for PV flat-roof installation. The output of the PV system LCA is the total kg CO_{2e}. Also, the total kg CO_{2e} is broken down by processes and components: PV panel, mounting structure, inverter, and electric installation.

Finally, a description of the chosen PV system construction process is given, followed by a ranking of the 25 most emitting processes and their visualization.

Step 3: break-even-point analysis

In the last step, a break-even-point analysis is conducted, which compares the environmental benefits of PV electricity production with the impacts of its construction; Eqs. 5 and 6. The estimated PV system's lifetime and a comparison value [unit/kWh] are necessary for user requirements. Comparison values can be chosen according to the selected impact category:

$$\mathrm{BE} = \text{month } m \text{ when } \mathrm{LCem} = \sum_{i=1}^{i=m} \mathrm{ESi}, \quad (5)$$

$$\mathrm{ES}_i = E_i \cdot \mathrm{GE}_i - \mathrm{em}_i, \quad (6)$$

where *BE*, break-even point in years; ES_i, emissions saved in the month "*i*"; E_i, electricity generated by the system in the month "*i*", and either consumed or delivered to the grid; GE_i, emissions allocated to the electricity of the grid in the month "*i*"; em_i, PV system operation emissions allocated to the month "*i*".

For climate change, it would be the CO_{2e} intensity of the electricity supply that will be substituted [g CO_{2e}/kWh], i.e., that of the country where the study is carried out. The electricity mix is very different among European countries; hence, this is an important parameter. For the case study, the Spanish mix is used [46]. Indeed, the monthly profile for each country that is considered as an annual average mix is not precise. PV production mainly occurs in the summertime when the mix is different from the annual average. When PV electricity is supplied to the grid, the transmission system operator avoids buying the most expensive electricity production (marginal process), which is generally from thermal plants with high GHG emissions [47].

In this last step, both the yearly and the total impact savings after the stated PV system's lifetime are calculated and the model delivers the estimated amount of years, weeks, and days needed by the PV system to reach its impact break-even point depending on its location, configuration and chosen PV panel technology.

Validation through case studies was previously explained; due to the energy-intensive PV production, the tool was run under the IPCC 2021 climate change 100a GWP LCA method. In the first case study, the residential building with its flat rooftop is once simulated to be covered with single-Si PV panels and once with multi-Si PV panels, respectively. In the second case study at the office building with its slanted rooftop, multi-Si PV panels are compared to their multi-Si laminate equivalents. Furthermore, the multi-Si are also analyzed in an optimized scenario, which means that local restrictions of 14° inclination and an east/west facing slanted rooftop are not considered. Instead, the PV panels' optimized slope and azimuth maximize the electricity output over the year.

GHG emissions of the system components

As can be seen in Fig. 6, the initial set-up of the 267 kWp flat PV installation emits 553,107 kg with single-Si and 471,279 kg CO_{2e} with multi-Si PV panels. Most CO_{2e} emissions are caused by the PV panels (77.1% single-Si, and 70.7% multi-Si), followed by the mountings structure (11.3% and 13.7%, respectively), the rest (6.7% and 9.8%), the inverter (3.5% and 3%) and the electric installation (2.4% and 2%).

On the slanted rooftop of case study 2 an initial set-up of a 336 kWp PV installation with multi-Si PV panels would in total emit 727,814 kg CO_{2e}. The highest GHG contributors are the PV panels (511,393 kg CO_{2e}; 70.3%). On comparing the PV panel and PV laminates installation, their main components contribute similarly in terms of the shares of their overall GHG emissions. For example, for the multi-Si PV laminates the caused CO_{2e} emissions are only 0.1% less in proportion (464,140 kg CO_{2e}; 70.2%). For the other components, the shares are similar as well: the mounting structure of the PV laminates contributes 1% less, the "Rest" 0.5% more, the inverter 0.4% more, and the electric installation 0.3% more. With shares under 5% of the total GHG emissions, the inverter and the electric installation do not contribute significantly.

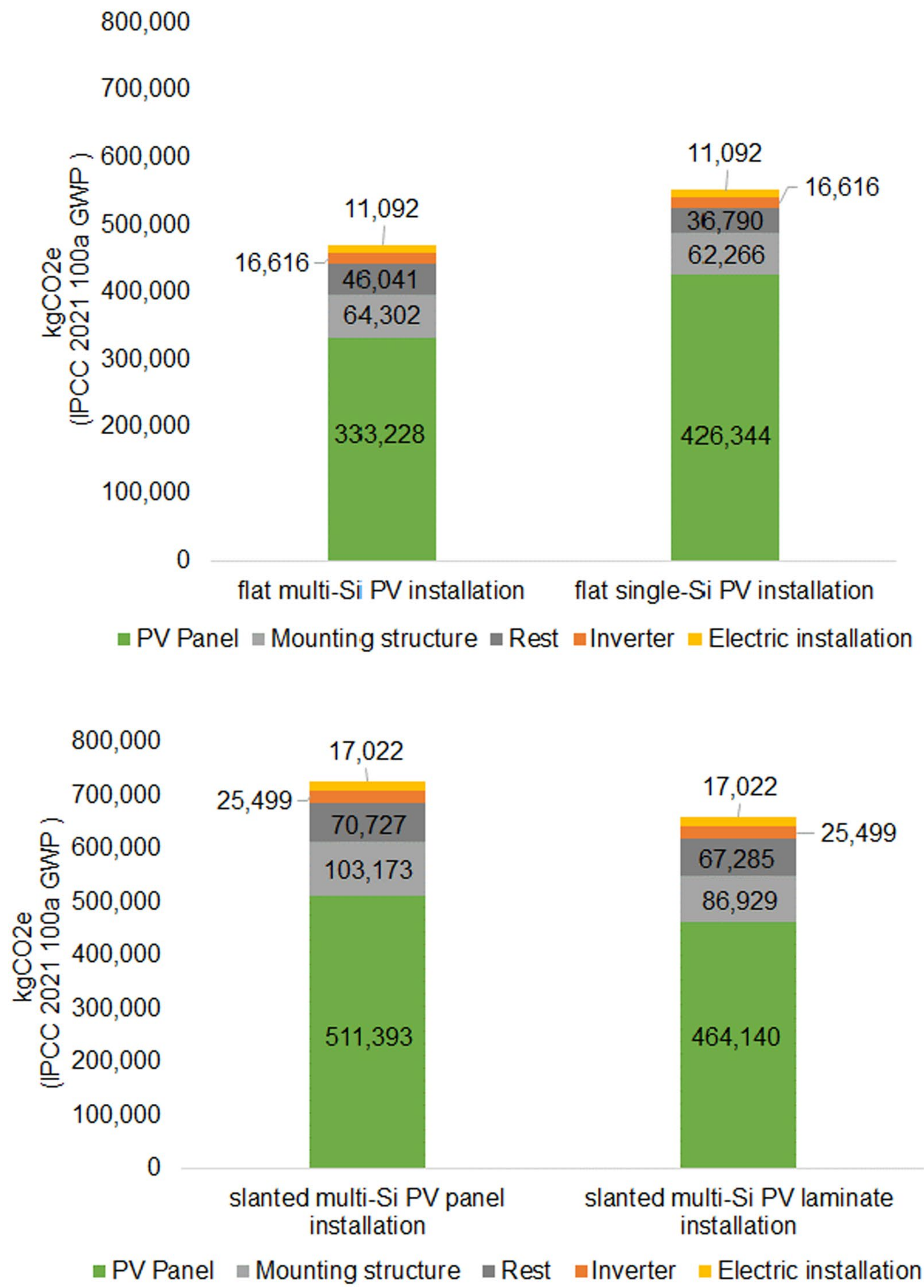

Fig. 6 GHG emissions of PV components for cases 1 and 2

Contribution of life cycle stage processes to GHG emissions

The tool also allows to find out which processes in the life cycle of the installations contribute most to GHG emissions. For example, in the case of the initial

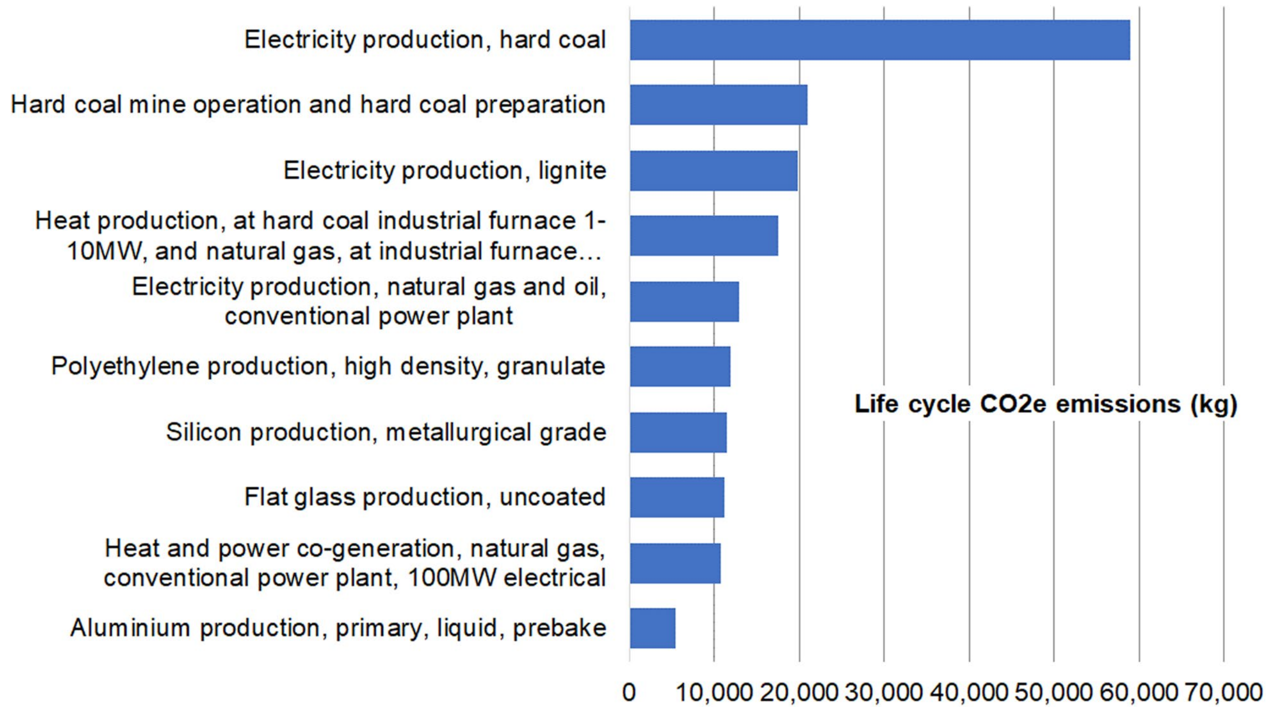

Fig. 7 Ten most emitting processes—flat rooftop, 267 kWp multi-Si PV panel

configuration of the 267 kWp multi-Si flat-plate PV system, see Fig. 7, the direct and indirect GHG emissions from energy consumption amount to more than 75%. They are mainly due to the life cycle of the panels, in this case manufactured in China. The materials polyethylene, silicon, glass and aluminum also produce significant emissions, in large part also due to energy consumption in China, where they are extracted and processed.

As advanced, what is presented in the article is a proof of concept, it is more related to the backend. For the development of the frontend of the tool, meetings with potential users are necessary to determine what results to present and how to do it. Figure 7 shows the terminology of Ecoinvent, it remains to be studied how to reorganize this information in a way that is more interesting for the lay people.

Break-even-point analysis

However, apart from the significant energy consumed during the production of the panels and other equipment required for installation, as well as the associated GHG emission PV installations are expected to produce more energy. Moreover, this energy must replace more polluting energy to improve the energy mix environmentally. Thus, as advanced, the tool makes it possible to calculate from which year of operation the installation has avoided as many GHG emissions as it has produced and will produce during its life cycle. This is called the break-even point of CO_{2e} emissions. Figure 8 shows the CO_{2e}-break-even point-analysis for both case studies (Step 3). The lifetime of the potential PV systems is displayed on the x-axis in relation to the amount of kg CO_{2e} emissions on the y-axis.

Starting with the flat rooftop building (lower part of Fig. 8), the initial GHG emissions of the single-Si PV installation are 82,000 kg CO_{2e} higher than the multi-silicon option. During its lifetime, it is not compensated by the higher electric generation of the former. Indeed, 37 t CO_{2e} emissions more are avoided using the multi-Si option. This is even though a higher quantity of multi-Si PV panels is required to reach the desired 267 kWp installation with single-Si PV panels. The multi-Si PV installation reaches its CO_{2e}-break-even point around 38 weeks earlier, which means after slightly more than four years and 51 weeks. The result behind this is the final allocation of 42.26 g CO_{2e}/kWh delivered of the single-Si PV panels, compared to the 36.16 g CO_{2e}/kWh with multi-Si PV panels, over the whole lifetime of the PV installation. All this is assuming that the electricity supply features do not change over the lifetime (in 2021 for example, Spanish electricity reached an average CO_{2e} grid intensity of 265.4 g CO_{2e}/kWh). It is interesting to keep in mind this assumption because, like other European governments, Spain aims to reach 0 CO_{2e}/kWh of its electricity supply in 2050 [48]. However, as long as there remains a part of the electricity production

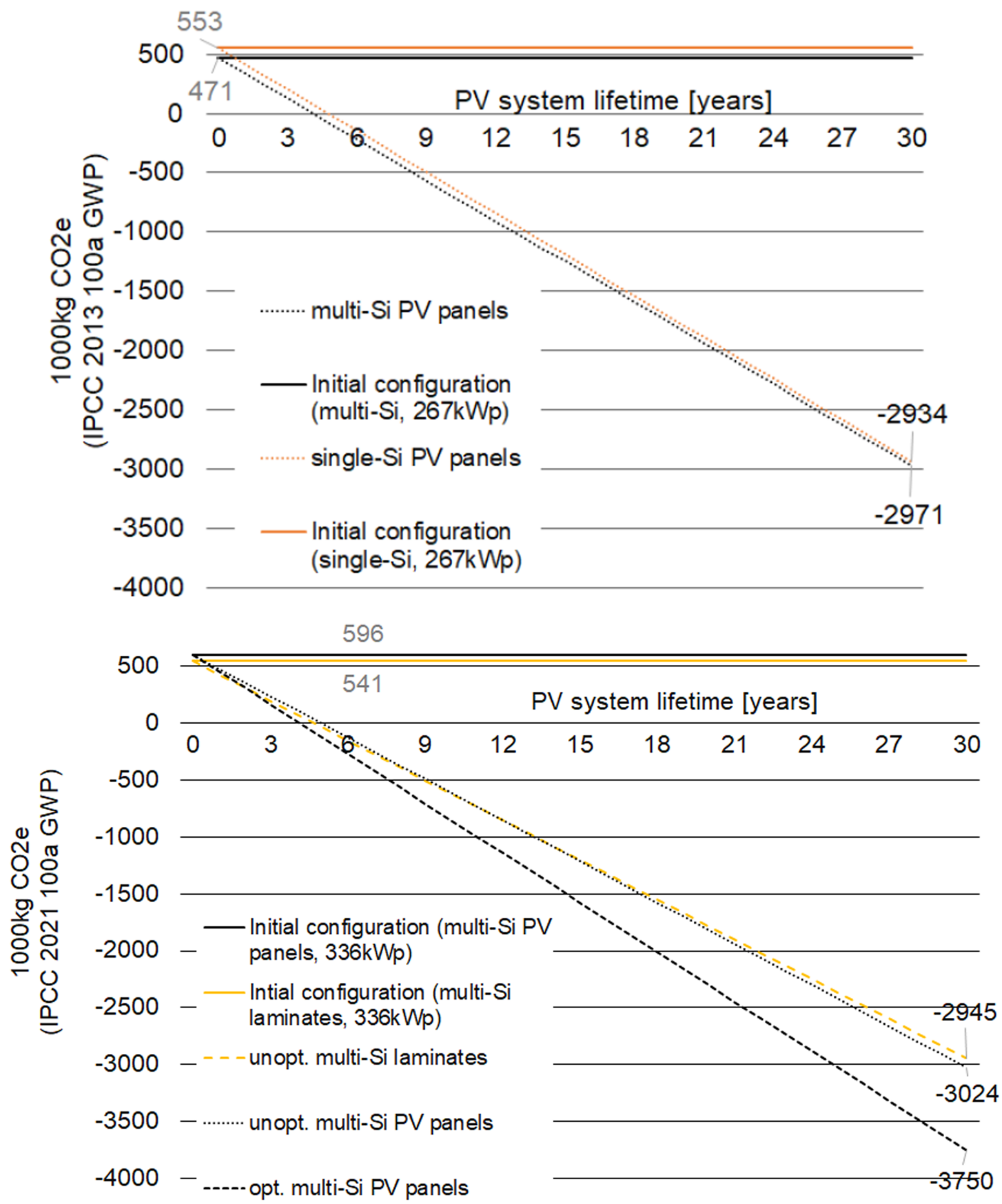

Fig. 8 CO_{2e} break-even-point analysis for case 1 (flat roof, 267 kWp) and case 2 (slanted roof, 336 kWp)

with higher emissions in the mix as in the PV system, introducing a new PV system will be beneficial compared to the marginal mix even if its GHG emissions per kWh are higher than those of the average mix.

On the upper part of Fig. 8, the break-even-point analysis of the GHG emissions shows the potential 336 kWp slanted rooftop PV installation for the initial configuration with PV panels and laminates, and for unoptimized multi-Si PV laminates, unoptimized and optimized multi-Si PV panels. The initial GHG emissions for a PV laminate installation are lower. The CO_2-break-even point is crossed 34 weeks later by the equivalent unoptimized multi-Si PV panel installation, e.g., after around six years and one week. However, the CO_{2e} savings after a lifetime of 30 years are 79 tCO_{2e} higher, in total 2945 tCO_{2e} for a multi-Si PV panels configuration. For the unoptimized multi-Si PV panel configuration, the GHG emissions per delivered kWh to the grid would be 44.56 g $CO_{2e,}$ and for the multi-Si PV laminates, 41.18 g $CO_{2e.}$

Furthermore, it is assumed that the PV laminates replace rooftop parts, hence saving impacts at the construction stage, which is usually only economically reasonable for new rooftops or complete roof renovations. That is why the impact for the mounting structure is 15.7% less (16,244 kg CO_{2e} less). Furthermore, the minor weight of the PV laminates causes 3441 kg GHG emissions less for their transportation in the category "Rest". However, the higher generation of electricity from the panels compensates for all these lower emissions.

Parametric analysis

Finally, the tool allows the effect of changes in the parameters to be checked. For example, reviewing the decision of the optimized multi-Si PV installation not following the local restrictions of an east/west facing 14° inclined slanted rooftop. If they are optimally aligned, instead of aligning with the building axis, after a lifetime of 30 years, additional 726,132 kg CO_{2e} emissions are saved, and the CO_{2e}-break-even point is already crossed after slightly more than four years, i.e., around one year earlier than with the unoptimized multi-Si PV installation, and would result in 36.43 g CO_{2e} per delivered kWh to the grid. Therefore, the PV system would contribute less to climate change, although it may be less economically interesting due to the higher costs of panels and mounting structures.

Discussion

The proposed model aims to assess the environmental impacts over the life cycle of urban PV power systems quicker than the conventional procedure but with the same accuracy. Besides, it enables testing and showing all key parameters' influence. Although the model relies on generic data of Ecoinvent 3.8 and therefore misses some accuracy, non-LCA-expert users can quickly run it and compare different PV configurations and their environmental outcomes in different impact categories.

The tool requires making several choices about the parameters for which training is preferable: choices about equipment, its lifespan, the period of analysis, the available surface of the rooftop or facade, system losses, etc. However, all parameters are set by default to average values or the most probable quantities given the other choices. In this way, the tool can be used not only by designers of PV systems, but also by other stakeholders like potential prosumers of energy (producers and consumers), city council officers, real estate managers, etc.

Potential PV configurations can be environmentally improved by choosing different silicon PV technologies and components and considering their efficiencies and overall losses. The latter are subject to local restrictions like the PV panels' inclination, orientation, or shadow time, which can be simulated.

The environmental break-even point analysis compares the initial impacts of the construction phase with the beneficial substitution of the environmental profile of the local electricity grid or another electricity source, for example In this way, by combining the outcomes of the two analyses, environmentally beneficial decisions can be supported.

The flexibility of the methodology can be used to analyze the influence of the different parameters on the PV system performance, especially its life cycle impacts. Indeed, fixing the rest of the parameters and testing different values of the parameter under study allows the energy yield and impacts to be quickly assessed. This way, one can test the influence of the geographic location, the shadows, the orientation and inclination, the origin of the supplier, the evolution of the substituted electricity supply, etc., on urban PV power systems.

This is also closely related to another major component of an LCA: sensitivity analysis. As the LCA is parameterized, it is easy to test changes in any of the parameters, leaving the other parameters fixed, and to calculate how much it influences the final result. So, for example, for the case studies, if it is not foreseen precisely how many trips the installer will have to make, it is not sensitive, doubling the figure or halving it hardly changes the final result. However, whether the panel is Chinese or European has a big influence because the energy mix is very different and this has a big impact on the manufacturing of the silicon wafers. Changing the company and origin of the panels, for similar yields, can halve the final LCA result, improving performance environmentally, but perhaps not economically. In any case, even with Chinese panels, the case studies give positive results for the environment.

In fact, verifying the model with the two case studies provides interesting results. For example, in the first case study, multi-silicon PV panels were considered preferable to single-silicon PV panels in terms of GHG emissions. The higher efficiency of the latter, assumed to be 0.4% more, does not pay off for their higher initial CO_{2e} emissions during the construction stage.

Furthermore, thanks to the second step of the model, it is clear that the PV panel production is an environmental hotspot, which causes 70.3% of CO_{2e} emissions during the construction stage for single-Si, and 70.2% for multi-Si. Therefore, by choosing a supplier with a better environmental profile in terms of efficiency and consumed energy the overall environmental impact would be proportionally improved.

In the second case study, PV laminates do not have natural cooling through the wind, integrated into the building. However, PV panels do not get as hot and stay, therefore more likely under better electricity production conditions. The impact of the production losses on the environmental benefits of the PV installation can be seen in CO_{2e}-break-even point analyses. Over the assumed lifetime of 30 years, more electricity can be produced with the multi-Si PV panels, therefore more electricity from the Spanish grid can be substituted, which results in a better environmental outcome for multi-Si PV panels. However, the CO_{2e}-break-even point is crossed earlier by the multi-Si laminates due to the minor initial GHG emissions. These results are consistent with those obtained by previous studies, based on a complete LCA (see Table 2), and other studies described in [49].

Conclusions

This research work presents a proof of concept of a parameterized environmental assessment tool for photovoltaic power systems for self-consumption in urban areas. The tool is of a decision-supporting nature regarding potential PV installations in urban areas and provides different views on the environmental impacts and benefits. Thus, this research serves to enable PV system experts, but non-experts in LCA, to perform LCA in the early stages of the design of PV systems for the built environment. The results validate the approach with parameters that are well known to PV experts (whether installers or planners), a parametric LCA can be performed as rigorously as a conventional one. As of writing this article, the frontend of the future tool is being developed and the first tests are being carried out with the target users. Making it really easy and intuitive is another interesting line of work that specialists in the discipline are now carrying out.

The LCA model takes the main technological, temporal and geographical key parameters into account and allows for a quick comparison between different PV configurations, enabling a wider range of users and reducing time and resource intensity.

The estimation of the PV performance (PVGIS) is combined with the environmental assessment of the system configuration to an impact-break-even point analysis, which shows the user after how much time a PV installation at a specific location does environmentally pay off.

The proposed methodology determines these influential parameters in energy generation, assesses the greenhouse gas emissions over the life cycle per unit of supplied electricity, allocates the emissions per component and life cycle stage and allows the break-even point, at which the avoided electric grid's emissions compensate those of the power system to be calculated.

Although the model uses generic data, because it relies mainly on Ecoinvent 3.8 rather than on project-specific data, the combination of Brightway2 and Python allows future improvements and developments to accomplish higher accuracy in LCA calculations. One of these improvements will be to replace Ecoinvent with an open-access database, although existing open-access databases, such as the public ILCD, are still very limited in comparison.

Furthermore, the cradle-to-grave data by Ecoinvent 3.8 mainly provide information on waste and dismantling processes including very little about possible recycling options, hence failing to consider this important aspect. Other relevant influencing factors could complement the presented environmental assessment model in the future, e.g., the recycling rate of silicon wafers. In addition, the evaluation of more than one impact category at a time would make it quicker to visualize environmental tradeoffs. Moreover, the possibility of the alternation of production process origins instead of the usage of averaged values could enhance the accuracy of LCA calculation by taking local differences, for instance, the electricity mix of consumed energy, into account. Therefore, estimations can be based on more project-specific properties instead of relying on averaged generic data; considering for example the significant difference in caused CO_{2e} emissions between a PV panel produced in China, where currently the majority originates, compared to one manufactured in Europe.

However, the model delivers decision-making support for concrete potential PV installations in urban areas by assessing the environmental impacts. Its flexibility enables trying different system configurations striving for optimization. Therefore, the proposed model contributes to the aimed urban energy transition, helping promoters and policymakers.

Abbreviations

CdTe	Cadmium telluride solar cell
CIS	Copper indium selenide solar cell
CO_{2e}	Equivalent carbon dioxide emissions (aggregates different greenhouse gases)
EPBT	Energy payback time
EROI	Energy return on energy invested
GHG	Greenhouse gases
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
PV	Photovoltaic

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Author contributions
All authors contributed significantly to the completion of the work presented in the manuscript. CS and TGN contributed to the development of the research plan and completed the case study application of the framework. CVS and DDB contributed significantly to the structuring of the document, draft preparation, and editing process of the manuscript. TGN read and approved the final manuscript.

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