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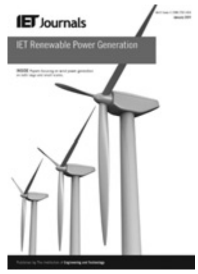

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Methodology for the design optimisation and the economic analysis of grid-connected photovoltaic systems

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Abstract: In this study, a methodology for the design optimisation and the economic analysis of photovoltaic grid-connected systems (PVGCSs) is presented. The purpose of the proposed methodology is to suggest, among a list of commercially available system devices, the optimal number and type of system devices and the optimal values of the photovoltaic (PV) module installation details, such that the total net economic benefit achieved during the system operational lifetime period is maximised. The decision variables included in the optimisation process are the optimal number and type of the PV modules and the DC/AC converters, the PV modules optimal tilt angle, the optimal arrangement of the PV modules within the available installation area and the optimal distribution of the PV modules among the DC/AC converters. The economic viability of the resulting PVGCS configuration is explored according to the net present value, the discounted payback period and the internal rate of return methods. The proposed method has been applied for the optimal design of a PVGCS interconnected to the electric network of an island with significant solar irradiation potential and the corresponding optimal sizing and economic analysis results are presented.

Nomenclature

B	total length of the metallic rods required for the installation of the entire PVGCS
B_1	total length of the metallic rods required to construct the metallic frames of a vertical line
B_2	total number of the intermediate vertical rods of each side of a vertical line
B_B	total volume of the concrete foundation bases required to support the PVGCS PV module metallic mounting frames
B_{tot}	total length of the vertical rods of each side of a vertical line
C_O	selling price of the PVGCS generated energy
C_B	total manufacturing and installation cost of the PVGCS mounting structures
$C_c(\boldsymbol{x})$	total capital
C_{INV}	capital cost of each DC/AC converter
C_L	cost of purchasing the required installation area
$C_m(\boldsymbol{x})$	maintenance cost
C_{PV}	capital cost of each PV module
c_B	per unit volume cost of the concrete foundation bases
c_l	cost of the installation land per unit area
c_S	per unit length cost of the metallic rods
D_1	southern dimension of the actual installation area
D_2	western dimension of the actual installation area
DIM_1	southern dimension of the total available installation area
DIM_2	western dimension of the total available installation area
d	day
E_{tot}	total annual energy injected to the electric grid by each PV module
$\mathrm{FF}^d(t, \beta)$	fill factor

F_y	distance required between adjacent rows
$G^d(t, \beta)$	global irradiance incident on the PV module placed at tilt angle β^o
g	annual inflation rate
H_1	maximum height of a PV module tilted at an angle equal to β^o
H_T	maximum height of each row
h_w	concrete foundation base height
IRR	internal rate of return
$I_{SC,STC}$	PV module short-circuit current under STC
$I_{SC}^d(t, \beta)$	PV module short-circuit current
i	nominal annual discount rate
$J(\boldsymbol{x})$	PVGCS total net profit function
K_I	short-circuit current temperature coefficient
K_V	open-circuit voltage temperature coefficient
k^*	year numbers that the DC/AC converters must be repaired
L_{pv1}	length of each PV module
L_{pv2}	width of each PV module
L_T	total length of each row
M_{INV}	annual maintenance cost per unit of the DC/AC converters
M_{PV}	annual maintenance cost per unit of the PV modules
MTBF	mean time between failures of the DC/AC converters
N_1	PVGCS total number of PV modules
N_2	number of lines per row
N_{block}	maximum possible number of PV modules allocated to each DC/AC converter
NCOT	nominal cell operating temperature
N_{dc}	the PVGCS total number of DC/AC converters
N_p	parallel branches of PV modules
N_{p1}	parallel branches of PV modules connected to a single DC/AC converter
N_{pmax}	maximum number of the PV modules parallel branches connected to each DC/AC converter
NPV	net present value
N_r	the number of DC/AC converters repairs which must be performed during the PVGCS lifetime
N_{row}	total number of rows comprising the PVGCS installation
N_s	PV modules connected in series
N_{s1}	PV modules connected in series to a single DC/AC converter
N_{ser}	number of PV modules installed in each row
N_{sermin}	number of PV modules installed in each line
N_{smax}	maximum number of PV modules which can be connected in series in each branch
N_{smin}	minimum number of PV modules which can be connected in series in each branch
n^*	discounted payback period
n_b	total number of vertical lines comprising the PVGCS installation
n_{INV}	DC/AC inverter power conversion efficiency
n_{MPPT}	conversion factor indicating the accuracy of the MPP tracking operation performed by the DC/AC converter
n_t	maximum number of PV modules which can be installed within a line
$P_E(\boldsymbol{x})$	total profits achieved from selling the produced energy to the electric grid during the system operational lifetime period
$P_M^d(t, \beta)$	maximum output power of a PV module on day d ($1 \leq d \leq 365$) and at hour t ($1 \leq t \leq 24$)
P_{max}	DC/AC converter DC input nominal power rating
$P_{M,max}$	maximum possible PV module output power level at the MPP
p_{bm}	boundary mutation probability
p_{num}	non-uniform mutation probability
p_{sac}	simple arithmetical crossover initial probability
p_{sc}	simple crossover probability
p_{um}	uniform mutation probability
p_{wac}	whole arithmetical crossover initial probability
R_{cost}	repair cost of each DC/AC converter
R_{TC}	present value of the total cost of repairing the DC/AC converters
round_up($\cdot$)	ceiling function
round_down($\cdot$)	floor function
SF	over-sizing factor
s	capital subsidisation rate
$T_A^d(t)$	ambient temperature
t	hour
t_w	concrete foundation base thickness
V_{imax}	maximum permissible DC/AC converter input voltage levels
V_{imin}	minimum permissible DC/AC converter input voltage level
$V_{M,min}$	minimum voltage at the MPP
V_{ocmax}	maximum open-circuit voltage at the maximum power point (MPP)
$V_{OC,STC}$	open-circuit voltage under STC
$V_{OC}^d(t)$	open-circuit voltage
W_1	width of the area covered by a PV module tilted at an angle of β^o
W_T	area occupied by each row of PV modules

$\boldsymbol{x}$	vector of the decision variables
x_i	number of DC/AC converters each comprised of N_{block} PV modules
y	number of PV modules ($0 \le y < N_{\text{block}}$), connected to a single DC/AC converter
Δt	simulation time step
β	tilt angle
δ	solar declination angle
φ	installation area latitude
ω	solar hour angle

1 Introduction

The continuously increasing electric energy demands the significant rise of the oil price and the decrement of the fossil fuel reserves, combined with the environmental pollution caused by the conventional, thermal electric energy generating units has led to a worldwide concern on the development of alternative electric energy production methods. Aiming towards the achievement of this goal, the photovoltaic grid-connected systems (PVGCSs) are widely used in order to inject the energy produced by photovoltaic (PV) modules to the electric grid. The installation of PVGCSs by private investors is frequently supported in many countries by means of subsidisation of the corresponding investment capital cost. In this case, the main target of the PVGCS design is the maximisation of the total economic benefit achieved by selling the PV generated energy to the electric grid.

The block diagram of a generalised PVGCS is shown in Fig. 1. Several DC/AC converters (inverters) are used to interface the DC output voltage of PV modules to the electric grid AC requirements. A PV array is connected to the DC input of each DC/AC converter, consisting of a number of parallel branches of PV modules, while each branch is comprised of several PV modules connected in series. Typically, the DC/AC converters employ a maximum power point tracking (MPPT) operation in order to extract the maximum available power from the PV power sources.

The impact of the PV array surface inclination and orientation on the PVGCS power production was investigated in [1] using the TRNSYS simulation platform. The optimal value of the PVGCS sizing ratio, which is defined as the quotient of the PV array total nominal power capability to the DC/AC converter nominal power rating, was investigated in [2] using the TRNSYS simulation tool for various system components costs and incident solar irradiation scenarios. The optimal PVGCS sizing ratio value, which minimises the total system cost, is highly affected by both, the installation site solar irradiation conditions and the DC/AC converter efficiency. The PVGCS sizing ratio optimisation, targeting to minimise the total system cost, has also been investigated in [3], based on numerical simulations of the system operation for several locations in Finland, Denmark, Italy and USA. It has been figured out that the optimal sizing ratio value depends on the DC/AC converter operational characteristics, the PV array orientation and the PVGCS components (PV modules and DC/AC converters) costs. An economic analysis based on simulations for the selected sites indicated that an optimal sizing ratio value ranging from 1.2 to 1.5 is widely applicable as a cost-effective solution for the majority of the systems simulated.

A cost analysis of PVGCSs is performed in [4] for several European countries. It is concluded that the main factors influencing the economic viability of the grid-connected PV systems are the initial capital cost of the system, the feed-in tariff and the PVGCS capital cost subsidisation rate.

Methods for computing the net present value (NPV) and the internal rate of return (IRR) of an investment on PVGCSs are proposed in [5, 6], taking into account the cash inflows and the life-cycle expenses. A method for the economic and environmental analysis of PVGCSs is presented in [7]. The economic analysis is based on the computation of the NPV and the discounted payback period. The environmental analysis is performed by computing the pollutant emission reduction achieved by using the PVGCS.

The effect of the PVGCS configuration on the system economic profitability is explored in [8]. Depending on the available solar irradiation conditions and the operational characteristics of the PV modules and the DC/AC converters, the economic benefit achieved during the PVGCS operation is highly altered if a single DC/AC converter of high-power rating or multiple DC/AC converters of low-power capability and lower cost are used to implement the PVGCS.

A design methodology for the PVGCSs optimal sizing and spatial allocation in distribution feeders is proposed in [9]. This methodology achieves the best compromise between technical and economic goals using a multi-objective optimisation approach. The technical objectives are related to the voltage stability and the quality of the power provided by the feeder, because of the stochastic PV energy production variation, which depends on the weather conditions. The economic objectives are related to the PVGCS economic profitability, which is evaluated according to the cash inflows achieved by selling the produced energy to the electric network, the system maintenance cost and the cost of the feeder power losses.

A methodology for the optimal selection of the PVGCS installation site is presented in [10]. The optimal installation site of the PVGCSs is determined by combining multi-criteria analysis and an analytic hierarchy process with geographical information systems (GIS)

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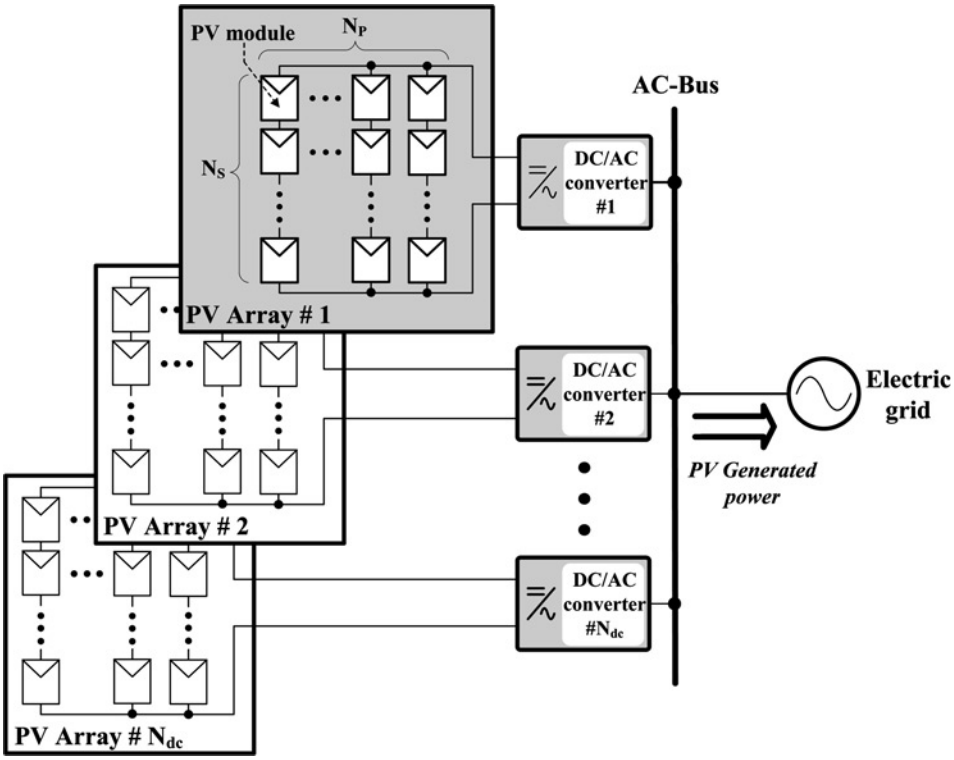

Figure 1 *Block diagram of a generalised PVGCS*

technology, taking into account environmental, topographic and climate factors.

Common disadvantage of the PVGCS design methods described above is that the proposed methods do not take into account one or more of important PVGCS design aspects, which can highly influence the total economic benefit achieved by performing this type of investment, such as the operational and economical differences between various PV module and DC/AC converter types, the PV modules tilt angle, the cost of the land required to install the PVGCS and the cost of the PV modules mounting structures. Additionally, the optimisation methodologies implemented are usually based on linear programming techniques, which do not guarantee convergence to the global optimal solution without highly increased computational efforts.

In this paper, a methodology for the optimal design of PVGCSs is presented. The purpose of the proposed methodology is to suggest, among a list of commercially available system devices, the optimal number and type of the PV modules and the DC/AC converters, the PV modules optimal tilt angle, the optimal arrangement of the PV modules within the available installation area and the optimal distribution of the PV modules among the DC/AC converters, such that the total net economic benefit achieved during the system operational lifetime period is maximised. The total net economic benefit achieved is equal to the difference between the profits achieved from selling the produced energy to the electric grid and the total expenses during the PVGCS operational lifetime period. The PVGCS total expenses are calculated according to the capital and the maintenance costs of the PVGCS components (PV modules and DC/AC converters), the cost of the land where the target PVGCS will be installed and the cost of the PV module mounting structures. The maximisation of the total net profits function (objective function) is implemented using genetic algorithms (GAs). Compared to conventional optimisation methods, such as the dynamic programming and the gradient techniques, the GAs have the ability to calculate the global optimal solution with relative computational simplicity even in the case of complicated problems with non-linear cost functions or non-linear constraints, because of the probabilistic production of the potential optimal solutions.

2 The proposed methodology

The block diagram of the proposed methodology is shown in Fig. 2. A database containing the technical characteristics of commercially available PV modules and DC/AC converters, combined with their associated per unit capital and annual maintenance costs, is input to the optimisation algorithm. The input database is implemented in the form of text files for easier maintenance.

At the first step of the optimal sizing procedure it is examined whether a PVGCS configuration, defined by the

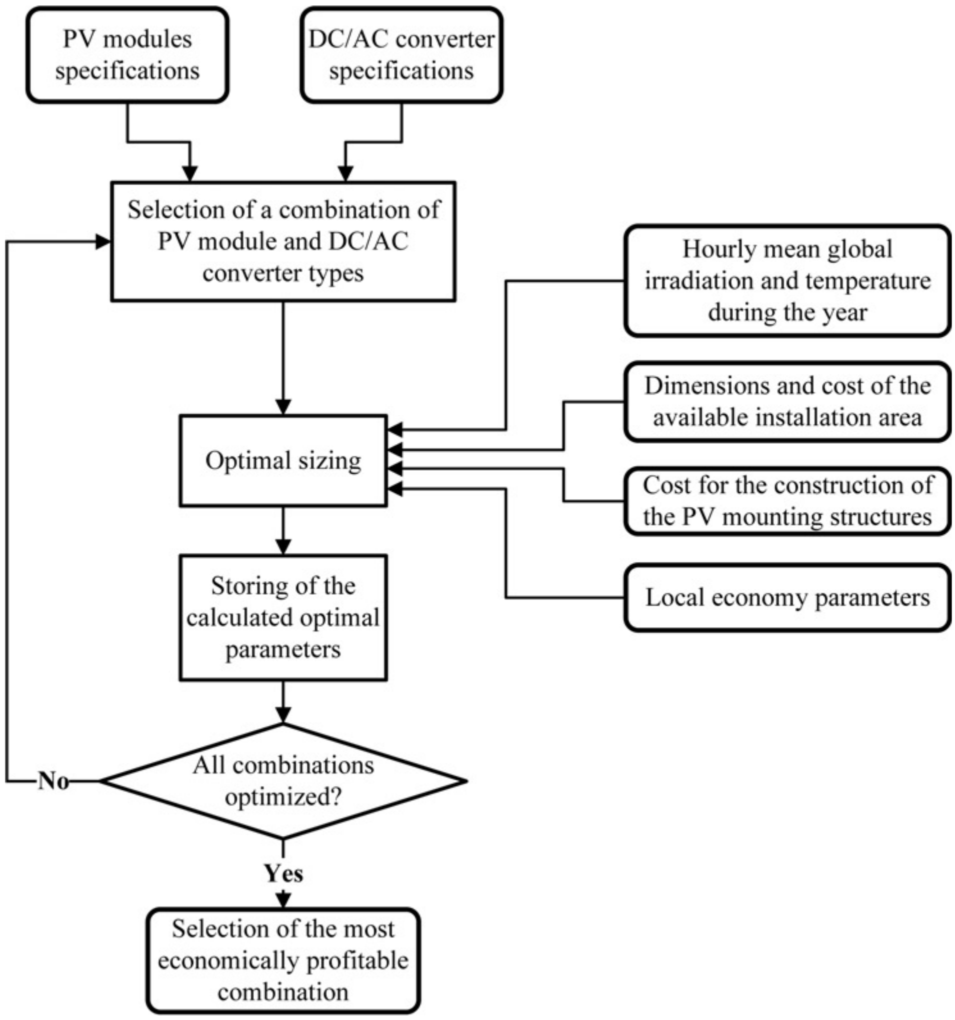

Figure 2 *Flowchart of the proposed optimisation methodology*

total number of the PVGCS PV modules and the PV module installation details, satisfies the available installation area dimension limitations, while simultaneously guarantees the feasible allocation of the available PV modules among the DC/AC converters according to the technical constraints imposed by the PV modules and the DC/AC converters specifications.

The second step of the optimal sizing procedure consists of a GA-based optimisation procedure, which dynamically searches for the PVGCS configuration, which subject to the criterion set in the first step, maximises the PVGCS total net profits achieved during the system operational lifetime period. The data used in this case are the hourly solar irradiation and ambient temperature values during the year. The yearly PVGCS energy production and the corresponding cash inflows resulting from the generated electric energy purchase to the electric grid are calculated by simulating the system operation for a 1 year time period. For each combination of input system device types, the optimal sizing procedure is performed computing the corresponding optimal total net profit and the corresponding optimal configuration of the input devices. After all device-type combinations have been optimally sized, the combination achieving the highest net profit during the PVGCS operational lifetime period and the corresponding input device types comprising this system is displayed as the overall optimal PVGCS structure.

3 The PVGCS modelling

In the proposed methodology it is assumed that all of the energy produced by the PVGCS PV modules is supplied to the electric grid and it is calculated on an hourly basis for a 1 year time period. The calculated annual PVGCS energy production is constant during all years of the system total operational lifetime period.

The current–voltage and power–voltage characteristics of a PV module are shown in Fig. 3. The maximum output power of a PV module on day $d(1 \le d \le 365)$ and at hour $t(1 \le t \le 24)$, $P_{\mathrm{M}}^{d}(t, \beta)$(W), is calculated using the specifications of the PV module under standard test conditions (STC, cell temperature $= 25°\mathrm{C}$ and solar irradiance $= 1\ \mathrm{kW/m^2}$), provided by the manufacturer, as well as the solar irradiation and ambient temperature

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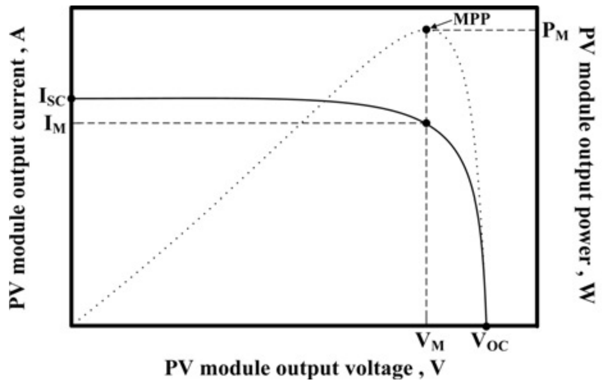

Figure 3 *PV module current–voltage and power–voltage characteristics*

conditions, according to the following equations

$$P_M^d(t, \beta) = V_{OC}^d(t) I_{SC}^d(t, \beta) FF^d(t, \beta) \quad (1)$$

$$I_{SC}^d(t, \beta) = \{I_{SC,STC} + K_I[T_C^d(t) - 25°C]\} \frac{G^d(t, \beta)}{1000\,W/m^2} \quad (2)$$

$$V_{OC}^d(t) = V_{OC,STC} + K_V[T_C^d(t) - 25°C] \quad (3)$$

$$T_C^d(t) = T_A^d(t) + \frac{NCOT - 20°C}{800\,W/m^2} G^d(t, \beta) \quad (4)$$

where $I_{SC}^d(t, \beta)$ is the PV module short-circuit current (A), $V_{OC}^d(t)$ is the open-circuit voltage (V), $I_{SC,STC}$ is the PV module short-circuit current under STC (A), $G^d(t, \beta)$ is the global irradiance (W/m^2) incident on the PV module placed at tilt angle β^o, K_I is the short-circuit current temperature coefficient (A/°C), $V_{OC,STC}$ is the open-circuit voltage under STC (V), K_V is the open-circuit voltage temperature coefficient (V/°C), $T_A^d(t)$ is the ambient temperature (°C), NCOT is the nominal cell operating temperature (°C), provided by the PV module manufacturer and $FF^d(t, \beta)$ is the fill factor [11].

The value of $G^d(t, \beta)$ is calculated using the daily solar irradiation on the horizontal plane as analysed in [12]. The PV modules tilt angle, β(°), is constant during the year. As shown in Fig. 1, each PV array connected to a DC/AC converter consists of N_p parallel branches of PV modules ($N_p \geq 1$), while each branch is comprised of N_s PV modules connected in series ($N_s \geq 1$). The minimum and the maximum number of PV modules that can be connected in series in each branch, N_{smin} and N_{smax}, respectively, is calculated according to the DC/AC converter DC input voltage range, as follows

$$N_{smin} = \text{round\_up}\left(\frac{V_{imin}}{V_{M,min}}\right) \quad (5)$$

$$N_{smax} = \text{round\_down}\left(\frac{V_{imax}}{V_{ocmax}}\right) \quad (6)$$

where round_up(·) and round_down(·) are the ceiling and floor functions, respectively, V_{imin} and V_{imax} are the minimum and the maximum, respectively, permissible DC/AC converter input voltage levels (V), specified by the DC/AC converter manufacturer and V_{ocmax} and $V_{M,min}$ are the maximum open-circuit voltage (V) and the minimum voltage (V) at the maximum power point (MPP), respectively, which can be developed at the PV module output terminals according to the incident solar irradiation and ambient temperature conditions prevailing at the PVGCS installation site.

Initially, the value of N_s is set equal to N_{smax} in order to reduce the power loss on the cables which connect the PV modules to the DC/AC converter. However, in case that the resulting power generated by each string is higher than the DC/AC converter DC input nominal power rating, P_{max} (W), then the value of N_s is progressively reduced by one until the following conditions are satisfied

$$N_{smin} \leq N_s \leq \frac{P_{max}}{P_{M,max}} \quad (7)$$

where $P_{M,max}$ (W) is the maximum possible PV module output power level at the MPP according to the incident solar irradiation and ambient temperature conditions prevailing at the PVGCS installation site.

The maximum number of the PV modules parallel branches connected to each DC/AC converter, N_{pmax}, depends on the PV modules and the DC/AC converter nominal power ratings and it is calculated using the following equation

$$N_{pmax} = \text{round\_down}\left(\frac{P_{max}}{N_s P_{M,max}}\right) \quad (8)$$

In order to fully exploit the power capability of each DC/AC converter, thus reducing the total system cost since the total number of DC/AC converters required is minimised, the maximum possible number of PV modules, N_{block}, is allocated to each DC/AC converter

$$N_{block} = N_s N_p = N_s N_{pmax} \quad (9)$$

The PVGCS total number of PV modules, N_1, are connected to x_i DC/AC converters in blocks, each comprised of N_{block} PV modules, while the rest of the available PV modules, $y(0 \leq y < N_{block})$, are connected to a single DC/AC converter

$$N_1 = x_i N_{block} + y \quad (10)$$

The y available PV modules, which are connected to a single DC/AC converter, are arranged in N_{p1} parallel branches, each comprised of N_{s1} PV modules connected in series

$$y = N_{p1} N_{s1} \quad (11)$$

The values of N_{p1} and N_{s1} are computed subject to the following limitations, which ensure that the DC/AC converter input voltage requirements are satisfied

$$N_{\text{smin}} \le N_{s1} \le N_{\text{smax}} \tag{12}$$

$$1 \le N_{p1} \le N_{\text{pmax}} \tag{13}$$

$$N_{\text{smin}} \le y < N_{\text{block}} \tag{14}$$

The PVGCS total number of DC/AC converters, N_{dc}, is calculated as follows

$$N_{\text{dc}} = \begin{cases} x_i + 1 & \text{if} \quad y > 0 \\ x_i & \text{if} \quad y = 0 \end{cases} \tag{15}$$

In the proposed methodology, it is assumed that the available installation area shape is rectangular, facing south. The PV modules are arranged within the available installation area in multiple rows, where each row is comprised of multiple lines, as illustrated in Fig. 4. The width, W_{T}(m), of the area occupied by each row is calculated according to the following equations

$$W_{\text{T}} = W_1 N_2 \tag{16}$$

$$W_1 = L_{\text{pv2}} \cos \beta \tag{17}$$

where N_2 is the number of lines per row ($0 < N_2 \le N_1$), $W_1(m)$ is the width of the area covered by a PV module tilted at an angle equal to β° and L_{pv2}(m) is the width of each PV module, specified by the PV module manufacturer.

The maximum height, H_{T}(m), of each row is calculated as follows

$$H_{\text{T}} = H_1 N_2 \tag{18}$$

$$H_1 = L_{\text{pv2}} \sin \beta \tag{19}$$

where H_1(m) is the maximum height of a PV module tilted at an angle equal to β°.

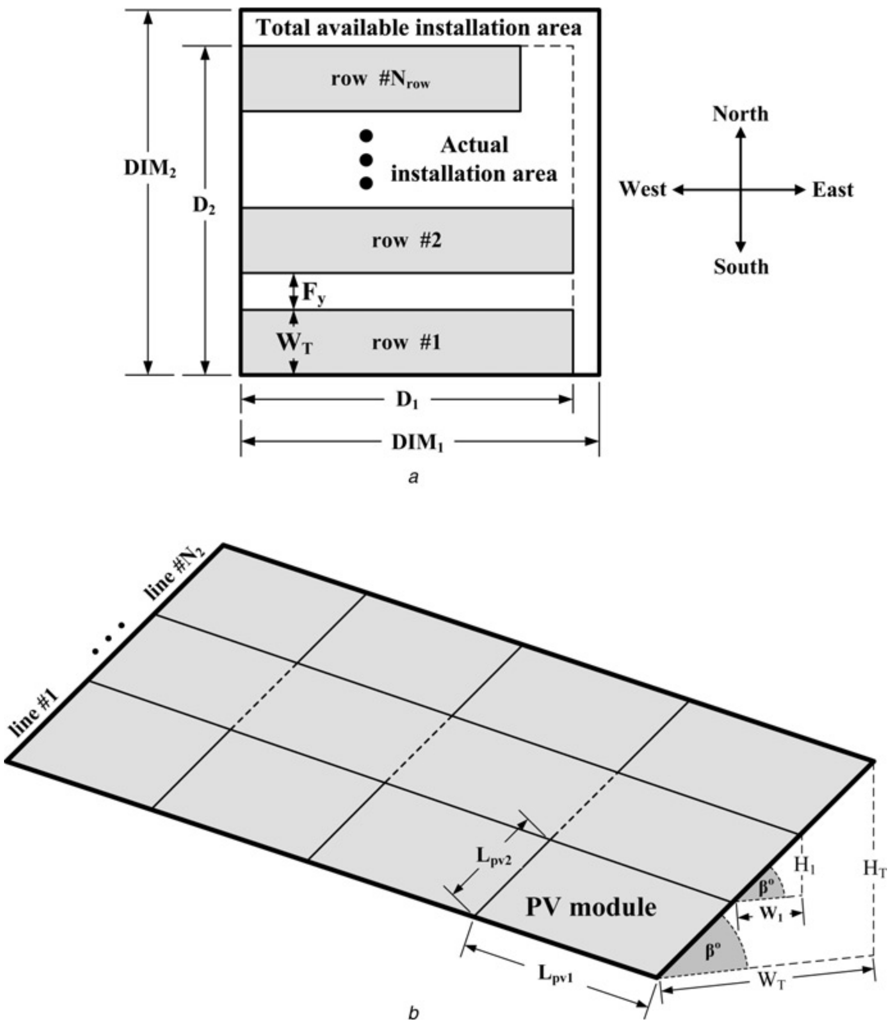

Figure 4 *Arrangement of the PV modules*

a In rows within the available installation area
b In lines within each row

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The total number of the PVGCS PV modules that must be installed, N_1, are arranged in multiple lines within the installation area. The maximum number of PV modules that can be installed within a line, n_t, is calculated according to the length of the southern side of the available installation area, DIM_1(m), and the length of each PV module, L_{pv1}(m), that is specified by the PV module manufacturer, as follows

$$n_t = \text{round\_down}(\mathrm{DIM}_1/L_{pv1}) \tag{20}$$

Thus, the total number of PV modules contained in each line, N_{sermin}, is calculated as follows

$$N_{sermin} = \begin{cases} n_t & \text{if} \quad N_1/N_2 > n_t \\ \text{round\_up}(N_1/N_2) & \text{else} \end{cases} \tag{21}$$

The total number of rows comprising the PVGCS installation, N_{row}, is calculated according to the total number of the PVGCS PV modules, N_1, the total number of PV modules installed in each line, N_{sermin}, and the number of lines per row, N_2

$$N_{row} = \text{round\_up}\left(\frac{N_1}{N_{ser}}\right) = \text{round\_up}\left(\frac{N_1}{N_{sermin}N_2}\right) \tag{22}$$

where N_{ser} is the total number of PV modules installed in each row.

As shown in Fig. 4*a*, the adjacent rows are installed with an adequate distance between them in order to avoid the mutual shading of the corresponding PV modules. The distance required between adjacent rows, F_y(m), is calculated according to the following equation [13]

$$F_y = H_T \frac{\sin\varphi \cos\delta \cos\omega - \cos\varphi \sin\delta}{\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega} \tag{23}$$

where $\varphi(^\circ)$ is the installation area latitude, $\delta(^\circ)$ is the solar declination angle and $\omega(^\circ)$ is the solar hour angle.

The values of δ and ω are calculated as described in [12]. The corresponding value of F_y is calculated for every hour of each day of the year. The required distance between the adjacent rows of the PVGCS installation is equal to the maximum of the calculated F_y values.

The dimensions of the actual installation area, which is practically used to install the target PVGCS, D_1(m) and D_2(m) in Fig. 4*a*, are calculated according to the total area requirements of each row and the spacing between the adjacent rows

$$D_1 = N_{sermin}L_{pv1} \tag{24}$$

$$D_2 = N_{row}W_T + (N_{row} - 1)F_y \tag{25}$$

However, the dimensions of the total available installation area, DIM_1 and DIM_2, impose an upper limit on the values of D_1 and D_2 calculated above

$$D_1 \le \mathrm{DIM}_1 \tag{26}$$

$$D_2 \le \mathrm{DIM}_2 \tag{27}$$

In order to incorporate the cost of the PV module mounting structures in the optimal sizing procedure, thus exploiting the effect of the corresponding cost on the PVGCS design characteristics, a generalised model of the PV module mounting structures has been developed. The PV modules mounting structures are constructed using metallic rods and the estimation of the corresponding cost is based on the calculation of the total length of the metallic rods required for the installation of the target PVGCS. The diagram of the mounting structures used to install the PVGCS PV modules is depicted in Fig. 5. Each PVGCS row is comprised of multiple, identical mounting structures. The intermediate vertical rods are installed at each point that the row vertical height has been increased by 2 m. The PV modules metallic mounting frames are installed on concrete foundation bases. The total length of the metallic rods, B(m), required for the installation of the entire PVGCS, is calculated as follows

$$B = B_1 n_b \tag{28}$$

$$B_1 = [2_{tot} + H_T + L_T) + (B_2 + 2)L_{pv2}] \cdot SF \tag{29}$$

$$n_b = \text{round\_up}(N_1/N_2) \tag{30}$$

$$B_{tot} = \sum_{i=1}^{B_2} i2 \tag{31}$$

$$L_T = N_2 L_{pv2} \tag{32}$$

$$B_2 = \text{round\_down}(H_T/2) \tag{33}$$

where B_1(m) is the total length of the metallic rods required to construct the metallic frames of a vertical line, n_b is the total number of vertical lines comprising the PVGCS installation, B_{tot}(m) is the total length of the vertical rods of each side of a vertical line, L_T(m) is the total length of each row, B_2 is the total number of the intermediate vertical rods of each side of a vertical line and $\mathrm{SF} = 110\%$ is an over-sizing factor that has been incorporated in order to account that, under practical conditions, a proportion of the initial raw material purchased is not used during the construction of the frames.

The total volume of the concrete foundation bases required to support the PVGCS PV module metallic mounting frames, $B_B(\mathrm{m}^3)$, is equal to the volume of the concrete foundation bases of a vertical line multiplied by the total number of the PVGCS vertical lines, n_b

$$B_B = (2 + B_2)h_w t_w L_{pv1} n_b \tag{34}$$

where h_w(m) is the concrete foundation base height and

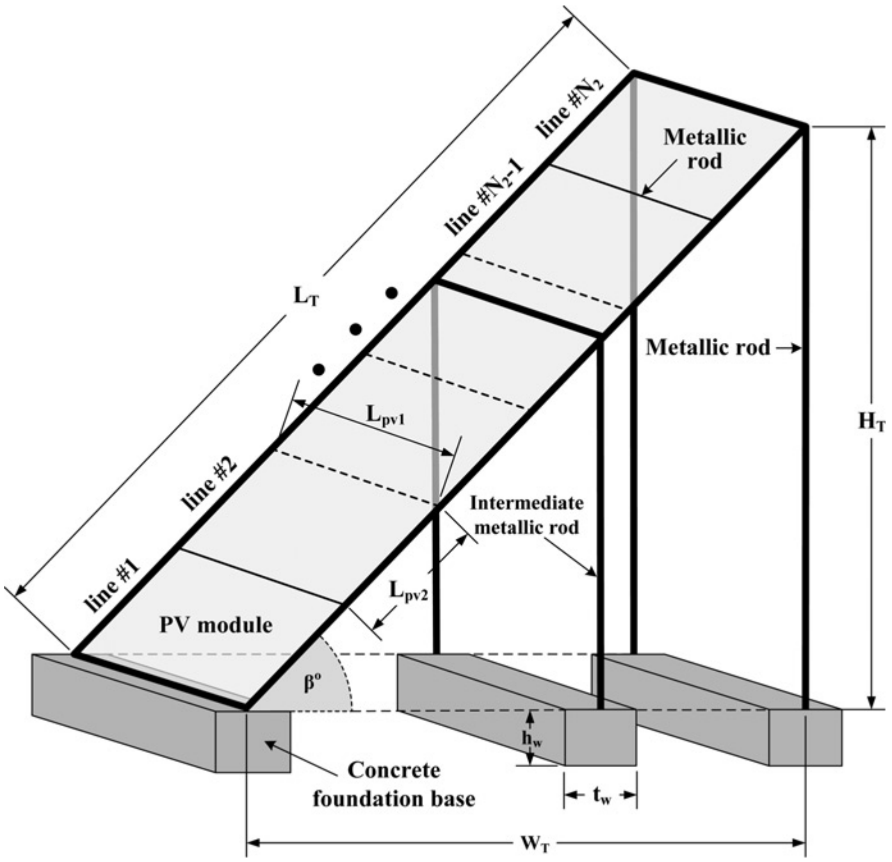

Figure 5 *Diagram of the mounting structures used to install the PV modules on each vertical line of a row*

t_w(m) is the corresponding thickness, both specified by the system designer at the beginning of the PVGCS optimal sizing procedure.

The total manufacturing and installation cost of the PVGCS mounting structures, C_B(€), is equal to the sum of the metallic rods and the concrete foundation bases costs

$$C_B = Bc_S + B_B c_B \tag{35}$$

where c_S(€/m) is the per unit length cost of the metallic rods and c_B(€/m^3) is the per unit volume cost of the concrete foundation bases.

The value of c_S depends on the required thickness and the type of the metallic rods construction material and it is specified by the system designer at the beginning of the PVGCS optimal sizing procedure according to the weight of the PV modules supported and the typical environmental conditions (e.g. humidity, air moisture salinity causing corrosion on metallic substrates etc.) prevailing at the PVGCS installation site.

4 PVGCS net profit maximisation using GAs

In the proposed method, the decision variables used during the GA optimal sizing procedure are the total number of the PVGCS PV modules, the number of PV modules lines comprising each PVGCS row and the PV modules tilt angle. The optimal total number of the PVGCS DC/AC converters, the optimal allocation of the available PV modules among the DC/AC converters and the dimensions of the actual installation area are calculated according to the PVGCS design methodology presented in Section 3, using the optimal values of the decision variables calculated during the GA optimal sizing process. The objective function that is maximised during the optimisation procedure is the PVGCS total net profit function, $J(\boldsymbol{x})$(€), which is equal to the difference between the present value of the total profits achieved from selling the produced energy to the electric grid during the system operational lifetime period, $P_E(\boldsymbol{x})$(€), and the sum of the total capital, $C_c(\boldsymbol{x})$(€), and maintenance cost, $C_m(\boldsymbol{x})$(€), functions

$$\max_{\boldsymbol{x}}\{J(\boldsymbol{x})\} = \max_{\boldsymbol{x}}\{P_E(\boldsymbol{x}) - C_c(\boldsymbol{x}) - C_m(\boldsymbol{x})\} \tag{36}$$

where $\boldsymbol{x}$ is the vector of the decision variables listed above.

The total net profit achieved during the PVGCS operational lifetime period depends on the amount of energy generated by the PVGCS PV modules and on the price that the energy produced by the PVGCS is sold to the electric grid and not on the price that the electric grid customers purchase the electric energy from the electric grid operator in order to fulfil their energy requirements, or

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the corresponding load profile. The impact of taxation has not been incorporated in (36), since the corresponding expenses depend on the investor tax rate, the state taxing system and the renewable energy promotion policies, which are characterised by a significant variation worldwide.

The total capital cost, $C_c(\boldsymbol{x})$, is calculated as follows

$$C_c(\boldsymbol{x}) = (1 - s)(N_1 C_{PV} + N_{dc} C_{INV} + C_L + C_B) \quad (37)$$

where s(%) is the capital subsidisation rate, C_{PV}(€) and C_{INV}(€) are the capital costs of each PV module and DC/AC converter, respectively, C_L(€) is the cost of purchasing the required installation area and C_B(€) is the manufacturing and installation cost of the PV modules mounting structures.

The cost of the required installation area, C_L, is calculated as follows

$$C_L = D_1 D_2 c_l \quad (38)$$

where c_l is the cost of the installation land per unit area (€/m^2).

The present value of the maintenance cost, $C_m(\boldsymbol{x})$, during the PVGCS operational lifetime period is calculated using the following equation

$$C_m(\boldsymbol{x}) = (N_1 M_{PV} + N_{dc} M_{INV})(1 + g) \times \left[\frac{1 - [(1 + g)/(1 + i)]^n}{i - g}\right] + R_{TC} \quad (39)$$

where M_{PV} and M_{INV}(€/year) are the annual maintenance costs per unit of the PV modules and the DC/AC converters, respectively, g(%) is the annual inflation rate, i(%) is the nominal annual discount rate and R_{TC}(€) is the present value of the total cost of repairing the PVGCS DC/AC converters.

The present value of the total cost of repairing the PVGCS DC/AC converters, R_{TC}(€), is calculated by reducing the future value of each DC/AC converter repair cost, R_{cost}(€), to the corresponding present value, as follows

$$R_{TC} = N_{dc} R_{cost} \left[\sum_{\forall j = k^*} \frac{(1 + g)^j}{(1 + i)^j}\right] \quad (40)$$

where k^* are the year numbers that the DC/AC converters must be repaired.

The value of k^* depends on the number of DC/AC converters repairs which must be performed during the PVGCS lifetime, N_r, which is calculated using the following equation

$$N_r = \frac{n 24 \cdot 365}{\text{MTBF}} \quad (41)$$

where MTBF(h) is the mean time between failures of the DC/AC converters, specified by the manufacturer.

Since the DC/AC converters are repaired only in specific years during the PVGCS lifetime, the sum in (40) is evaluated only for the specific values of year numbers, k^*, that the DC/AC converters must be repaired. For example, if the calculated value of N_r is 8 and the study is performed for $n = 25$ years, then the sum in (40) is evaluated for $k^* = 8$, 16 and 24.

The present value of the total profits achieved from selling the PV generated energy to the electric grid, $P_E(\boldsymbol{x})$(€), is calculated as follows

$$P_E(\boldsymbol{x}) = C_O N_1 E_{tot} \left[\frac{1 - (1/1 + i)^n}{i}\right] \quad (42)$$

$$E_{tot} = n_{INV} n_{MPPT} \sum_{d=1}^{365} \sum_{i=1}^{24} \frac{P_M^d(t, \beta)}{1000(\text{W/kW})} \Delta t \quad (43)$$

where C_O(€/kWh) is the selling price of the PVGCS generated energy, E_{tot}(kWh) is the total annual energy injected to the electric grid by each PV module, Δt is the simulation time step, set to $\Delta t = 1$ h, n_{INV} is the DC/AC inverter power conversion efficiency and n_{MPPT} is a conversion factor indicating the accuracy of the MPPT operation performed by the DC/AC converter.

The constraints of the GA optimisation procedure are the following

$$0 \leq \beta \leq 90^\circ \quad (44)$$

and

$$\text{Constraints}(N_1, N_2, \beta) = \text{Satisfied} \quad (45)$$

where Constraints(N_1, N_2, β) is the set of the PVGCS design constraints presented in Section 3.

In the proposed methodology, each GA chromosome represents a potential solution of the optimisation problem and consists of three genes in the form: $\boldsymbol{x} = [N_1|N_2|\beta]$. At the beginning of the GA optimisation process, an initial population of 30 chromosomes, comprising the first generation, is generated randomly and the PVGCS design methodology analysed in Section 3 is applied for each chromosome. If any of the initial population chromosomes violates the optimal sizing problem constraints imposed by inequalities (44) and (45), then it is replaced by a new chromosome, which is generated randomly and fulfils these constraints.

Each iteration (generation) of the GA optimisation process starts with the fitness function evaluation for each chromosome (potential solution). The PVGCS design methodology analysed in Section 3 is applied for each chromosome. The optimal value of the fitness function among all chromosomes of the specific population is stored as the optimal solution of the problem. This solution is replaced by better solutions during the evaluation of the subsequent GA generations. The roulette wheel method [14] is applied in order to select the chromosomes which will be subject to the crossover and mutation operators. The crossover mechanism uses the following three operators

- simple crossover with initial probability $p_{sc} = 10\%$,
- simple arithmetical crossover with initial probability $p_{sac} = 10\%$ and
- whole arithmetical crossover with initial probability $p_{wac} = 10\%$.

The mutation mechanism is performed using the following three operators:

- uniform mutation with probability $p_{um} = 10\%$,
- boundary mutation with probability $p_{bm} = 3\%$ and
- non-uniform mutation with probability $p_{num} = 35\%$, in order to enhance the GA fine local tuning capability during the optimisation process.

If the application of any of the crossover or mutation operators described above results in a chromosome which does not satisfy the optimisation problem constraints imposed by inequalities (44) and (45), then a 'repair' procedure is applied, which modifies the values of the genes of this chromosome such that these constraints are fully satisfied. However, that chromosome is not considered as a potential optimal solution. The GA optimisation process described above is repeated until a predefined number of population generations have been evaluated.

5 Economic analysis

The profitability evaluation of each optimally sized PVGCS is investigated using the NPV, the discounted payback period and the IRR methods.

The NPV of an investment is the sum of the present values of all cash inflows and outflows related to the investment. A PVGCS investment is considered to be economically profitable only if the corresponding NPV is positive. In the methodology presented in this paper, the PVGCS NPV is equal to the total net profits function, $J(\boldsymbol{x})$, which is calculated using (36).

The discounted payback period, n^* (years), is defined as the time period that sets the system NPV to zero

$$\mathrm{NPV} = J(\boldsymbol{x}) = 0 \text{ for } n = n^* \tag{46}$$

In case that (46) is satisfied for multiple values of n (e.g. because of emerging DC/AC converter repair expenses), then the maximum among these values of n is considered to be equal to the PVGCS discounted payback period.

The IRR is equal to the discount rate value that sets the system NPV to zero

$$\mathrm{NPV} = J(\boldsymbol{x}) = 0 \text{ for } i = \mathrm{IRR} \tag{47}$$

The values of n^* and IRR are calculated by solving (46) and (47), respectively, using numerical analysis methods. A PVGCS investment is considered to be economically viable only if NPV > 0, $n^* < n$ and the IRR value is higher than a predefined acceptance limit, which is equal to or higher than the nominal annual discount rate, i.

6 Optimal sizing and economic analysis results

The proposed methodology has been applied for the design of a PVGCS interconnected to the electric network of the island of Crete, Greece, where significant solar irradiation potential is available. The time sequences of the daily global solar irradiation on horizontal plane, the daily diffuse solar irradiation on horizontal plane and the hourly mean ambient temperature input to the optimal sizing program are depicted in Figs. 6 and 7, respectively. These data were recorded during the year 2003 using a properly developed data-acquisition system installed at the area of the Technical University of Crete, Greece (latitude: 35.53°, longitude: 24.06° and altitude: approximately 150 m above the sea level). The total solar irradiation, which is incident on horizontal plane during that year, is equal to 1.8431 MWh/m^2.

The technical characteristics and the capital and maintenance costs of various, commercially available, PV module and DC/AC converter types, which are input to the optimal sizing procedure, are shown in Tables 1 and 2, respectively. The installation cost has been incorporated in the corresponding capital cost of the devices. The annual maintenance cost of the PV modules and the DC/AC converters has been set at 1 and 1.5%, respectively, of the corresponding capital costs. According to the local market current standing prices, the manufacturing and installation cost of the metallic rods, c_S, was set equal to 33 €/m and the manufacturing and installation cost of the concrete foundation bases, c_B, was set equal to 230 €/m^3. The dimensions of the concrete walls have been set to $h_w = 0.25$ m and $t_w = 0.30$ m, respectively.

According to the local market conditions, the annual inflation rate, g, was set equal to 3% and the nominal annual discount rate, i, was set equal to 4.5%. According to the Greek State legislation, the selling price of the energy produced by the PVGCS has been set to $C_O = 0.45$ €/kWh for systems with installed peak power up to 100 kW

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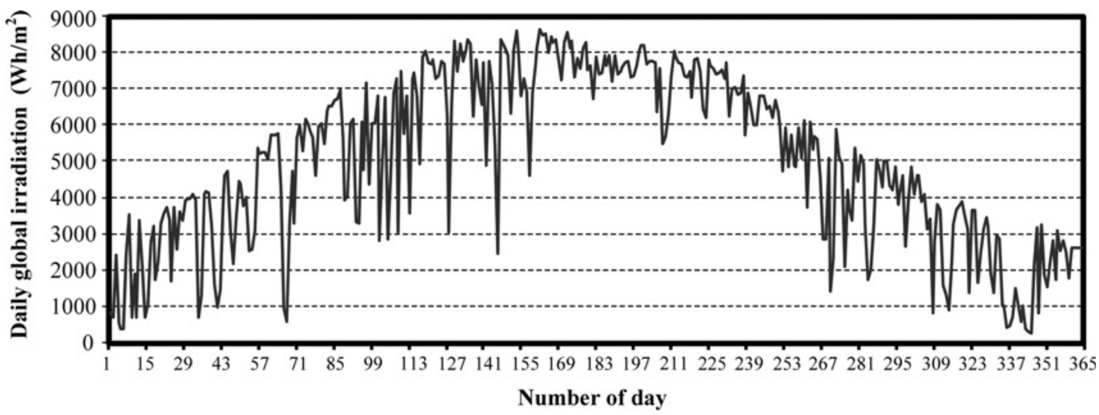
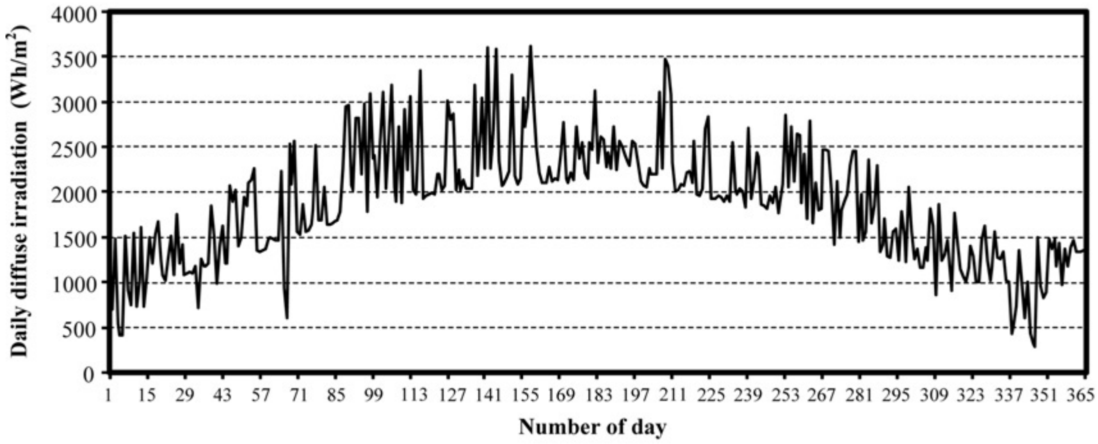


a



b

Figure 6 *Solar irradiation on horizontal plane during the year 2003*
a Daily global solar irradiation
b Daily diffuse solar irradiation

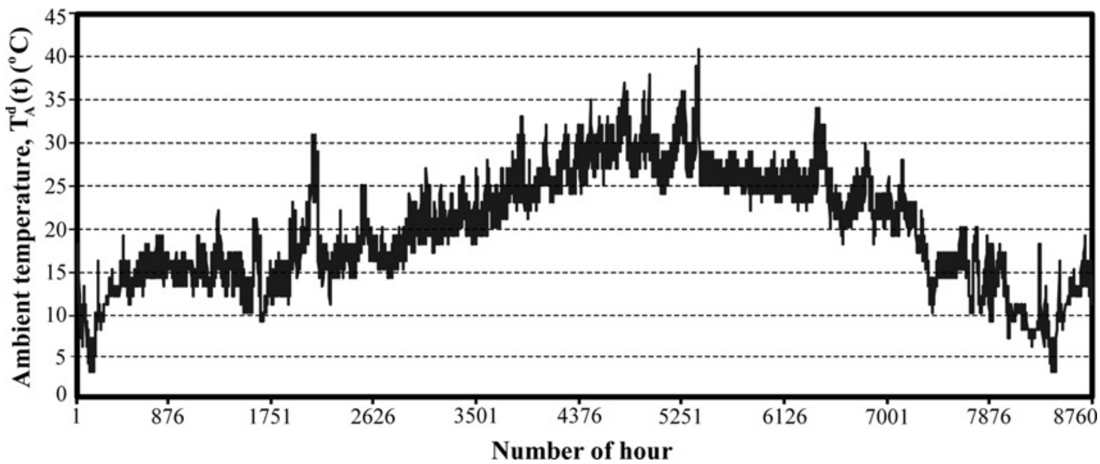


Figure 7 *Hourly mean temperature during the year 2003*

and to $C_O = 0.40$ €/kWh for systems with installed peak power higher than 100 kW. Also, the PVGCS operational lifetime period has been set equal to 25 years, which is equal to the guaranteed operational lifetime period of both PV module types input to the optimal sizing algorithm.

The optimal sizing results for all the combinations of input system device types in case that $s = 0\%$, $c_1 = 0$ €/m^2, $\text{DIM}_1 = 10$ m (southern side) and $\text{DIM}_2 = 100$ m (western side) are presented in Table 3. The overall optimal solution is the combination #2, which is composed by the

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Table 1 Specifications of the PV modules input to the optimal sizing algorithm

Type	$V_{OC,STC}$ (V)	$I_{SC,STC}$ (A)	V_M (V)	I_M (A)	Nominal power under STC (W)	NCOT (°C)	C_{PV} (€)	M_{PV} (€/year)	L_{pv1} (m)	L_{pv2} (m)	Guaranteed operational lifetime period (years)	K_V (V/°C)
1	29	8	23.4	7.27	170	47	515	5.15	1.29	0.99	25	−0.109
2	19.8	3.4	15.9	3.15	50	45	202	2.02	1.22	0.329	25	−0.07

Table 2 Specifications of the DC/AC converters input to the optimal sizing algorithm

Type	n_{INV} (%)	n_{MPPT} (%)	P_{max} (W)	MTBF (h)	C_{INV} (€)	M_{INV} (€/year)	V_{imin} (V)	V_{imax} (V)	R_{cost} (€)
1	94.4	100	3000	219 000	1450	25	150	450	14.5
2	95.3	100	7000	219 000	3008	45	335	560	30

Table 3 PVGCS optimal sizing results for all the combinations of input device types in case that $s = 0\%$, $c_l = 0$ €/m^2, $\mathrm{DIM}_1 = 10$ m, $\mathrm{DIM}_2 = 100$ m

Combination	PV module type	DC/AC converter type	N_1	N_{dc}	β (°)	NPV (€)	n^* (y)	IRR (%)
1	1	1	585	39	10	747 694.77	6	19
2	1	2	576	16	6	770 257.79	5.8	20
3	2	1	2000	46	7	655 337.41	8.1	14
4	2	2	1890	14	11	648 516.44	7.5	15

PV module type #1 and the DC/AC converter type #2. It is observed that the overall optimal PVGCS configuration is comprised of the PV module type with the highest nominal power rating and the DC/AC converter type with the highest values of nominal power rating and power conversion efficiency. All combinations of PV module and DC/AC converter types resulted in economically viable PVGCSs. The PV modules calculated optimal tilt angle, β, is relatively low because of the solar irradiation profile of the site under consideration, exhibiting prolonged cloudy intervals during the winter. Thus, the calculated low optimal β tilt angle value enables the maximisation of both the received diffuse radiation, which is the main component of the incident global irradiation under cloudy conditions according to the profile of the daily diffuse solar irradiation on horizontal plane, which is plotted in Fig. 6*b*, and the PV module energy production during the summer period. The optimal β tilt angle value produced using the proposed method is different from the typical angle values calculated using conventional design methods of grid-connected PV systems (e.g. based on the latitude of the installation site), since the target of the PV modules tilt angle optimisation in the proposed method is the maximisation of the total net economic benefit achieved during the system operational lifetime period and not the maximisation of the total PV generated energy during the year. Using the resulting optimally sized PVGCS configuration, the total PV generated electric energy injected to the electric grid during the year is 187.55 MWh.

The PVGCS optimal configuration details for all the combinations of input device types in case that $s = 0\%$, $c_l = 0$ €/m^2, $\mathrm{DIM}_1 = 10$ m and $\mathrm{DIM}_2 = 100$ m are tabulated in Table 4. In the case of the overall optimal solution (combination #2) the percentage of the available installation area which is practically utilised for the installation of the target PVGCS is approximately 86.2%. Also, the PV modules optimal arrangement consists of three rows with a 4.89 m distance between rows in order to avoid mutual shading conditions between them. The PV modules are distributed equally among 16 DC/AC converters.

The PVGCS optimal economic results in case that $s = 0\%$, $c_l = 0$ €/m^2, $\mathrm{DIM}_1 = 10$ m and $\mathrm{DIM}_2 = 100$ m are displayed in Table 5. The present values of the PVGCS total installation and maintenance costs of the overall optimal solution (combination #2) are 31.7 and 6.1%, respectively, of the present value of the total profits achieved from selling the PV generated energy to the electric grid.

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Table 4 PVGCS optimal configuration details for all the combinations of input device types in case that $s = 0\%$, $c_l = 0$ €/m^2, $DIM_1 = 10$ m, $DIM_2 = 100$ m

Combination	N_{row}	F_y (m)	N_2	N_{sermin}	D_1 (m)	D_2 (m)	N_s	N_p	N_{s1}	N_{p1}
1	4	5.89	21	7	9.03	99.56	15	1	0	0
2	3	4.89	29	7	9.03	95.45	18	2	0	0
3	2	8.17	125	8	9.76	89.81	22	2	20	1
4	4	6.14	60	8	9.76	95.94	27	5	0	0

Table 5 PVGCS optimal economic results for all the combinations of input device types in case that $s = 0\%$, $c_l = 0$ €/m^2, $DIM_1 = 10$ m, $DIM_2 = 100$ m

Combination	$C_c(\mathbf{x})$ (€)	$C_m(\mathbf{x})$ (€)	$P_E(\mathbf{x})$ (€)
1	442 402.89	83 061.06	1 273 158.72
2	396 531.81	84 674.84	1 251 464.44
3	534 102.36	88 395.52	1 277 835.29
4	487 409.10	96 588.78	1 232 514.32

According to the optimal sizing results presented in Tables 3–5, it is concluded that the total economic benefit achieved during the PVGCS operational lifetime period is influenced by the PV module and the DC/AC converter types used to compose the target PVGCS, the arrangement of the PV modules within the available installation area, the distribution of the PV modules among the DC/AC converters and the PV modules tilt angle, which affect both the corresponding mounting structures cost and the amount of the PV energy produced.

The NPV, the discounted payback period and the IRR, which result using the optimal combination of system devices (row #2 in Table 3) with $DIM_1 = 10$ m and $DIM_2 = 100$ m for several scenarios of installation area cost and PVGCS capital cost subsidisation rate, are plotted in Figs. 8–10. It is observed that the NPV is always positive, the discounted payback period is less than the PVGCS

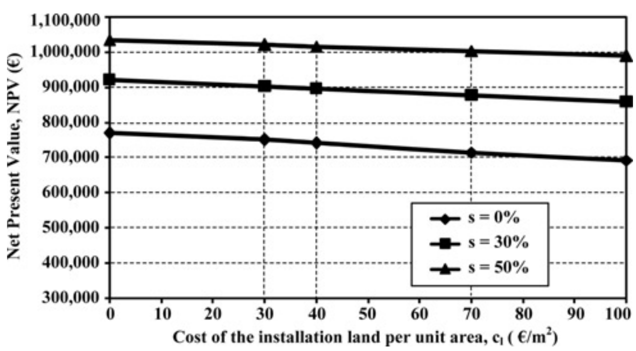

Figure 8 *Resulting NPV for various values of subsidisation rate and cost of the installation area*

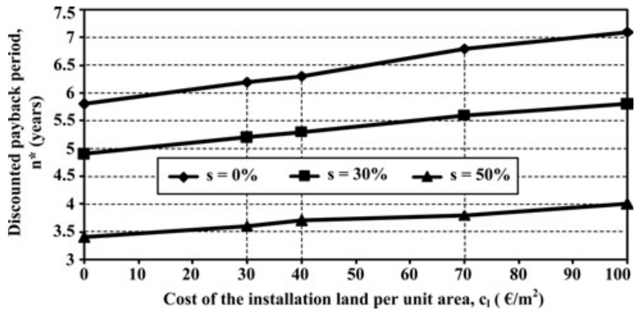

Figure 9 *Resulting discounted payback period for various values of subsidisation rate and cost of the installation area*

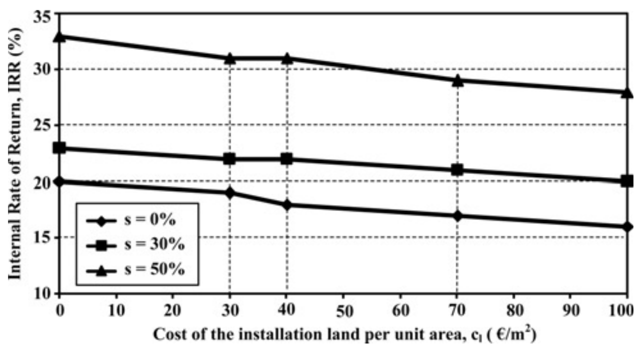

Figure 10 *Resulting IRR for various values of subsidisation rate and cost of the installation area*

operational lifetime and the IRR is always higher than the nominal annual discount rate $i = 4.5\%$, thus ensuring the investment economic viability and profitability. Also, the NPV and the IRR increase in proportion to the subsidisation rate of the investment. The increment of the investment subsidisation rate results in reduction of the resulting discounted payback period.

The diagrams of the optimal NPV and the optimal total power of the PV modules under STC for various PV generated energy selling prices, which result using the PV module and the DC/AC converter device types of combination #2 in Table 3, with $s = 0\%$, $c_l = 0$ €/m^2, $DIM_1 = 10$ m, $DIM_2 = 100$ m, are plotted in Figs. 11 and 12, respectively. It is observed that the PVGCS is economically profitable (i.e. NPV > 0) in case that the PV

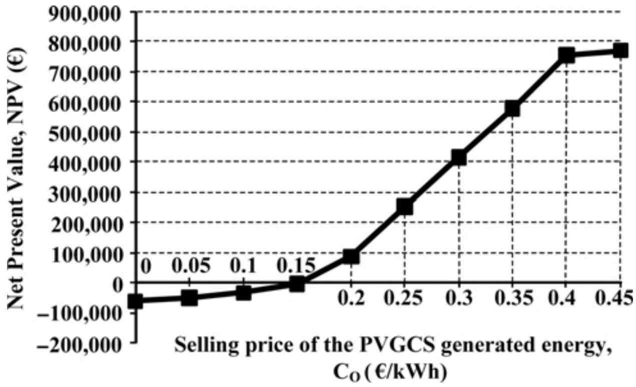

Figure 11 *Optimal NPV for various selling prices of the PV generated energy in case that $s = 0\%$, $c_l = 0$ €/m^2, $DIM_1 = 10$ m and $DIM_2 = 100$ m*

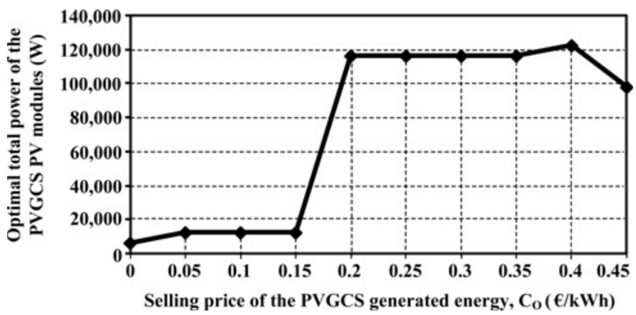

Figure 12 *Optimal total power of the PVGCS PV modules under STC for various selling prices of the PV generated energy in case that $s = 0\%$, $c_l = 0$ €/m^2, $DIM_1 = 10$ m and $DIM_2 = 100$ m*

generated energy selling price is higher than 0.20 €/kWh. The optimal total PV power is reduced in case that the electric energy selling price increases above 0.40 €/kWh because of the fact that according to the definitions of the Greek legislation, the selling price is equal to 0.45 €/kWh for a PVGCSs with nominal installed power up to 100 kW, whereas it drops to 0.40 €/kWh in case of higher nominal power rating. Thus, under the specific conditions holding for the PVGCS under study, a system with nominal power rating slightly lower than 100 kW and selling price equal to 0.45 €/kWh is more economically profitable than a system of higher nominal power rating but with a lower selling price (i.e. 0.40 €/kWh). The values of the discounted payback period and the IRR corresponding to the solutions presented in Figs. 11 and 12 with NPV $>$ 0, are presented in Figs. 13 and 14, respectively. The resulting IRR values increase in proportion to the PV generated electric energy selling price, while the discounted payback period is inversely proportional to the PV generated energy selling price.

The variation of the resulting optimal NPV in case that $s = 0\%$, $c_l = 0$ €/m^2 and various values of DIM_1 and DIM_2 are input to the optimal sizing procedure, has also

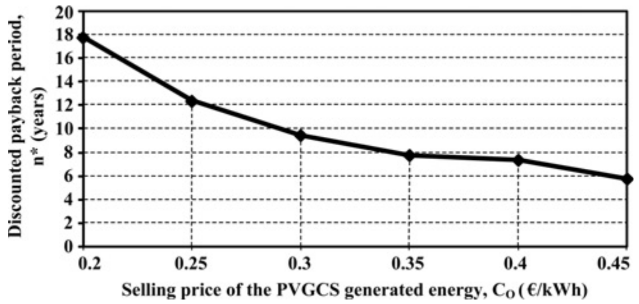

Figure 13 *Resulting discounted payback period for various selling prices of the PV generated energy in case that $s = 0\%$, $c_l = 0$ €/m^2, $DIM_1 = 10$ m and $DIM_2 = 100$ m*

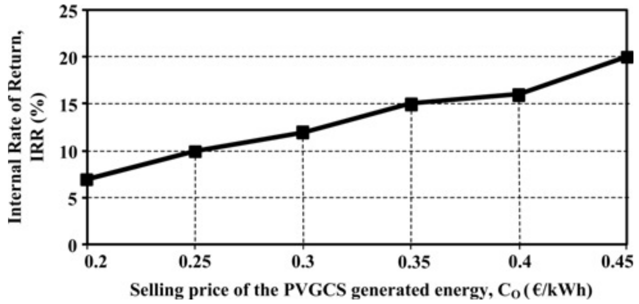

Figure 14 *Resulting IRR for various selling prices of the PV generated energy in case that $s = 0\%$, $c_l = 0$ €/m^2, $DIM_1 = 10$ m and $DIM_2 = 100$ m*

been explored. The corresponding results are plotted in the diagram depicted in Fig. 15. In all of these cases, the total available area is equal to 1000 m^2. It is observed that increasing the value of DIM_1 results in increment of the PVGCS optimal total net profits achieved, because of the better exploitation of the available installation area, since the requirements of free space between the adjacent PV rows are reduced, thus permitting the installation of more PV modules within the available installation area. The absolute maximum variation of the resulting optimal NPV

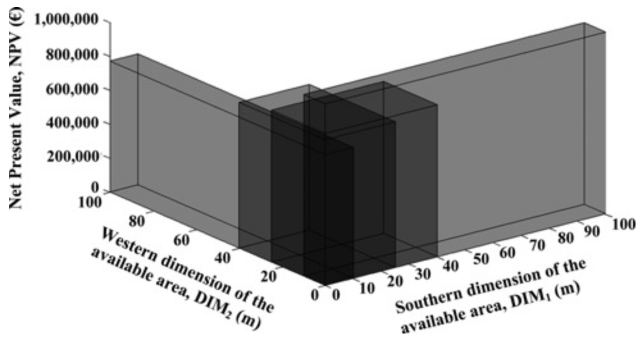

Figure 15 *Optimal NPV for various dimensions of the installation area in case that $s = 0\%$, $c_l = 0$ €/m^2 and the available installation area is equal to 1000 m^2*

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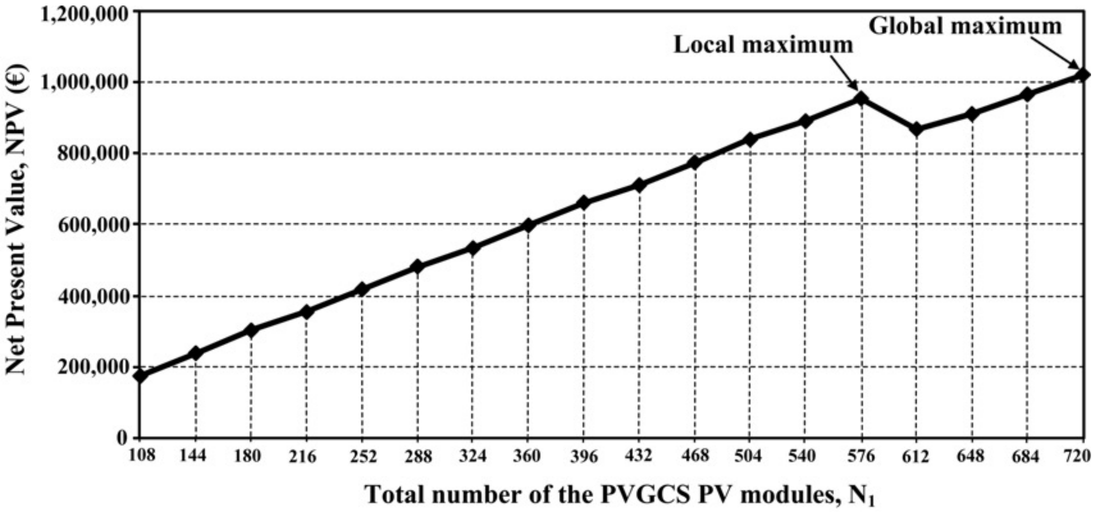

Figure 16 *Variation of the NPV against the total number of the PVGCS PV modules in case that $s = 50\%$, $c_l = 30$ €/m^2, $N_2 = 103$, $\beta = 12^\circ$ and the available installation area is equal to 1000 m^2*

values is 27.9% of the corresponding maximum NPV indicated in this diagram.

The variation of the NPV against the total number of the PVGCS PV modules (N_1), such that the design constraints imposed by inequalities (44) and (45) are satisfied, in case that the PV module and DC/AC converter device types of combination #2 in Table 3 are used, $s = 50\%$, $c_l = 30$ €/m^2, the available installation area is equal to 1000 m^2, $N_2 = 103$ and $\beta = 12^\circ$, is plotted in Fig. 16. It is observed that there is a local maximum solution in case that the total number of PV modules is equal to 576. However, the application of the proposed GA-based optimisation methodology, results in convergence to the global optimal solution where the total number of the PVGCS PV modules is equal to 720, because of the GA ability to avoid getting trapped in sub-optimal solutions during the PVGCS optimal sizing procedure. In this example, the application of conventional optimisation methodologies, such as the dynamic programming or the gradient techniques, could result in convergence to the local maximum solution where $N_1 = 576$.

The PVGCS optimal sizing software was developed using the Microsoft Visual C++ language and the CPU time required for the optimal sizing of each combination of input device types is approximately 5 min, using a PC with a 3.0 GHz CPU, while it requires approximately 1 MB of RAM.

7 Conclusions

The PVGCSs are widely used in order to inject the PV generated energy to the electric grid, thus contributing towards the fulfillment of the continuously increasing electric energy demands and the reduction of the pollution caused by the thermal, electric energy generating units. The installation of PVGCSs by private investors is frequently supported in many countries by means of subsidisation of the corresponding investment capital cost. In this case, the main target of the PVGCS design is the maximisation of the total economic benefit achieved by selling the PV generated energy to the electric grid.

A methodology for optimal sizing and economic analysis of PVGCSs has been presented in this paper. The purpose of the proposed methodology is to suggest, among a list of commercially available system devices, the optimal number and type of the PV modules and the DC/AC converters, the PV modules optimal tilt angle, the optimal arrangement of the PV modules within the available installation area and the optimal distribution of the PV modules among the DC/AC converters, such that the total net economic benefit achieved during the system operational lifetime period is maximised. The maximisation of the total net profits (objective) function is implemented using GAs. The economic viability of the resulting PVGCS configuration is explored according to the NPV, the discounted payback period and the IRR methods. Compared to the past-proposed PVGCS design methods, the methodology presented in this paper has the advantage of taking into account important PVGCS design aspects, which can highly influence the total economic benefit achieved by performing this type of investment, such as the operational and economical differences between various PV module and DC/AC converter types, the PV modules tilt angle, the cost of the land required to install the PVGCS and the cost of the PV modules mounting structures. Additionally, the proposed optimisation methodology is based on GAs, which have the ability to calculate the global optimal solution with relative computational simplicity even in the case of complicated problems with non-linear cost functions or non-linear constraints.

The proposed method has been applied for the optimal design of a PVGCS interconnected to the electric network

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of the island of Crete, Greece, where significant solar irradiation potential is available. According to the optimal sizing and economic analysis results, the total economic benefit achieved during the PVGCS operational lifetime period is influenced by the PV module and the DC/AC converter types used to compose the target PVGCS, the arrangement of the PV modules within the available installation area, the distribution of the PV modules among the DC/AC converters and the PV modules tilt angle, which affect both the corresponding mounting structures cost and the amount of PV energy produced. The PVGCS economic viability depends on the price that the PV generated energy is sold to the electric network and the PVGCS subsidisation rate offered to the investor. The simulation results verify the ability of the GAs to attain the global optimum solution during the PVGCS optimal sizing procedure, even in the presence of local maxima.

The proposed method can easily be modified such that it is applicable for the optimal design of grid-connected PV systems with sun-tracking facilities or building-integrated grid-connected PV systems.

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