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Ecodesign of photovoltaic grid-connected systems

J.R. Perez-Gallardo [a], C. Azzaro-Pantel [a,*], S. Astier [b], S. Domenech [a], A. Aguilar-Lasserre [c]

[a] Université de Toulouse, INPT, UPS, Laboratoire de Génie Chimique, 4 Allée Emile Monso, F-31432 Toulouse, France
[b] Université de Toulouse, INPT, UPS, LAPLACE (Laboratoire PLAsma et Conversion d'Energie), ENSEEIHT, 2 rue Charles Camichel, BP 7122, F-31071 Toulouse Cedex 7, France
[c] Instituto Tecnológico de Orizaba, Division of Research and Postgraduate Studies, Av. Instituto Tecnológico 852, Col. Emiliano Zapata, 94300 Orizaba, Veracruz, México

A R T I C L E I N F O

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Environmental impact
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A B S T R A C T

Optimization approaches for PV grid-connected system (PVGCS) have focused on optimizing the technical and economic performances. The main objective of this study is thus to propose an integrated framework that manages simultaneously technical, economic and environmental criteria. Life Cycle Assessment (LCA) is applied for the evaluation of environmental impacts of PVGCS. The proposed framework involves a PVGCS sizing simulator involving the computation of solar irradiance coupled to an outer optimization loop, based on a Genetic Algorithm. The objective is to maximize the annual energy generated by the facility. The analysis was carried out for different types of solar panel technologies: monocrystalline silicon (m-Si), polycrystalline silicon (p-Si), amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium diselenide (CIS). The environmental impact assessment was achieved by use of the IMPACT 2002+ method embedded in the SimaPro software tool with Ecoinvent database. The other chosen criteria based on technical and economic aspects concern the payback time of investment (PBT) and energy payback time (EPBT).

To select the best option among the five choices under study, a weighted evaluation is performed on all criteria in order to obtain a score for each technology. The technology with the lowest total score is the a-Si technology. A more relevant analysis is then performed taking into account the environmental impacts per kWh produced, as new criteria. In this case, the CIS PV module technology best meets the objectives.

1. Introduction

Solar Photovoltaic (PV) systems will be a major alternative in coming decades to cope with the scarcity of fossil fuels [1,2]. The direct conversion technology based on solar PV has several positive attributes. Although hydroelectric, thermal and nuclear power are cheaper in generation, solar PV has an edge over them since it requires almost no maintenance and neither depletes natural resources nor pollutes while in operation [3,4]. The energy source, our sun, is free and inexhaustible. PV technology is also very robust and has a long life.

The PV grid-connected system (PVGCS) performance depends exclusively upon the availability of solar energy at the site, system elements and configuration, and load parameters. The annual energy generated by a PVGCS is calculated as the sum of hourly production over the entire year. This hourly production depends on many parameters such as PV collector peak power, solar radiation on PV module plane, PV module temperature, shading, inverter efficiency and size, maximum power point tracking losses and the arrangement of the various electrical connections [5–8].

The size and configuration of a PVGCS are critical for evaluating profitability and environmental performance [9,10]. The search for an optimal arrangement of collectors in a field, trying to satisfy different objectives, constitutes an important challenge. The optimal deployment is principally based on production [5,6,11–14] or economic [9,12,15] criteria. Another criterion that has lately been used to evaluate PVGCS is the environmental impact [3,16–20].

As PVGCS is exclusively made with static components generating no particulate matter emission and requiring no fluid maintenance, the only potential impact of PVCGS during operation is related to the environmental impact on flora and fauna arising from change in land use. It can also cause changes in the economic activities. Emissions are generated by the use of fossil fuel-based energy [16,21,22] during the manufacture of the components, building and subsequent recycling of the components. This paper deals with this particular issue.

Although different models and tools have been developed to achieve the optimum PVGCS configuration, they are limited to a

* Corresponding author.
E-mail address: Catherine.AzzaroPantel@ensiacet.fr (C. Azzaro-Pantel).

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single objective evaluation, usually based on technical or economic criteria, and in few cases, on environmental criteria.

The goal of this work is to propose a system for generating alternative configurations of PV power plants, taking into account simultaneously three criteria based on technical, economic and environmental aspects, while considering different types of PV solar technologies through an optimization method. In the first part of this paper, the analysis of a literature review reports the different studies and tools that enable the modeling and design of a PVGCS. Secondly, the optimization approach is described in detail. Then, the results obtained after the proposed methodology was tested into single-objective studies are discussed. Finally, the major contribution of this work is highlighted along with some ideas that could be implemented in the future.

2. Literature review

System modeling forms a key part of the PV system design. It can provide answers to a number of important issues such as the overall array size, orientation and tilt, and the electrical configuration. The design criteria depend generally on the nature of the application. The applications of PVGCS vary from small building integrated systems to PV power plants. Modeling tools are available to provide solar radiation data, assess possible shading effects and produce the resulting electrical layout of the array as presented in what follows.

2.1. PV system design and sizing tools

When designing a PVGCS, it is very difficult to make an accurate assessment of the power generation through photovoltaic conversion because it depends on many uncertain parameters. A wide variety of software tools now exist for the analysis, simulation and sizing of photovoltaic systems. These tools present different degrees of complexity and accuracy depending on the specific tasks that each tool had been developed for. Examples of these sizing and simulation tools are given in Table 1. In general, they involve the estimation of solar radiation (using a meteorological database or a mathematical model) and/or the estimation of the energy generated by the system taking into account the characteristics and location of the PV components in the field (e.g. modules, the balance of system), weather consideration and solar radiation.

2.2. Solar radiation

Solar radiation on tilted surfaces is a very important aspect in the design of flat plate PV collectors for power plants. To eliminate the effects of local features, solar radiation is measured on horizontal surfaces, free of obstacles. Consequently, solar radiation data is most often given in the form of global radiation on a horizontal surface. Since PV modules are usually positioned at an angle to the horizontal plane, the radiation input to the system must be calculated from this data.

Global radiation on a tilted surface consists of three components, i.e., beam radiation, diffuse radiation and reflected radiation. The calculation of irradiance arriving on a tilted surface, used as input global horizontal data, raises two main problems, firstly, the separation of the global horizontal radiation into its direct and diffuse components and secondly, the estimation of the irradiance components incident on an inclined surface.

Over the years, different models have been developed to estimate solar radiation over tilted surfaces [23–25]. These models can be classified as isotropic or anisotropic models. However, a large majority of these models use the same method of calculating beam and ground-reflected radiation, the main difference being the treatment of the diffuse radiation.

Isotropic models assume that the intensity of the sky-diffused radiation is uniform over the sky dome. Hence, the diffuse radiation incident on a tilted surface depends on the fraction of the sky dome seen by it. The most widely used model belonging to this category is the one developed by Liu and Jordan (presented in Ref. [23]).

The second group of models assumes both, the anisotropy of the sky diffused radiation in the circumsolar region (sky near the solar disc) and, an isotropically distributed diffuse component from the rest of the sky dome.

2.3. Output energy estimation

The design of PVGCS must take into account the dimensions of the field, the balance of system components and, solar radiation data. In addition, shading and masking affect the collector deployment, by decreasing the incident energy on collector surfaces of the field.

In a solar field, an array of PV modules (collectors), are deployed in different rows with spacing; this allows tilting and facilitates maintenance. In this arrangement, a collector may cast a shadow on the adjacent row during the day, thus decreasing the amount of collected energy. This shading effect depends on the spacing between the collector rows, the collector height, the tilt angle, the row length and on the latitude of the solar field. The use of many rows of collectors, densely spread, not only increases the surface available to transform solar irradiation, but also increases the shading.

The spacing, and consequently, shading has also an influence on local environmental since it does not allow grass or farm crops to grow between the PV panels. This aspect will not be studied in this paper.

The balance of system (BOS), that encompasses all the components of a photovoltaic system besides the photovoltaic panels, also influences the estimation of the annual energy generated by the facility because of the efficiency of the electrical components.

2.4. Techniques for sizing PV systems

In any PVGCS, sizing represents an important part of the design. Besides being an economic waste, an oversized system can negatively affect further utilization of solar cells and energy generation. Undoubtedly, at the present stage of development of PV technology, the major impediment to a wider market penetration is the high investment costs of the PV systems [2].

The solar field design problem may be described by mathematical expressions. The configuration of PV is based on criteria such as the minimum field area required for producing a given amount of energy, the maximum energy generated from a given field or minimum cost of investment.

There are recent methods developed for sizing the parameters for PVCGS based on Artificial intelligence (AI) and Genetic algorithm (GA) techniques [6,15,26–29].

2.4.1. Genetic algorithm

Genetic algorithms (GA) are inspired by the way organisms adapt to the harsh realities of life in a hostile world, i.e., by evolution and inheritance. The algorithm imitates, in the process, the evolution of population by selecting only fit individuals for reproduction.

GAs were envisaged by Holland in the 1970s as an algorithmic concept based on a Darwinian-type survival-of-the-fittest strategy with sexual reproduction, where stronger individuals in the population have a higher chance of creating an offspring. A genetic algorithm is implemented as a computerized search and optimization procedure that uses principles of natural genetics and natural selection. The basic approach is to model the possible solutions

Table 1
System sizing and simulation programs.

Program	Source	Objective	Type of system	Main characteristics	Resultants	Advantages	Inconvenient
CalSol	Institut National de l'Energie Solaire (INES), France	Simulation and data analysis of PV system	Grid-connected, stand-alone and DC-grid system	- Economic analysis tool	- CO_2 balance - Report of yield production and monthly irradiation - Economic report	- Easy to handle - Pre-sizing - Available online	- Only French meteorological database - No PV components database. - Insufficient energy loss calculation and economic analysis - No interconnection with another program is allowed
PVGIS	Institute for Energy and Transport – European Commission	Estimation of solar radiation and simulation of a PV system	Grid-connected	- Meteorological database - Interactive maps	- Report of yield production - Monthly or daily radiation	- Easy to handle - Import meteorological data - Available online	- Exclusive to Europe and Africa - No PV components database - No energy loss calculation and economic analysis - No interconnection with another program is allowed
PVSOL	Solar Design Company, UK	Design, simulation and data analysis of PV system	Grid-connected and stand-alone	- Extensive meteorological and PV components database. - Calculation of shading losses –3D design tool - Economic analysis tool	- Report of yield production, efficiency of system and losses - Economic report	- Easy to handle –3D animation - Import of meteorological data - Possibility of parameter settings - Good quality results	- No interconnection with another program is allowed
PVsyst	University of Geneva, Switzerland	Sizing, design, simulation and data analysis of PV system	Grid-connected, stand-alone and DC-grid system	- Extensive meteorological and PV components database. - Calculate shading losses –3D design tool - Economic analysis tool	- Report of yield production, irradiation, efficiency of system and losses - Economic report	- Import of meteorological data –3D animation - Possibility of parameter settings - Good quality results	- Unfriendly use - Sizing restricted to collector configuration - No interconnection with another program is allowed
SolarPro	Laplace System Co., Japan	Design and simulation of PV system	Grid-connected	- Meteorological and PV components database –3D design tool - Calculation of shading losses	- Report of yield production	- Easy to handle	- No energy loss calculation and economic analysis - No interconnection with another program is allowed

to the search problem as binary strings. Various portions of these bit-strings represent parameters in the search problem. If a problem-solving mechanism can be represented in a reasonably compact form, then GA techniques can be applied using procedures to maintain a population that represent candidate solutions, and then let that population evolve over time through competition (survival of the fittest and controlled variation). A GA will generally include the three fundamental genetic operations of *selection*, *crossover* and *mutation*. These operations are used to modify the chosen solutions and select the most appropriate offspring to pass on to succeeding generations. GAs consider many points in the search space simultaneously and have been found to provide a rapid convergence to a near optimum solution in many types of problems: in other words, they usually exhibit a reduced chance of converging to local minima.

GA applications are appearing as alternatives to conventional approaches and in some cases are useful where other techniques have been completely unsuccessful. GAs are also used with intelligent technologies such as neural networks, expert systems, and case-based reasoning.

3. PVGCS optimization approach

As explained in the previous section, several programs and mathematical models have been developed to calculate either the solar irradiance received at a given point on the planet or size a PVGCS. Most of the studies reviewed [5,6,9,27,28,30] suggest optimizing PVGCS while considering only one criterion. Other authors [17,19,20,31] address only the issue of the environmental impact assessment of the elements of a PV system with emphasis on the PV module technology. Our main purpose consists of generating alternative PVGCS configurations, taking into account their technical, economic and environmental impact.

The main problem found in the programs described in Table 1 is the lack of an integrated approach that allows the optimization of the sizing of a PVGCS. The coupling of all elements, via an external program to optimize the model using a genetic algorithm, is difficult due to the closed structure used.

To overcome the problem of interoperability, the design of a simulator for received solar radiation coupled with a sizing module constitutes the most suitable option. The simulator must be designed in an open manner so that it can be interfaced easily with an outer optimization loop. The MULTIGEN environment previously developed in our research group [32] was selected as the genetic algorithm platform. It can treat both mono- and multi-objective problems. In this work, only the mono-objective case is considered. Hence, the potential of GAs to solve multi-objective problems serves as an incentive to use such an optimization strategy. This constitutes a natural way to extend this work. As it was initially developed in Visual Basic for Applications (VBA) in Excel, the same language is used for simulation purpose.

The main advantages include the automation of repetitive tasks and calculations, and the easy creation of macros in a friendly programming language.

Fig. 1 illustrates the system flow diagram for optimizing a PVGCS. The proposed system is a simulation tool coupled with an optimization module based on genetic algorithms for optimal configuration alternatives. The system involves the following models:

a) The estimated solar radiation received by the system according to the geographic location.
b) The PVGCS sizing based on a mathematical model that provides the annual energy generated from the characteristics of the system components and limitations on the design of the installation.
c) The evaluation of economic, technical and environmental criteria.
d) The optimization of the above criteria in order to generate alternatives for the optimal configuration of PVGCS.

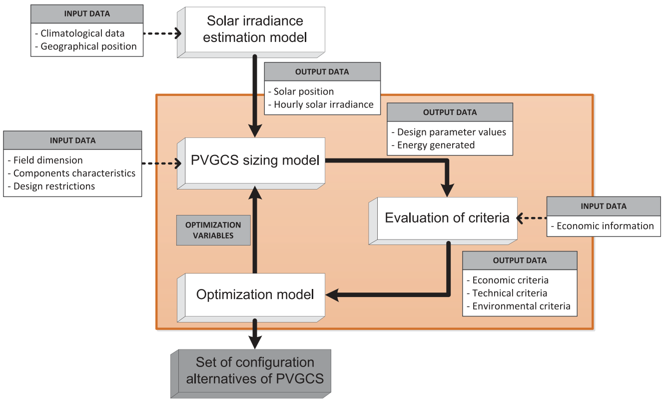


Fig. 1. Functional flow diagram of the proposed methodology.

3.1. Solar radiation model

The solar radiation model computes the radiation received at the site where the future plant will be built. Fig. 2 shows the input data necessary for the operation of the model, sub-models and the outputs.

The inputs for this module are classified into two groups. The former group is composed of meteorological data of the studied site. The average hourly temperature is available from various databases. Another important element to establish the relationship between solar radiation on the surface of the Earth and the extra-terrestrial radiation is the index of transparency of the atmosphere or *clearness index* (Kt). This index is the radio between the horizontal radiation of a particular hour and the extra-terrestrial radiation for that hour, as expressed by:

$$\mathrm{Kt} = \frac{G}{G_0} \qquad (1)$$

The latter group is composed of all the data inherent to the geographic location of the site where the facility will be placed. This information allows us to estimate the position of the sun and the solar radiation that the facility will handle every hour.

When radiation passes through the atmosphere of Earth, changes in its trajectory may occur because of the elements present in it. Elements such as ozone, oxygen, carbon dioxide and water vapor absorb radiations; some are reflected by the clouds. Dust and water droplets also cause disturbances. The result is the decomposition of the incident solar radiation into a receiver placed on the surface in different components [33].

The estimation of diffused radiation is very complex because it depends on the composition, shape and position of the elements that cause the scattering of radiation and this may vary with time. Diffused radiation is essentially anisotropic. The amount of reflected radiation is affected by the nature of the ground and by a wide range of features (snow, vegetation, water, etc.).

Solar radiation received on a horizontal surface is split into its beam and diffused components. These components provide the basis for estimating solar radiation on tilted surfaces. Fig. 3 shows the relations among the different levels of solar radiation.

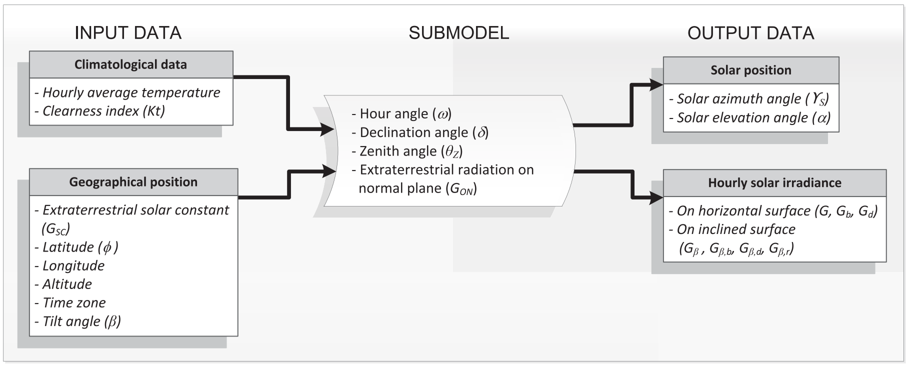


Fig. 2. Data flow diagram of solar irradiance estimation model.

3.1.1. Components of hourly radiation on horizontal surface

Hourly irradiance received on the horizontal surfaces may be expressed by:

$$G = G_b + G_d \tag{2}$$

Presented in Ref. [23], Miguel et al. establish a correlation between the *diffuse fraction* of hourly global horizontal irradiance and the *clearness index*. This correlation is given by the following expressions:

$$\frac{G_d}{G} = \begin{cases} 0.995 - 0.081\text{Kt} & \text{if Kt} < 0.21 \\ 0.724 + 2.738\text{Kt} - 8.32\text{Kt}^2 + 4.967\text{Kt}^3 & \text{if } 0.21 \le \text{Kt} \le 0.76 \\ 0.180 & \text{if Kt} > 0.76 \end{cases} \tag{3}$$

Then, the beam irradiance can be calculated by reformulating Eq. (2) as follows:

$$G_b = G - G_d \tag{4}$$

3.1.2. Components of hourly radiation on tilted surface

The most appropriate procedure to calculate the global irradiance on a tilted surface is to obtain separately the components to be defined after, as expressed by:

$$G_\beta = G_{\beta,b} + G_{\beta,d} + G_{\beta,r} \tag{5}$$

3.1.2.1. Beam irradiance. The amount of beam irradiance on a tilted surface can be calculated by multiplying the beam horizontal irradiance by the *beam ratio factor* (r_b).

$$G_{\beta,b} = G_b r_b \tag{6}$$

$$r_b = \frac{\cos\theta}{\cos\theta_z} \tag{7}$$

One consideration must be taken into account in calculating this component, when the sun shines on the back of the surface ($\cos\theta < 0$) the irradiance on the PV modules is normally not utilized, $G_{\beta,b} = 0$. A factor max (0, cos θ) is introduced in Eq. (7).

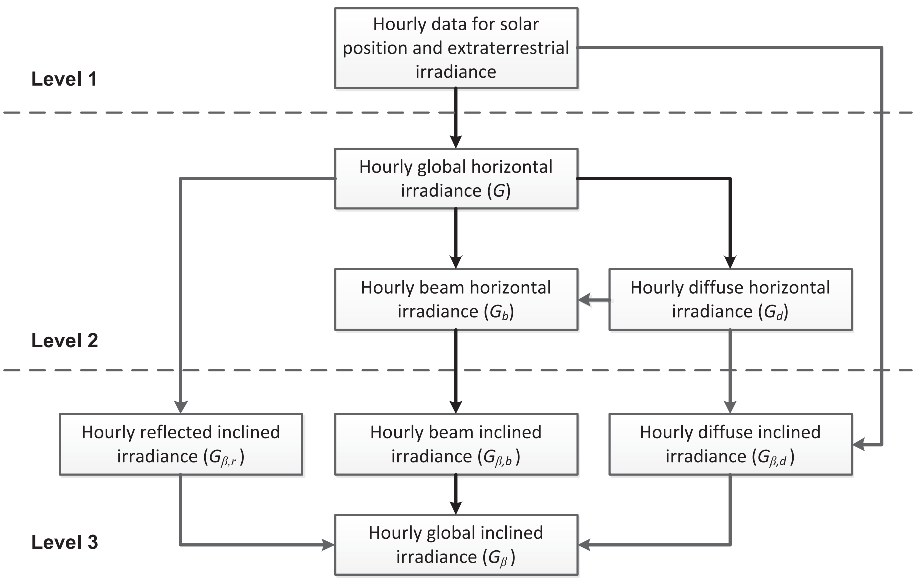


Fig. 3. Sequence for determination of hourly global tilted irradiance.

$$r_b = \frac{\max(0, \cos\theta)}{\cos\theta_z} \quad (8)$$

3.1.2.2. Reflected irradiance. The reflectivity of most types of ground surfaces is rather low [33] except snow and ice. Consequently, the contribution of this type of irradiance falling on a receiver is low. Eq. (9) computes ground-reflected irradiance.

$$G_{\beta,r} = \rho G \frac{1-\cos\beta}{2} \quad (9)$$

where ρ is the reflectivity of the ground and depends on the composition of the ground. A value of 0.2 is commonly adopted.

3.1.2.3. Diffuse irradiance. The methods used to estimate the diffuse irradiance on a tilted surface are classified as either *isotropic* or *anisotropic* models. The isotropic models assume that the intensity of diffuse sky radiation is uniform over the sky dome. Hence, the diffuse irradiance incident depends on the fraction of the sky dome where the surface is located.

A well-known *isotropic* model was proposed by Liu and Jordan (1963).

$$G_{\beta,d} = G_d \frac{1+\cos\beta}{2} \quad (10)$$

Better results are obtained with the supposed *anisotropic* models. These type of models include a circumsolar brightening, which assumes that the highest intensity is found at the periphery of the solar disk and decreases with increasing angular distance from the periphery.

Hay and Devis (consulted in Ref. [23] propose a model based on the assumption that all that is diffused can be represented by a circumsolar component coming directly from the sun and an isotropic component coming from the entire celestial hemisphere. The diffuse irradiance on a tilted surface is then:

$$G_{\beta,d} = G_d r_d \quad (11)$$

$$r_d = \frac{G_b}{G_o} r_b + \left(1 - \frac{G_b}{G_o}\right)\left(\frac{1+\cos\beta}{2}\right) \quad (12)$$

Reindl et al. propose another model (presented in Ref. [23], (Eq. (13)). This model extends the Hay and Davies model by adding the *horizon brightening*. The horizon brightening is assumed to be a linear source at the horizon, independent of azimuth. In fact, for clear skies, the horizon brightening is highest at the horizon and decreases in intensity away from the horizon. For overcast skies, the horizon brightening has a negative value.

$$r_d = \frac{G_b}{G_o} r_b + \left(1 - \frac{G_b}{G_o}\right)\left(\frac{1+\cos\beta}{2}\right)\left[1 + \sqrt{\frac{G_b}{G_o}} \sin^3\left(\frac{\beta}{2}\right)\right] \quad (13)$$

3.1.3. Validation

The simulator was used to estimate the annual radiation received in 4 different positions: Toulouse, France (43.4° N, 1.2° E, altitude 152 m), Sydney, Australia (33.5°S, 151.1° E, altitude 42 m), Mexico City, Mexico (19.2° N, 99.1° W, altitude 2277 m) and Singapore, Singapore (1.1° N, 104.1° E, altitude 5 m). The results were compared with those estimated for the same cities by PVsyst software [34] and MIDC SOLPOS Calculator 2.0 [35]. MIDC SOLPOS Calculator 2.0 was developed by the National Renewable Energy Laboratory (NREL), a research laboratory for the U.S. Department of Energy. This software tool contains a Solar Position Algorithm (SPA) [36] for solar radiation applications developed by the NREL. The algorithm can calculate the sun zenith and azimuth angle with uncertainties equal to ±0.0003°. MIDC SOLPOS Calculator calculates the position of the sun in the sky and its intensity for any given location, day, and time. It is valid from the year 1950–2050 and has an uncertainty of ±0.01° [37].

As we mention in Table 1, PVsyst is a PV simulation tool developed at the University of Geneva, Switzerland to be used by architects, engineers and researchers. In 2011, PVsyst got excellent results in the PHOTON Magazine evaluation [38]. The evaluation considered approximately 20 different PV simulation software available on the market, for the study of PV systems yield, and tried to assess the accuracy of irradiance data in the horizontal plane and ambient temperature, as well as horizon shading,

The lowest statistical difference between the result of our simulator and those of the PV simulation software tools considered as references was found when the formula developed by Hay et al. reported in Ref. [23] for diffused radiation was used (eq. (12)).

3.2. PVGCS sizing model

The second model of the system aims at calculating annual energy generated by the system from the radiation computed by the first model and the characteristics of the electrical components. This model considers the following aspects:

a) The field dimension where the PVGCS will be installed;
b) Technical aspects of the different elements of the PVGCS.
c) Design restrictions due to maintenance and safety purposes. These restrictions concern not only the maximum weight of the structures that will support the PV modules but also the standards and best practices to ensure appropriate maintenance in case of problems during operation of the PVGCS.

Fig. 4 describes the main elements of this model.

3.2.1. PVGCS mathematical sizing model

Weinstock and Appelbaum [9] formulated the PVGCS sizing problem as a mathematical problem. The optimal design parameters of the solar field were determined to obtain the maximum annual incident energy on the collector planes for a given field size.

The improvements that were implemented relative to the model presented in Ref. [9] concern the computation of the output power of the system, mainly in the following aspects:

- The equation used to calculate the diffuse irradiance received by the collector was replaced by the anisotropic model of Hay et al. [24].
- The reflected irradiance was included in the calculation of the radiation received by the installation.
- The method used to calculate energy loss caused by the shadow generated by adjacent collectors was changed. An array indicating the number of panels covered in a collector was created following the method proposed by Ziar et al. [39]

The model considers a horizontal field without elevations with a fixed length L and a fixed width W. It comprises K rows of solar collectors with a horizontal distance D between the rows; each collector has a length L_C, a height H, and are tilted by an angle β with respect to the horizontal (Fig. 5). Each collector is an array of PV modules arranged in N_r rows and N_c columns. The length of collector row L_C and its height H_C are given by:

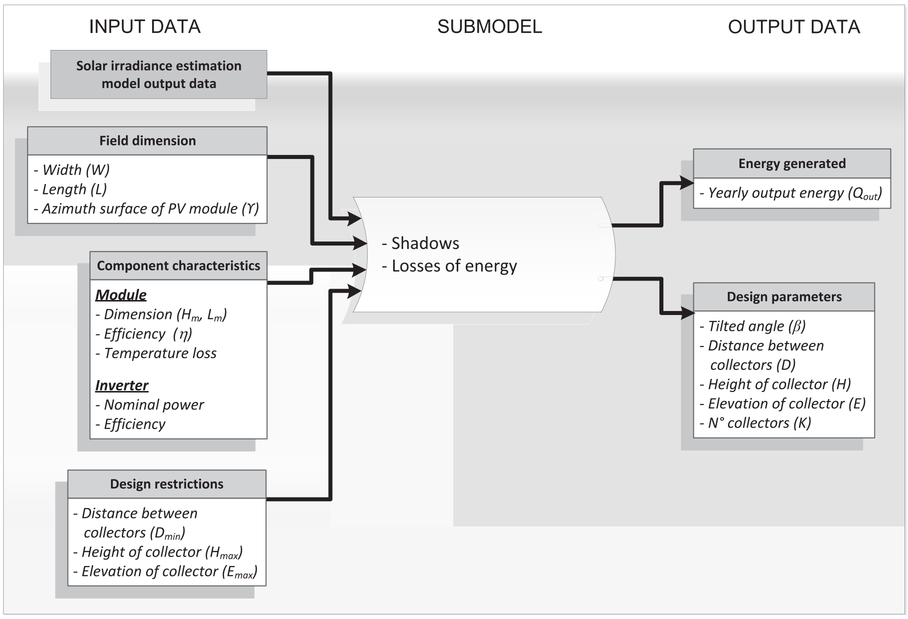


Fig. 4. Data flow diagram of PVGCS model.

$$L_c = N_c L_m \quad (14)$$

$$H = N_r H_m \quad (15)$$

The variables considered in this model are β, D, K, H where K is a discrete variable. The following constraints are also involved:

- The variation of the collector parameter values and distances are considered by the field width, i.e.:

$$KH\cos\beta + (K-1)D \le W \quad (16)$$

- The space between collector rows D is less than the distance D_{min}, i.e.:

$$D \ge D_{min} \quad (17)$$

- Maintenance and installation constraints required to limit the height of collector above the ground E_{max}, i.e.:

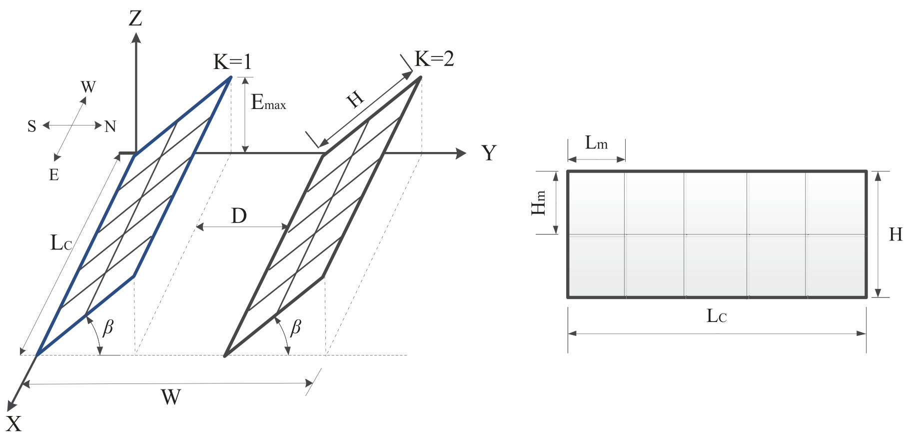
$$H\sin\beta \le E_{max} \quad (18)$$

- The collector height H itself can be limited by the solar field construction, maintenance and by PV module manufacturer, i.e.:

$$H \le H_{max} \quad (19)$$

- The collector tilt angle may vary in the range of 0°–90°:

$$0^\circ \le \beta \le 90^\circ \quad (20)$$



a) Position of two tilted collectors   b) Solar collector configuration

Fig. 5. Solar collector field. a) Position of two tilted collectors b) Solar collector configuration.

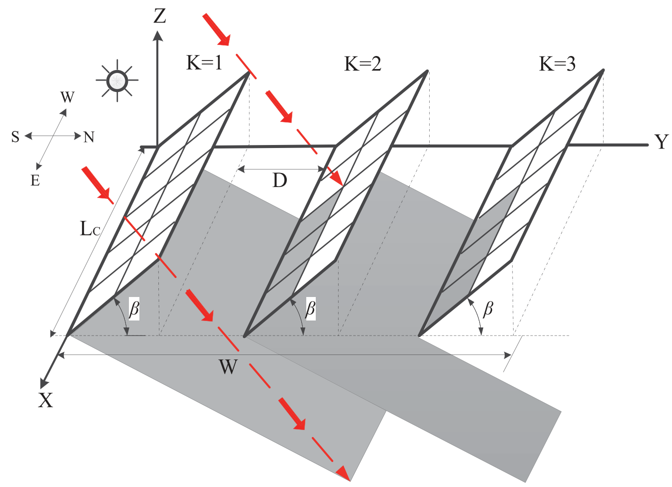


Fig. 6. Shading by collectors in a stationary solar field [9].

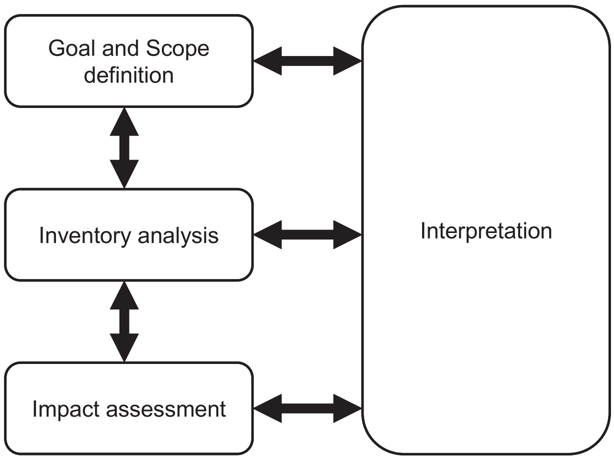


Fig. 8. Life Cycle Assessment framework.

- The number of collector rows of the configuration is less than or equal to 2 and discrete:

$$2 \leq K \in Z^{+} \tag{21}$$

3.2.2. Direct shading

In the case of large-scale solar plants, collectors are set in several rows and shading by neighbors may become inevitable. The shadow that is projected from a collector to another one varies throughout the day and can be determined geometrically [39,40].

The amount of shading depends on the distance between the collector rows D, their height H, the row length L_c, the tilt angle β and the latitude ϕ (see Fig. 6).

A status matrix is defined, $M(j,\ k,\ t,\ n)$, as follows in order to determine the shaded modules of the collector in a specific hour t and in a specific day n [28]:

$$M(j,k,t,n) = \begin{cases} 1 \text{ if module in column } j \text{ and row } k \text{ is unshaded at hour } t \text{ in day } n \\ 0 \text{ if module in column } j \text{ and row } k \text{ is shaded at hour } t \text{ in day } n \end{cases} \tag{22}$$

This matrix makes it possible to determine if a module receives solar irradiation during the whole day or only at given hours of the day. In addition, the status matrix assumes that any partially shaded module at a given time is considered as a fully shaded module.

3.2.3. Output energy of solar field

The output power of the modules in a row connected in series depends on three main factors: module efficiency (η), module temperature (T_m), and the number of shaded modules at a given time. The meteorological data at the specific site together with the geographical coordinates of the site allow calculating the power delivered by a module as a function of time.

$$Q_m(t) = \eta A G_\beta(t) \tag{23}$$

The module temperature was calculated according to Van Overstraeten et al. [13], eq. (24), and the loss of power due to temperature rises over 25 °C is taken into account in eq. (25) for the power delivered by a module at time t and day n:

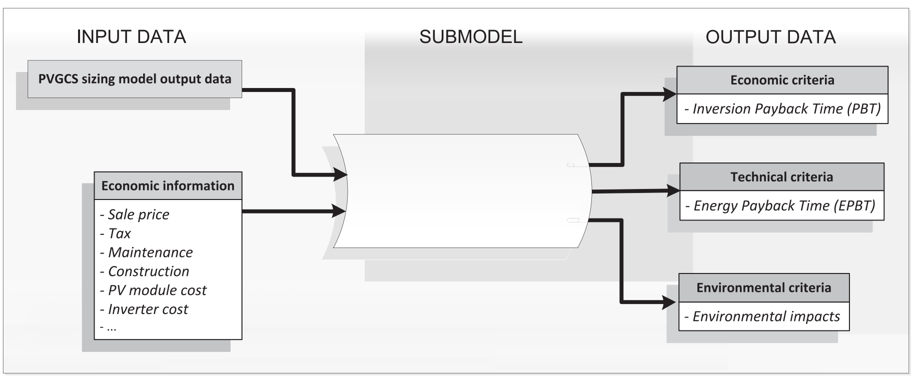


Fig. 7. Evaluation of criteria model.

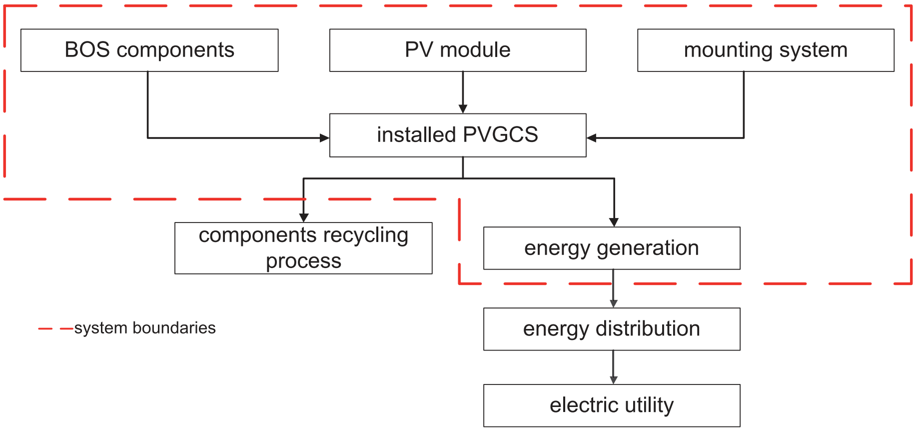


Fig. 9. Boundaries fixed for LCA in a PVGCS.

$$T_m(t) = 20 + 0.035 G_\beta(t) \tag{24}$$

$$Q_m(t,n) = \eta A G_\beta(t,n)[1 + T_k(T_m(t,n) - 25)] \tag{25}$$

The integration of eq (25) over a year predicts the annual energy produced by a module.

The yearly incident solar energy of the field is given by:

$$Q_{out} = N_r N_c \sum_{n=1}^{365} \sum_{t=1}^{24} Q_m(t,n) + (K-1) \sum_{n=1}^{365} \sum_{t=1}^{24} \sum_{k=1}^{N_r} \sum_{j=1}^{N_c} M(j,k,t,n) Q_m(t,n) \tag{26}$$

The first part of the equation (26) represents the energy produced by the unshaded first collector and the second part comprises the energy produced by the $K-1$ shaded collectors.

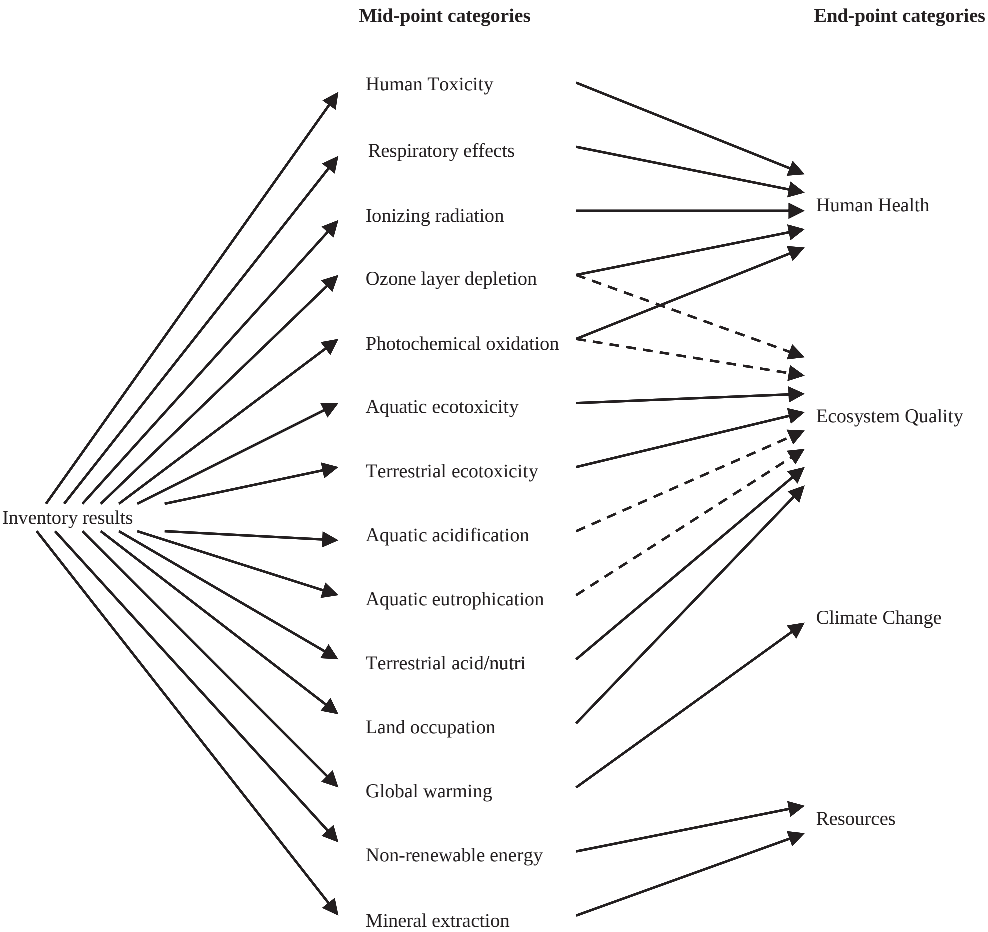


Fig. 10. IMPACT 2002+ framework: Mid-point and End-point categories [42].

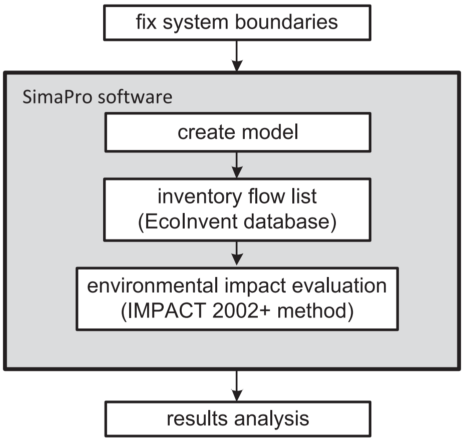


Fig. 11. Process for evaluate environmental criteria.

3.3. *Evaluation of criteria*

The third model of the integrated system is dedicated to the evaluation of the three criteria. For each criterion, a performance index was selected. These indexes will allow the evaluation and comparison of the resulting options. Fig. 7 summarizes the different elements required by this model.

3.3.1. *Techno-economic criteria*

The technical and economic criteria chosen in this study concern the *payback time of investment* and *energy payback time*, respectively. Their choice is summarized in the following.

In project evaluation and capital budgeting, the *payback time* (PBT) is an estimation of the time that will be necessary for an investor to recover the initial investment. It is used to compare investments that might have different initial capital requirements. It is calculated by the following expression:

$$\text{PBT} = \frac{\text{Cost of project}}{\text{Annual Cash Inflows}} \quad (27)$$

The cost of project considers all the components that make up the installation (PV modules, cables, mounting system…), the construction and the edification cost as well as the cost of connection to grid. Annual cash flow represents the income generated by selling all the energy produced.

Energy payback time (EPBT) is the time in which the input energy during the PV system life-cycle (which includes the energy requirement for manufacturing, installation, energy use during operation, and energy needed for decommissioning) is compensated by electricity generated by the PV system.

Table 2
Comparison between both approaches.

		K	B (°)	Q_{out} (kWh)
Maximum incident energy	WAP	58	24.62	2,641,034
	PB	58	24.62	3,201,915
Maximum output energy without energy loss	WAP	58	24.62	328,048
	PB	58	24.62	397,793
Maximum output energy with energy loss	WAP	57	21.33	268,000
	PB	57	21.26	327,338

A = Results of Weinstock and Appelbaum (WAP). PB = Results of our approach (PB model, Perez-Gallardo et al.).

Table 3
Typical features of various commercial PV modules technologies.

PV module	H_m (m)	W_m (m)	η (%)	T_k (%/°C)	Nominal power (W_p)
m-Si [43]	1.56	1.05	20.10	−0.380	327.00
p-Si [44]	1.64	0.94	15.50	−0.485	300.00
a-Si [45]	1.31	1.11	7.20	−0.200	105.00
CdTe [46]	1.20	0.60	11.50	−0.250	82.50
CIS [47]	1.26	0.98	12.20	−0.310	150.00

$$\text{EPBT} = \frac{\text{Primary energy required for manufacturing}}{\text{Annual primary energy produced}} \quad (28)$$

Primary energy required for manufacture is obtained as a result of a LCA study. It is reported into the *Non-renewable energy* category. The yearly energy produced is converted to annual primary energy produced. A conversion factor of 2.58 is used to transform 1 kWh electricity into primary energy [41].

3.3.2. *Environmental criteria*

Environmental assessment is performed following the methodology of Life Cycle Assessment (LCA) established by ISO-14040-44. LCA is a technique that characterizes and assesses the total environmental burdens associated with a product or a system, from raw materials acquisition to end-of-life management. This method compares the environmental damage of different products, processes or systems together, and analyses the different stages of the life cycle of a product. LCA provides support elements for industrial policies such as the choice of design and improvement of products or the selection of a production method, and is also interesting for public actions. According to the norms, LCA is divided into 4 parts (Fig. 8):

- *Goal and scope definition.* The objectives and scope of the study are described and a functional unit to which emissions and extractions are reported is established. The system boundaries are fixed;
- *Inventory analysis.* It involves creating an inventory of flows from and to nature. Inventory flows include inputs of water, energy and raw materials as well as emissions to air, water and soil. The input and output data needed for the construction of the inventory are collected for all activities within the system boundary;

Table 4
Results obtained for the best configuration that maximizes the output energy of the system.

PV module	β (°)	K	D (m)	Yearly Q_{out} (kWh)
m-Si	18.42	55	0.84	430,397
p-Si	21.22	60	0.80	328,453
a-Si	17.01	54	0.81	131,021
CdTe	34.86	78	0.80	227,324
CIS	19.73	56	0.88	225,536

Table 5
PBT and EPBT for each configuration.

PV module	EPBT (yr)	PBT (yr)
m-Si	2.36	5.90
p-Si	2.67	7.59
a-Si	2.04	7.59
CdTe	1.77	9.23
CIS	2.14	6.29

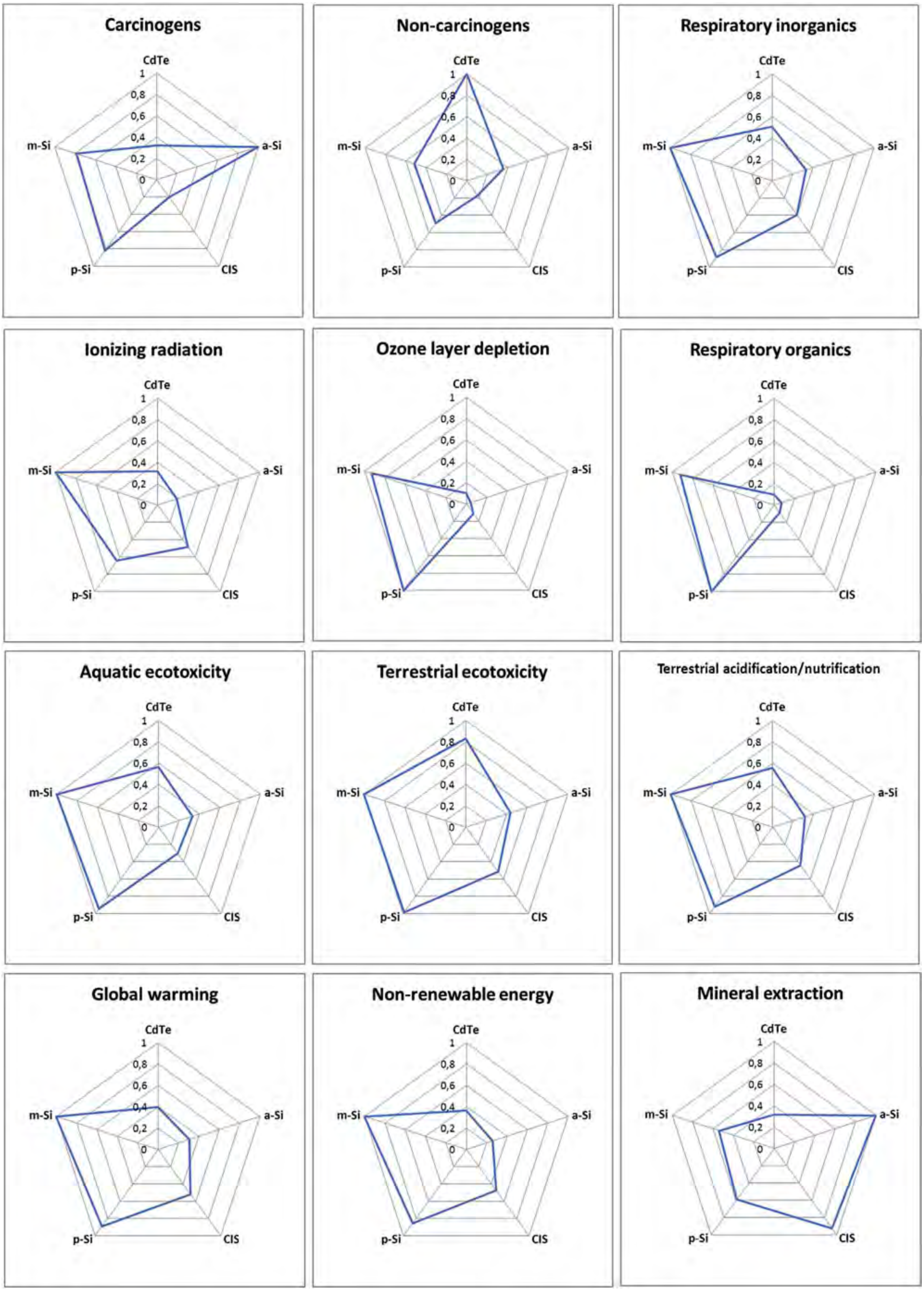


Fig. 12. Results of the environmental impacts normalized to unity.

- *Impact assessment.* It consists to assess the potential environmental impacts based on the inventory made in the previous phase;
- *Interpretation of results.* Based on the results of the impact assessment, it is possible to establish a set of conclusions and recommendations for the study.

Following the guidelines indicated by the LCA methodology for environmental impact analysis for PVGCS, the first step is to set the boundaries of the system under analysis. Fig. 9 illustrates a simplified PVGCS with the boundaries fixed in order to apply the LCA methodology. It must be emphasized that a thorough application of an LCA methodology would require to take into account the recycling phase of the PV panels. Hence, this issue suffers from a lack of data for all PV technologies. This explains mainly why it was not included in the environmental assessment and is an area that merits further exploration.

The software tool SimaPro 7.3 was used here for modeling the system under analysis and the calculation of environmental impacts. This program involves the Ecoinvent database that allows determining the flow of materials, energy and emissions in order to make the inventory flow list of the system. Ecoinvent has over 4000 industrial process databases in different sectors such as energy, transport, building materials, chemicals, washing agents, paper & board, agriculture and waste management.

IMPACT 2002+ [42], included in SimaPro 7.3, was selected as a method for evaluating the environmental impacts. This method proposes a feasible implementation of a combined midpoint/damage approach linking the environmental evaluation results of the inventory flow list via 14 midpoint categories which can then be regrouped into four damage categories (Fig. 10). Midpoint/damage approach performs environmental impact assessment of a process at relatively early stages in the cause-effect chain (midpoint categories) and as far back as possible in the cause-effect chain (damages categories). All midpoint scores are expressed in units of a reference substance and related to the four damage categories.

The impacts grouped into the midpoint categories of different flows of material, energy and emission involved in the manufacturing and commissioning of the plant are obtained from the characterization factors determined by the method selected as follows (eq. (29)):

$$SI_i = \sum_S FI_{s,i} \times M_S \tag{29}$$

where SI_i represents the characterization score for the impact category i, $FI_{s,i}$ is the characterization factor for the substance S in the impact category i, and M_s is the mass of substances from the different flows.

Fig. 11 summarizes the process followed to evaluate the environmental impacts generated by a PVGCS.

3.4. Decision variables

The optimization is performed here in a mono-objective mode. The technique adopted is a genetic algorithm to facilitate its extension to a multi-objective mode. The decision variables that are used are the same as indicated in the mathematical model (β, D, K, H).

4. Optimization of annual energy output

The example given by Weinstock and Appelbaum [28] (referred as WAP in the following) is used to validate the relevance of the proposed approach. The maximization of annual energy generation by the facility is the objective function. In all cases, the same geographical position (Tel Aviv), the same type of PV module and the available surface are considered. The same limitations as those used for the WAP example are used: minimum space between collector rows (D_{min}) equal to 0.80 m, maximum collector height (H_{max}) equal to 1.98 m and height of collector above the ground (E_{max}) equal to 1.80 m. The technology of the panel used in the WAP study is not mentioned explicitly but the computation is performed with the assumption of a 12% efficiency. The GA parameters are the following ones: number of generations equal to 200; crossover rate of 0.90 and mutation rate of 0.50. Table 2 shows the comparison between the results obtained by our approach and the WAP example [28].

In order to verify the relevance of our model, the same criteria as those used in the approach proposed by Weinstock and Appelbaum [28] were used in the optimization procedure. They involve respectively the maximum solar incident energy of the field without any type of energy losses, then the maximum output energy of the PVGCS at the incident irradiance only considering the module efficiency and shading, and finally the maximum output energy of the PVGCS while accounting all possible energy losses.

Table 2 shows that a good agreement is obtained between both models. Not surprisingly, the difference in the amount of output power for the three cases is mainly due to the improvement in the computation of irradiance received at the facility as presented in Section 3.2.1.

Optimization runs were then performed for different types of solar panel technology. In the simulations, only one technology is assumed per field which means that no mixed technologies are allowed. In what follows, the maximum output energy, taking into account all possible energy losses, was considered as an objective function. Table 3 provides information for five different PV commercial module technologies that were tested: monocrystalline silicon (m-Si), polycrystalline silicon (p-Si), amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium diselenide (CIS).

The best configuration for maximizing the output energy of the field was searched for in each PV module technology (Table 4). The location, assumptions and constraints for the new set of optimizations are the same as in the previous case. The GA parameters are the following ones: number of generations equal to 200; crossover rate of 0.90 and mutation rate of 0.50.

The results suggest that the configuration using PV modules based on m-Si generates the highest amount of annual energy under the conditions given in the case studied.

The result of the evaluation of PBT and EPBT for each configuration (Table 5) shows that the lowest EPBT is achieved by using PV modules based on CdTe but this technology does not lead to the lowest PBT value. Even though the m-Si PV module generates the maximum output energy, its EPBT is high due to the amount of energy required during the manufacturing phase.

The results of the environmental impact assessment (12 main midpoint categories) for each configuration are shown in Fig. 12 by the use of radar charts. To facilitate the comparison, normalization was performed by assigning the value 1 to the maximum value of

Table 6
Final ranking of alternatives.

PV module	Final weighted evaluation	Ranking
CdTe	40	3
a-Si	32	1
CIS	36	2
p-Si	58	4
m-Si	58	4

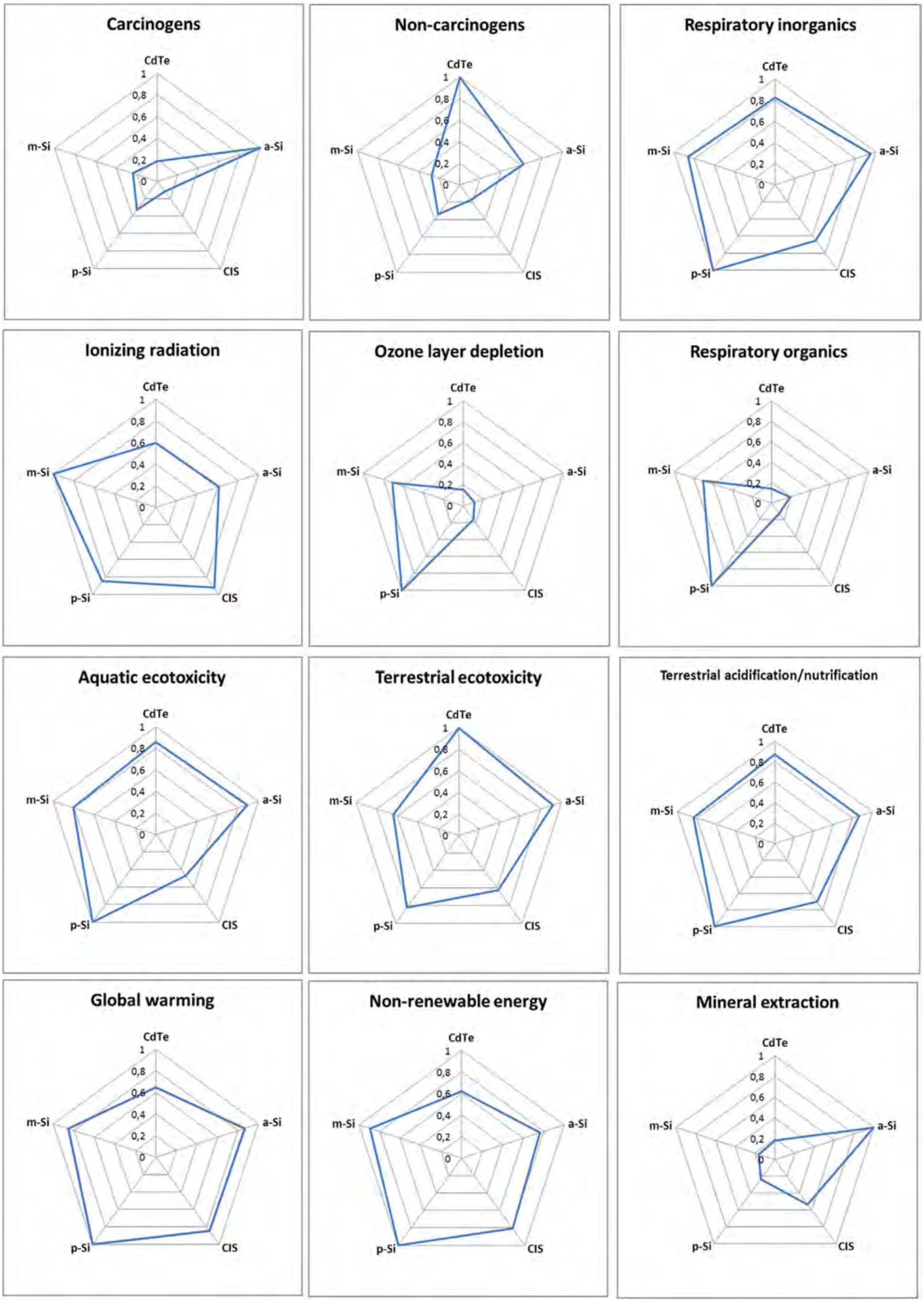


Fig. 13. Results of the environmental impacts per annual energy generated ratio normalized to unity.

Table 7
Final ranking of alternatives (environmental impact per kWh produced).

PV module	Final weighted evaluation	Ranking
CdTe	39	2
a-Si	47	4
CIS	30	1
p-Si	63	5
m-Si	45	3

each category. The computed relative impacts represent the ratio between the environmental impact and this maximum value.

The result analysis shows that among seven of the 12 categories, the highest impacts occur when m-Si technology is used to build the PV power plant e.g. in *Global Warming* category, where the CO_2 in the air is the reference flow, the installation with PV modules based on m-Si, generates more kg of CO_2 after the characterization of all inventory flows. Likewise, for the *Non-renewable Energy* category, the most MJ of non-renewable primary energy consumed by the entire process evaluated within the boundaries set for the LCA study was found at installations with m-Si based PV modules. In spite of its low EPBT, the solar plant with CdTe modules has a significant impact within the category of *Non-carcinogens*, i.e., the characterization of the different flows in the inventory for CdTe module installation results in a large amount of chloroethylene C_2H_3Cl into the air, a substance that affects human health. The potential consequence is not related with carcinogenic effects.

To select the best compromise among the five alternatives proposed by our model relative to the set of possibilities, a weighted evaluation is performed for the 15 goals (maximizing final energy generation output, minimizing PBT, minimizing EPBT and minimizing 12 environmental impacts). First, a classification for each solar plant configuration at each goal was made giving a value of 1 to the choice that best meets the objective and 5 the worst. The value assigned to each choice in a given goal is multiplied by a weighting factor. This factor depends on the importance of each of the goal for the person responsible for making the final choice. An equal factor was assigned to the 15 goals. Then, the scores obtained by each alternative are added to give a cumulative score. As can be seen in Table 6, the alternative with the lowest total score is the a-Si technology.

Another analysis is then performed taking into account the energy generated by each configuration. This new analysis consists in assessing the environmental impact per kWh produced, as follows:

$$\text{index} = \frac{SI_i}{Q_{out}} \quad (30)$$

The weighting factor is the same for all objectives. The results are presented through radar charts normalized to unity (Fig. 13). It can be highlighted that the PV technology with the higher ratio is the one based on p-Si modules (7 of 12 categories). Although the environmental impacts of m-Si based technology are higher, these are offset by the large amounts of energy generated annually.

The same weighted evaluation is made for this analysis and the results are reported in Table 7. The CIS PV module technology best meets the objectives.

Reviewing the results obtained from the weighted evaluation in Tables 6 and 7, if all criteria have the same weights, the conversion efficiency of PV module takes an important role depending on the form of the evaluation of the environmental categories. It may serve as a mitigating circumstance to the values reported for the different environmental categories. e.g. the alternative based on a-Si PV module proved to be the best trade-off for all the objectives considered when only the results obtained from the LCA study is taken into account but it falls to fourth position if these values are divided by the amount of energy produced. Table 7 shows that the configuration with m-Si has a better performance than p-Si for silicon-based PV modules even if they have the highest impacts in almost all environmental categories in Fig. 12. The configuration with CIS and CdTe has the best trade-off in both cases. Further work would now consist in encompassing PV recycling in the LCA step in order to study if the same trend is observed.

5. Conclusions

The goal of the present work was to develop a new approach for generating alternative configurations of PV power plant by adding an environmental assessment to the traditional way of determining the optimum PV power plant configuration. An integrated framework based on a PVGCS sizing simulator involving the computation of solar irradiance coupled to an outer optimization loop was thus designed and tested.

Our approach was applied to the maximization of annual energy generation by the facility as the objective function. The analysis was carried out for different types of solar panel technology, with only one technology assumed per field: monocrystalline silicon (m-Si), polycrystalline silicon (p-Si), amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium diselenide (CIS). The environmental impact assessment was achieved by use of the IMPACT 2002+ method embedded in the SimaPro software tool with Ecoinvent database. The 12 main midpoint impact categories were computed for each configuration as well as PBT and EPBT. The result analysis shows that among seven of the 12 environmental categories, the highest impacts occur when m-Si and p-Si technologies are used. Despite a low EPBT value, CdTe modules have a significant impact within the category of *Non-carcinogens*.

To select the best compromise among the five options proposed by our model, a weighted evaluation was then performed on all criteria in order to obtain a score for each technology. The alternative with the lowest total score was the a-Si technology. A similar analysis was then performed by taking into account the environmental impacts per kWh produced as new criteria. In this case, the CIS PV module technology best meets the objectives.

Finally, this investigation highlighted that the early design stage of PVGCS should take into account not only economic performance but also the environmental impacts as those proposed in LCA methodology. The proposed framework is now extended to the multi-objective optimization case by considering simultaneously the conflicting criteria. For this purpose, the selection of GAs will facilitate an easy extension to a multi-criteria investigation, as already carried out in previous investigations [32]. Another suggestion is to extend the system boundaries to consider the recycling phase of the module.

Nomenclature

A	PV module area, m^2
D	distance between collector rows, m
D_{min}	minimum distance between collector rows, m
E	equation of time, min
E_{max}	maximum collector height above ground, m
$FI_{s,i}$	characterization factor
G_o	extraterrestrial irradiance, W/m^2
G_{on}	normal extraterrestrial irradiance, W/m^2
G	global irradiance, W/m^2
G_b	beam irradiance, W/m^2
G_d	diffuse irradiance, W/m^2
G_β	global irradiance onto PV module tilted, W/m^2

$G_{\beta,b}$	beam irradiance onto PV module tilted, W/m^2
$G_{\beta,d}$	diffuse irradiance onto PV module tilted, W/m^2
$G_{\beta,r}$	reflected irradiance onto PV module tilted, W/m^2
H	collector height, m
H_m	PV module height, m
H_{max}	maximum collector height, m
I	global irradiation for an hour, Wh/m^2
K	number of solar collector rows
L	solar field length, m
L_c	collector length, m
L_m	PV module length, m
Lon_{Loc}	longitude of the location
LST	local solar time
LSTM	local standard time meridian
$M_{j,k,t,n}$	status matrix of unshaded modules in a collector
M_s	mass of substance from the energy, material or emission flow
n	day number; 1–365
N_c	number of PV modules columns in the collector
$N_{c,max}$	maximum number of PV modules columns in the collector
$N_{c\ min}$	minimum number of PV modules columns in the collector
N_r	number of PV modules rows in the collector
$N_{r\ max}$	maximum number of PV modules rows in the collector
$P_{i\ max}$	inverter maximum power, W
$P_{m\ max}$	PV module's maximum output power at MPP, W
Q_m	PV module's output energy, kWh
Q_{out}	yearly output energy of the field, kWh
SI_i	characterization score for the impact category
ST	solar time
t	hour number, 1–24
T_k	temperature coefficient for nominal power, %/°C
T_m	PV module temperature, °C
$V_{i\ max}$	maximum voltage level of the AC/DC converter, V
$V_{i\ min}$	minimum voltage level of the AC/DC converter, V
$V_{m\ mpp}$	voltage at the PV module's maximum power point, V
$V_{m\ oc}$	PV module's open circuit voltage, V
W	solar field width, m
Z^+	positive natural number set
α	sun elevation angle, degree
β	collector inclination angle, degree
ϕ	latitude, degree

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