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Extended Design Investigation Based on Techno-Economic and Environmental Considerations of a Grid Connected PV System: Application to a 100 kWp PV System Installed in Eastern Macedonia Region of Greece

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Abstract: In recent years significant efforts have been made for the purpose of wider exploitation of RES and in particular of PV systems for power production due to their techno-economic & environmental advantages. For an actual design study of a PV system a detailed examination of a number of technical and economical issues must be first investigated thoroughly. In this work the main steps for the systematic design study of a PV system are presented in compact form and include: a) the meteorological data collection and assessment for the examined site, b) the selection of the most suitable PV panel-inverter combination, c) the cable sizing, and d) the overall economic analysis of the considered system. This proposed procedure is applied to a 100 kWp PV system being installed at Myrtofyto, Kavala in Eastern Macedonia region of Greece. The economic analysis is based on the values of the well known economic indices NPV, IRR, DPBP, BCR, and CoE. Additionally, the benefits to the environment are estimated by the computation of the relevant avoided emissions of main pollutants. The conducted sensitivity analysis is based on key technical and economical system parameters, including the consideration of using either a single or a double shaft sun tracking system.

Keywords: PV system installation, design study, techno-economic analysis, sensitivity analysis, sun-tracking considerations.

1. INTRODUCTION

The photovoltaic (PV) technology is one of the most promising technologies as far as extended exploitation of the solar energy is concerned. The materials commonly used for manufacturing the PV modules are Si, GaAs, $CuInSe_2$, CdTe and TiO_2Si. Relative new technologies are the hybrid modules, the infrared technology modules, and the concentrated modules. In recent years a significant effort has been made for the wider spreading of the PV systems in terms of the global installed capacity and their contribution to the relevant total produced energy [1-6]. In every case, an energy balancing and planning analysis must be conducted at national or regional level, using appropriate energy models, in order to determine in reliable manner the suitable percentage (in terms of safe and economic grid operation) of RES penetration to the electric grid, especially when wind and PV systems are considered due to their stochastic character. A reliable overall planning analysis may lead, in some cases, to a very high percentage of RES penetration/utilization, which among the other advantages offers to the involved country the beneficial exploitation of its existing energy sources (e.g. solar, wind and biomass energy) [7, 8].

The first essential step for the design study of a grid connected PV system is the proper selection of a suitable inverter and its MPP tracker. In most cases the inverter uses MOSFET and IGBT and the output voltage is controlled using PWM methods. The grid connected inverters must satisfy the applicable grid code requirements, e.g. the IEC 61000-3-2 [9-11].

The proper selection of the cables (in the AC and DC side of the PV system) is a significant step for the design study of the PV system and takes into consideration the current and the relative thermal losses, which must not be greater than 14%. Also the use of electric panels is necessary for the interruption and protection of the associated electric circuits. The direct and indirect contact protection is based on standard IEC EN 61730. For the protection of any PV installation the use of lighting and surge arresters are required [12].

The metal construction of the PV system is usually made from Al, which provides small weight and electrolytic corrosion protection. For this reason the metal frames of the PV modules are also constructed from Al. With respect to the sun tracking options the PV system is classified in three categories: a) with fixed base system, b) with 1–axis sun tracking system, and c) with 2–axis sun tracking system. Due to their physical construction the sun trackers are more exposed to meteorological phenomena.

In Greece, the relevant energy Laws 2773/99 and 3468/06 constitute the legislation framework for the energy production and exploitation by RES [13]. If the installed capacity of a PV system is up to 5 kWp, then it is connected to a single phase of the LV grid. The PV systems from 5 kWp to 100 kWp are connected to the three phases of the LV

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Table 1. k Values for Certain Types of Installation of PV Modules

Types of Installation	k (°C)
free support system	20
system on the roof with space ventilation provision	30
system on the roof without space ventilation provision	45

grid. The PV systems from 100 kWp to 20 MWp are connected to the three phases of the MV grid. In the case where the PV system is connected to the LV grid, according to its nominal capacity, it is classified in 7 interconnection subcategories [14]. The power quality of these PV systems is assured by the proper application of the standards EN 50160 and IEC 61000. The main PV system connection criteria to the grid are the network strength/capacity, the contribution to the fault levels [15], the slow and fast voltage variation, the flicker level, the total harmonic distortion (based on standards IEEE Std. 519, IEC 61000-3-6 [16]), the proper operation of the protection equipment of the grid and the PV unit [17], and the effect on audio-frequency ripple control.

The economic analysis of the PV system investment is based mainly on the calculation of the cash flows during the economic (useful) life of the investment (which is normally taken as 20 to 25 years). The well known economic criteria NPV, IRR, DPBP, BCR and CoE are used for the evaluation and attractiveness of the PV system investment [18].

The present work is organized as follows: a) in Section 2 the overall mathematical overview for the modeling/simulation and techno-economic and environmental evaluation of a PV system is presented, b) in Section 3 the main steps of the proposed design procedure of such systems are summarized and presented in block diagram form, c) in Section 4 this procedure is applied as a case study to the installation of a 100 kWp system (including the necessary economic analysis with emphasis on the sun tracking options), and d) the inferred main conclusions are given in Section 5.

2. OVERVIEW OF RELEVANT MATHEMATICAL CONSIDERATIONS OF A PV SYSTEM

The global solar irradiance (W/m^2) falling on an inclined plane is calculated using the Aguiar's algorithm and Markov's tables from (1):

$$G_T = (G_B + G_D A_i)\cdot R_b + G_D(1-A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1+f\sin^3\left(\frac{\beta}{2}\right)\right] + Gp_g\left(\frac{1-\cos\beta}{2}\right) \quad (1)$$

Therefore, the energy produced by a PV panel is given by:

$$P_{PV} = f_{PV}\cdot Y_{PV}\cdot\left(\frac{G_T}{G_s}\right) \quad (2)$$

2.1. Irradiation on Inclined Plane

The total daily irradiation Hdm (kWh/m2) on an inclined plane is computed from:

$$\mathrm{H_{dm}}(\beta,a) = \sum_{-\omega_S}^{\omega_S} H_{hm}(\beta,a) \quad (3)$$

Thus, pertinent meteorological data may be used for various slopes and orientations of the PV modules.

2.2. Shading Calculations

The possible shading of the PV module must be taken into account in the computations of the annual produced energy by the PV system. The shading consists of direct and diffuse components.

The diffuse irradiation is reduced due to the shading of the PV modules by the surrounding objects. Unlike the direct irradiation, the diffuse irradiation has no specific direction.

Finally, the diffuse irradiation on an inclined and shadowed surface in $G_{t,S}$ is given by

$$G_{t,S} = (1-f_D)\cdot G_t \quad (4)$$

For the calculation of the f_D a suitable algorithm is used [19].

In practical terms the direct irradiation on a PV module is reduced during the shading period at each stage of the calculation.

2.3. Modeling/Simulation of a PV System

The calculation of the total output power of the PV system is obtained by simulating its various sub-systems, e.g. the PV modules, the inverters, etc. Also the characteristic P-V curve is used for various levels of irradiation. For the determination of the temperature effect, the linear model of temperature (indicating the temperature of the PV cell via the linear dependence on incident solar irradiation, G) is used, as follows:

$$T_{cell} = T_a + k\cdot\left(\frac{G}{G_{STC}}\right) \quad (5)$$

The value of the constant k depends on the installation method of the PV modules and the measurement of the maximum temperature at maximum solar irradiance (G_{STC} = 1000W/m^2), compared with the ambient temperature T_a.

Typical values of k for different types of installation of the PV modules are given in Table **1**.

Besides the efficiency of the PV cell, the simulation model (which uses characteristic V-I curve) takes into account the following additional losses:

- Deviation from the spectrum of AM 1.5.
- Mismatch or lower production due to manufacturing defects in materials.
- Losses of diodes.

These losses are deducted percentage wise from the output of the PV cell. In addition, the reflection losses, the losses of cables, and surface losses are computed.

The power output of the inverter, P_{AC}, is computed by:

$$P_{AC} = P_{DC}\cdot\eta_{DCnom}\cdot\eta_{rel} \quad (6)$$

The overall simulation results of the PV system are:

- The solar energy at the surface of the PV modules.

- The produced energy (in AC side) minus self-consumption of the inverter.
- The produced energy injected to the electric grid.
- The efficiency of the PV modules at STC.

Finally, the total energy produced by the PV system for a given time period is:

$$P = f_{PV} \cdot Y_{PV} \cdot \left(\frac{G_T}{G_s}\right)\eta_{DCnom.} \cdot \eta_{rel} - Q_{temp} - P_{Cu} - P_{losses} \quad (7)$$

2.4. Economic Analysis

The economic viability/attractiveness of the investment of the examined PV system is assessed by the commercially available computer program using widely acceptable economic criteria, such as: (a) NPV, (b) the IRR, (c) the DPBP and (d) the BCR. An essential criterion for any electric energy production unit installation is the cost per electric kWh produced by it, or simply the CoE. The computation of the above economic indices is based mainly on the calculation of the cash flows for the economic life of the investment. As income one considers: a) the amount of applicable subsidy (or other incentives), b) the loan amount, and c) the resulting benefit by selling the energy being produced by the PV system. On the other hand as expenditures one considers: a) the total initial capital (including the cost of design study, installation, interconnection equipment, etc.), b) the maintenance and insurance cost, and c) the taxes.

2.5. Socio-Environmental Analysis

It is assumed that the installation and operation of a grid connected PV system substitutes an equal amount of energy otherwise produced by a conventional centralized energy production system. Besides the direct benefit coming from its installation (e.g. creation of new jobs, economic enhancement of remote areas, etc.), the installation also leads to significant environmental benefits in terms of reduction of associated emitted pollutants and corresponding use of possible imported conventional fuels. In the environmental analysis of a PV system one must conduct a life cycle assessment, including the produced energy by the PV system and also the needed energy for its production (since the energy consumption and the amount of emitted pollutants for the production process of PV modules are not negligible). For the calculation of the avoided emissions it is assumed that the operation of the PV system and the energy it produces substitutes an equal amount of energy by a conventional power system. More specifically the operation of a PV system may be compared with the operation of one type of conventional power station (e.g. diesel, lignite, etc.), or with the simultaneous operation of a mix power station [20].

2.6. Sensitivity Analysis

When the economic analysis is completed, it is necessary to perform a sensitivity analysis by considering certain key PV system parameters, i.e. the assessment of the economic behavior of the project when important system parameters, such as the first year feed-in tariff cost, secured level of subsidy, loan amount, etc. are changed with respect to their base values. In the sensitivity analysis the variation of other key technical parameters (e.g. system size, etc.) may also be examined.

3. SYSTEMATIC DESIGN PROCEDURE

The design study of a PV system should include, among other things, the selection of the proper inverter(s), the PV modules, the sun tracking system, etc. The overall systematic study including the economic analysis may be conducted for a specific installation location taken into account the applicable national energy and development laws. The main steps of this systematic design procedure are given in block diagram form (see Fig. **1**).

4. CASE STUDY

4.1. PV System Configuration and Pertinent Results

The actual PV system under consideration is installed at Myrtofyto, Kavala of the Eastern Macedonia-Thrace region of Greece (see Fig. **2**).

The nominal size of the examined PV system is 100 kWp (99.96 kWp) and uses 12 automatically driven single shaft sun tracking systems (for east-west orientation). Each single shaft sun tracker may also be manually adjusted (for north-south orientation) with 6 predetermined positions (one for each month).

The necessary meteorological data are taken from the known data base of the Photovoltaic Geographical Information System (PVGIS) [21]. In this case the daily (and no monthly) data for the selected site are used in order to take into consideration more analytical and precise values for the parameters being used in the simulation algorithm including the variation of ambient temperature. On the other hand, the use of yearly data allows the estimation of annual energy production, which turns out to be 1180 kWh/kWp for a fixed base PV system.

The main technical characteristics of the installed PV system are summarized in Table **2**. The PV system consists of 12 PV arrays/subsystems. Each subsystem includes the associated PV modules, the inverter and the sun tracking system. An electrical panel is used for each array including the PLC (with the appropriate sun tracking software) and the switching and protection equipment. Using the central A.C. panel the PV system is divided in 3 groups (3 x 4 PV subsystems), so that each group is connected to one phase of the three phase grid. According to the Greek grid code practices the PV system must be connected to the LV grid, since its nominal power does not exceed the 100 kWp [14]. The simplified single line diagram of the used topology of the PV system is shown in Fig. (**3**).

From Table **2** it is clear that the selected inverters secure that the operation of the PV system will be within the applicable limits by the grid codes (e.g. IEC 61000-3-2).

The calculated average annual energy production of the examined PV system is equal to 154354 kWh, whereas the measured average annual energy production from the installed PV system is 166651 kWh. The percentage deviation between the calculated and associated measured energy is 7.96 %, and is primarily due to possible inaccuracies of the meteorological data being used. The monthly variation of calculated and measured energy production and the monthly

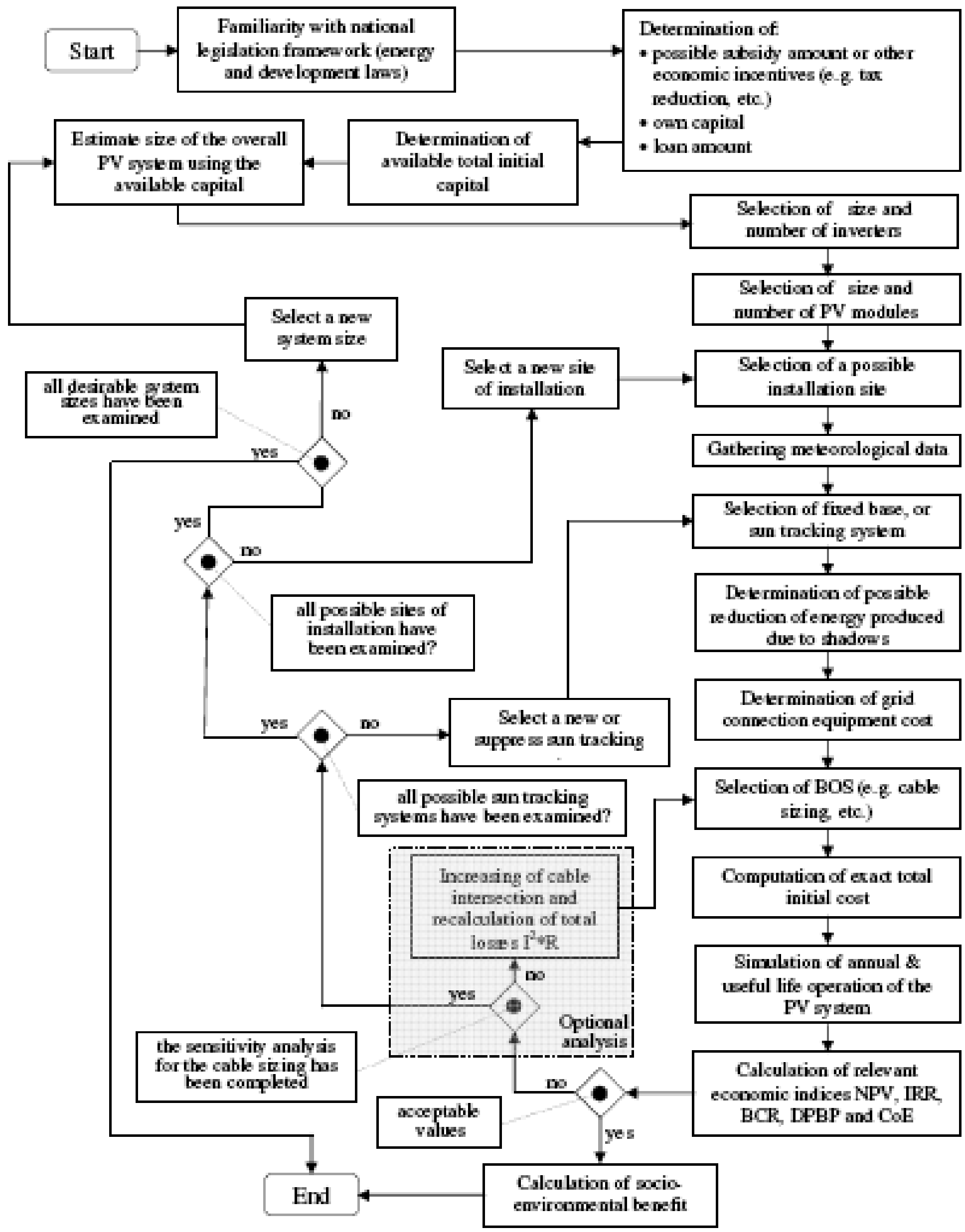

Fig. (1). Simplified block diagram of the systematic design procedure for the installation of a PV system.

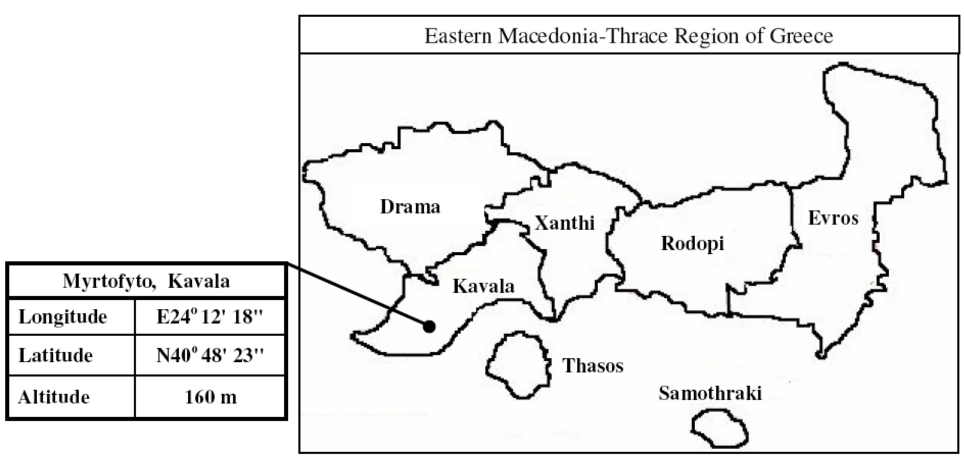

Fig. (2). Selected final site for the installation of the considered PV system.

Table 2. Main Technical Data of the Examined 100 kWp PV System

Characteristic	Value	Unit
PV system		
Total number of PV modules	588	
Total number of inverters	12	
Total number of sun trackers	12	
Nominal power	99960	Wp
PV module		
Type	BP Solar (3170N)	
Max. power	170 (-3%/+5%)	Wp
Open circuit voltage (V_{os})	44.3	V
Max. power point voltage (V_{mpp})	35.6	V
Short circuit current (I_{sc})	5.3	A
Max. power point current (I_{mpp})	4.8	A
Temperature coefficient I_{sc}	0.065 (±0.015)	%/K
Temperature coefficient V_{oc}	-0.36 (±0.05)	%/K
Temperature coefficient P_{mmp}	-0.5 (±0.05)	%/K
Module efficiency	13.5	%
Dimensions	1593 (±3) x 790 (±3) x 50	mm
Weight	15.4	kg
Inverters		
Type	SMA Sunny Mini Central SMC 9000TL-10 (~1ph)	
Max. DC power	9300	W
Max. DC voltage	700	V
PV voltage range, MPPT	333 - 500	V
Max. input current	28	A
Number of MPP trackers	1	
Max. number of strings (parallel)	5	
Nominal AC output	9000	W
Nominal AC voltage	220 – 240 (180 – 260)	V
AC grid frequency (self-adj.)	50 (±5%)	Hz
THD	<3	%
Power factor (cosφ)	1	
Max. efficiency	98	%
EuroETA	97.6	%
Operating temperature range	-25 to+60	°C
Consumption: operating (standby) / night	<10 / 0.25	W

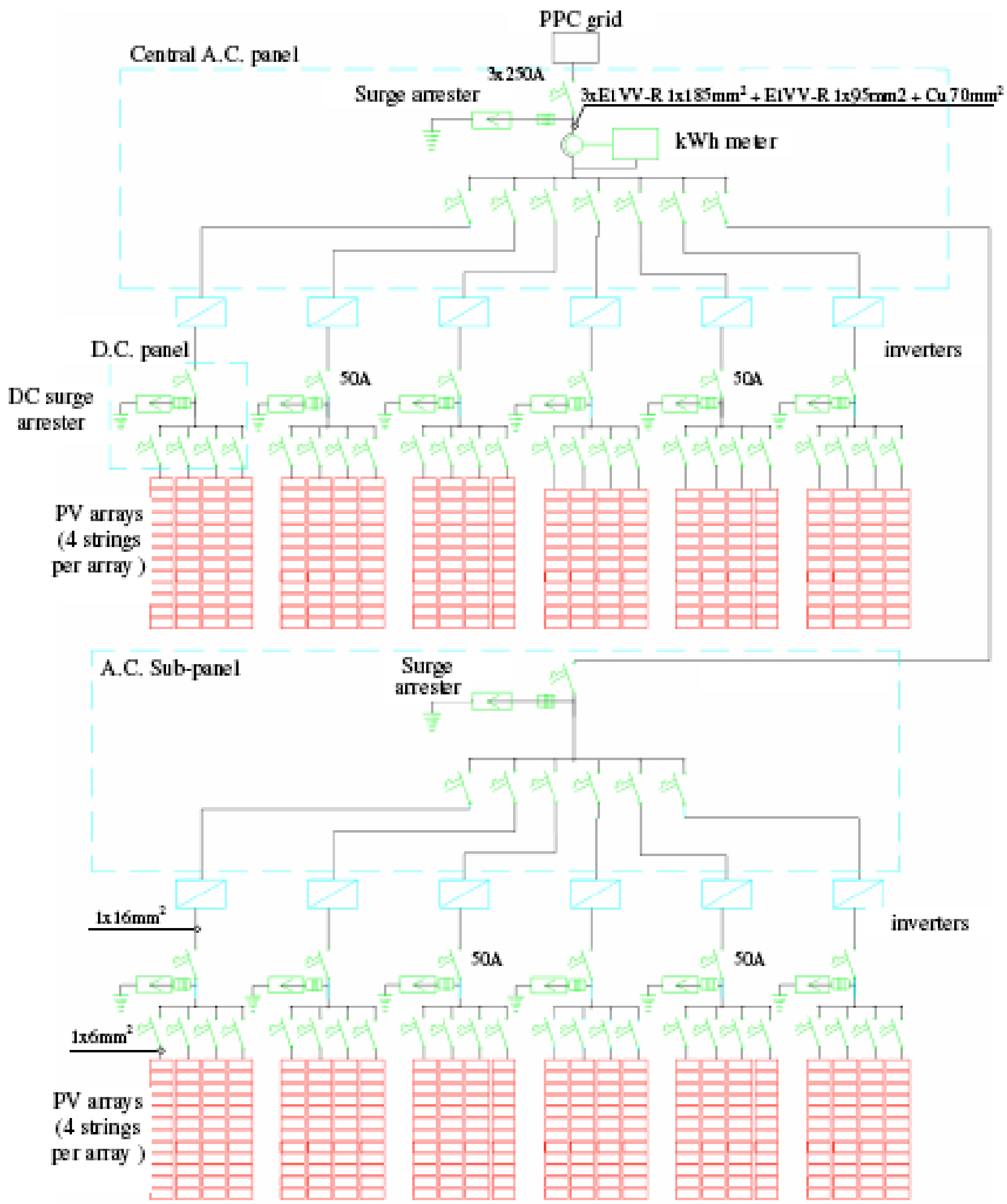

Fig. (3). Simplified diagram of the installed 100 kWp PV system topology.

variation of average sum of global irradiation per square meter received by the modules are shown in Fig. (**4**). Fig. (**5**) shows the daily variation of estimated energy production, measured energy production, and solar irradiation for the worst day of the year (17 December) concerning the energy produced by the PV system. Fig. (**6**) gives similar information with Fig. (**5**), but for the best day of the year (08 August). It is noted that in summer months the measured energy production exceeds the estimated value, whereas in winter months the estimated value for the produced energy is higher than the measured one.

The calculated results of the economic analysis show that the examined investment for the 100 kWp PV system is definitely economically viable, which is clear when one examines the data given in Table **3** together with the results of Table **4**.

The associated avoided emissions are calculated assuming that the electric energy produced by the PV system is substituting an equal amount of energy produced otherwise only by: Lignite stations; Diesel stations; NG stations; or by operation of mix power station of Greece for the production of each kWh. The considered life cycle analysis includes the amount of emitted pollutants for the production of the used PV modules and their efficiency reduction (derating), i.e. the yearly reduction of produced energy. The computed values of the associated avoided main pollutants (for one year and twenty years of operation of the PV system) are shown in Table **5**.

Fig. (**7**) depicts the dependence of the four economic indices on % variation of the first year feed-in tariff cost. The PV system investment remains economically viable even if a decrease of the feed-in tariff of 50% is applicable. In case

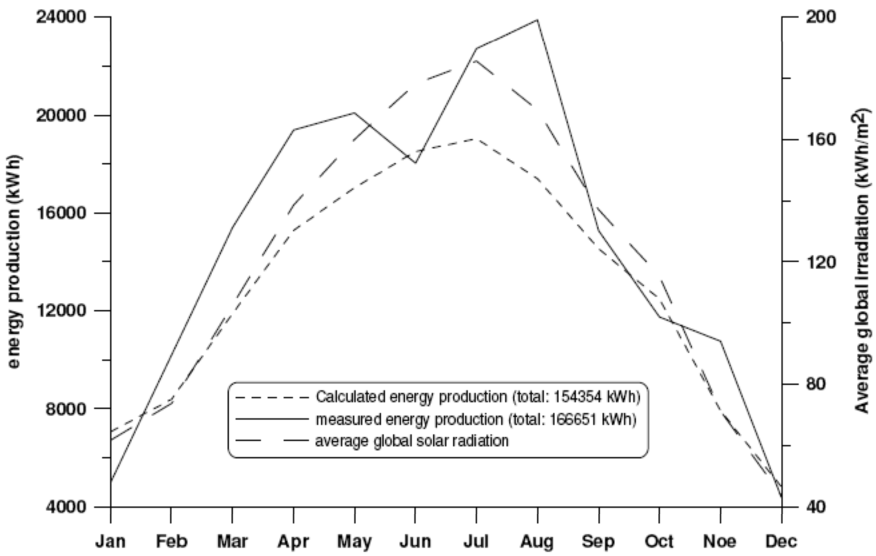

Fig. (4). Monthly variation of calculated & measured energy production and monthly variation of average sum of global irradiation.

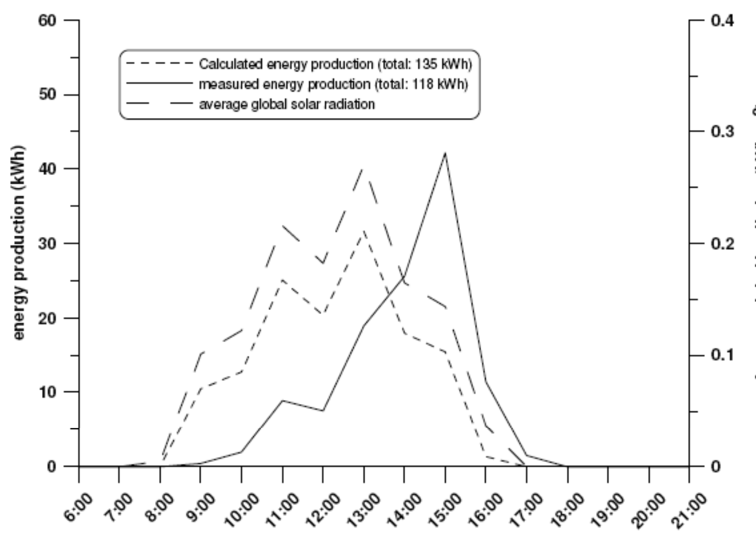

Fig. (5). Daily variation of calculated & measured energy production and daily variation of average global irradiation in the day of 17 December (worst day of the year).

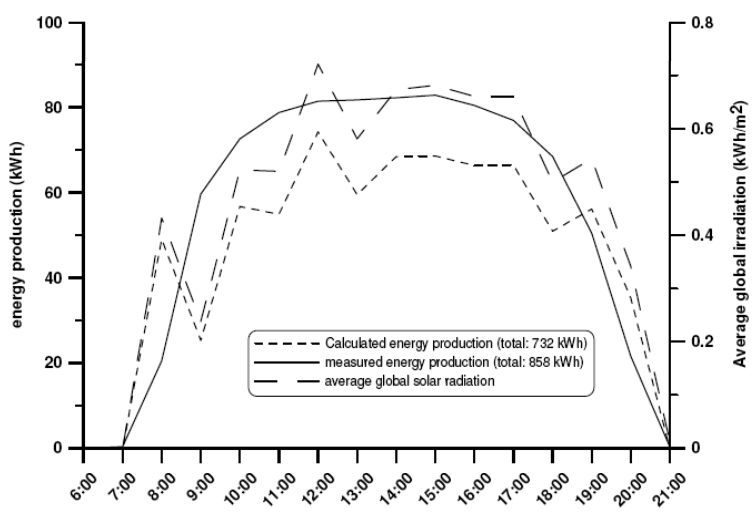

Fig. (6). Daily variation of calculated & measured energy production and daily variation of average global irradiation in the day of 08 August (best day of the year).

Table 3. Main Economic Data of the Examined PV System Investment

Data	Value	Unit
Total initial cost	490000	€
Subsidy	40	% of total initial cost
Loan	35	% of total initial cost
Annual loan interest	3.1	%
Loan payback period	10	yrs
Subsidy of loan interest	0	%
Economic life	20	yrs
Salvage value	0	€
Desired average rate of return	10	%
Straight line depreciation	20	yrs
Tax rate	25	%
Applied feed-in tariff	0.45714	€/kWh_e
Annual increase of feed-in tarif	2	%
Annual mainteneance cost	0.5	% of total initial cost
Annual increase of maintenance cost	2	%
Annual self-consumption cost	220	€

Table 4. Computed values of Relevant Economic Indices

NPV (€)	IRR (%)	DPBP (yrs)	BCR	CoE (€/kWh)
359 982	26.6	6.5	1.73	0.18

Table 5. Computed Values of Associated Avoided Amount of Main Pollutants Due to PV Operation

Avoided Emissions								
Main Pollutants	**With Lignite(100%)**		**With Diesel (100%)**		**With NG (100%)**		**With Greek Energy Production Mix[a]**	
	kg/yr	ton/(20yrs)[b]	kg/yr	ton/(20yrs)[b]	kg/yr	ton/(20yrs)[b]	kg/yr	ton/(20yrs)[b]
CO_2	159516	2905	117202	2134	82007	1493	126578	2305
SO_2	925	17	22	0.4	0	0	614	11
NO_X	386	7	370	7	77	1.4	292	5.3

[a] Lignite: 66.19%, Diesel: 6.83%, Large hydro: 11.11%, NG: 15.84% and RES: 0.03%

[b] Includes the emissions for the factory production of the 100 kWp PV system, i.e. 139.2 ton CO_2, 1.81 ton SO_2, 0.46 ton NO_X [22]

that the tariff is decreased by about 10% the DPBP value remains smaller than 8 years.

Fig. (**8**) shows the dependence of the five economic indices on the variation of total initial cost. Since the purchase price of PV systems is constantly decreasing, this investigation is necessary for any investor to have a clear picture of the economic attractiveness of such future PV systems installations. If the total initial cost is decreased by about 10% the DPBP value is decreased from 6.5 yrs to 5.8 yrs.

According to the latest development law (Law 3299/2004) in Greece, for the investor to secure the allowable subsidy he must invest as own capital at least 25% of the total initial cost. For the examined site of installation this law foresees max. % of subsidy 40% of total initial cost. In the following sensitivity analysis it is assumed that the subsidy and own capital level may reach 60% and 20%, respectively (in order to cover possible economic incentives of future development law). Figs. (**9** and **10**) depict

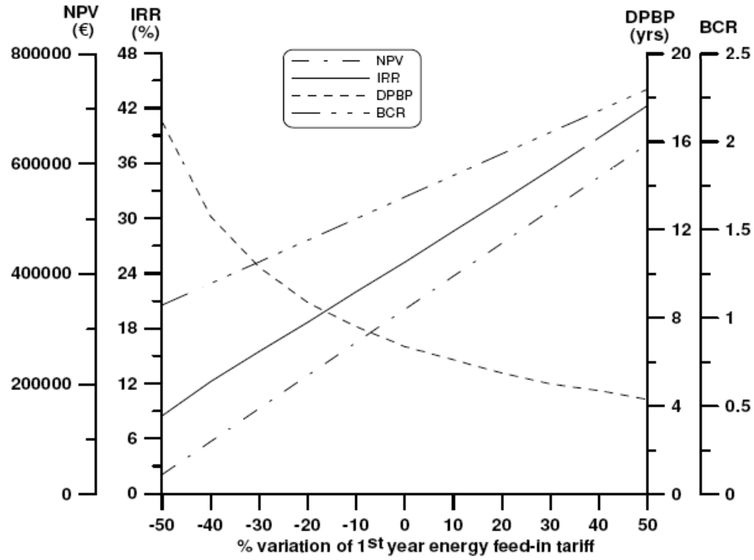

Fig. (7). Dependence of NPV, IRR, DPBP and BCR on % variation of the first year energy feed-in tariff (from base value of 0.4571€/kWh).

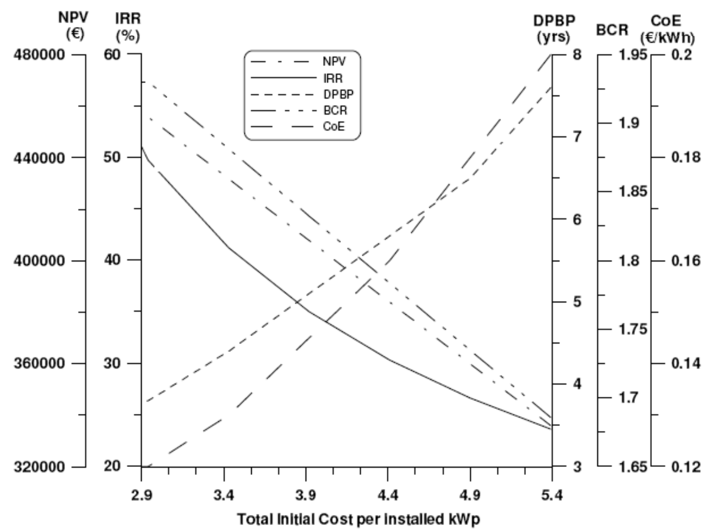

Fig. (8). Dependence of NPV, IRR, DPBP, BCR and CoE on variation of total initial cost (from base value of 4.9 €/ installed kWp).

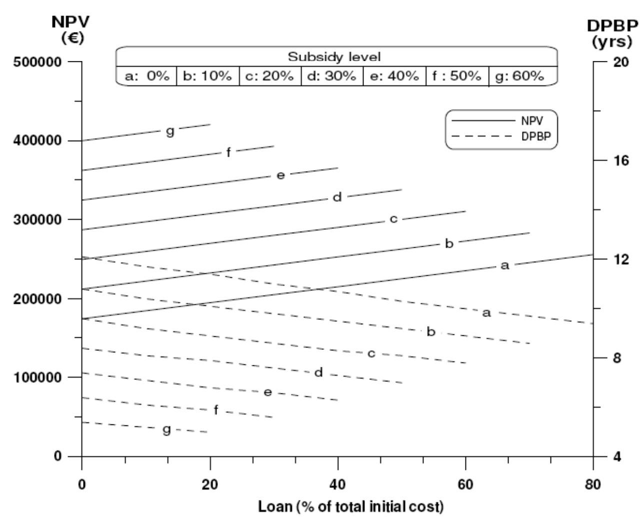

Fig. (9). Dependence of NPV and DPBP on % variation of loan amount for different levels of subsidy (where max. allowed subsidy for the site is 40%).

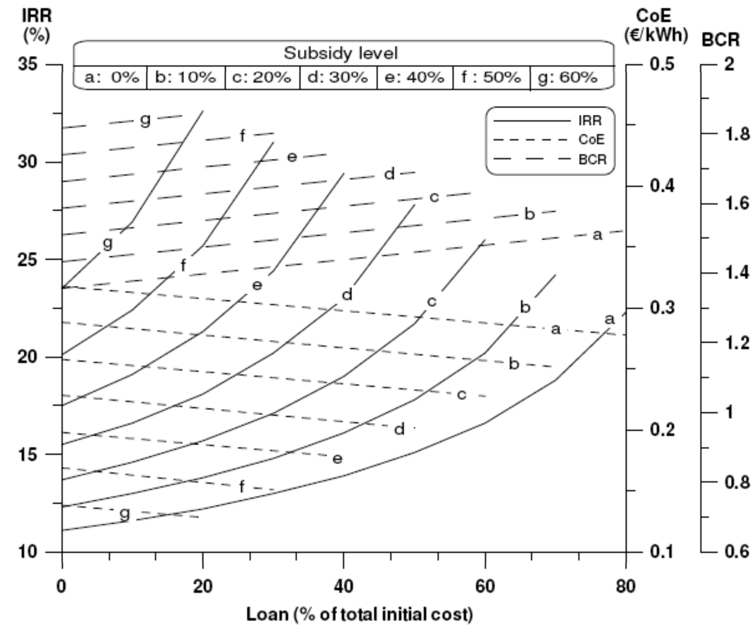

Fig. (10). Dependence of IRR, CoE and BCR on % variation of loan amount for different levels of subsidy (where max. allowed subsidy for the site is 40%).

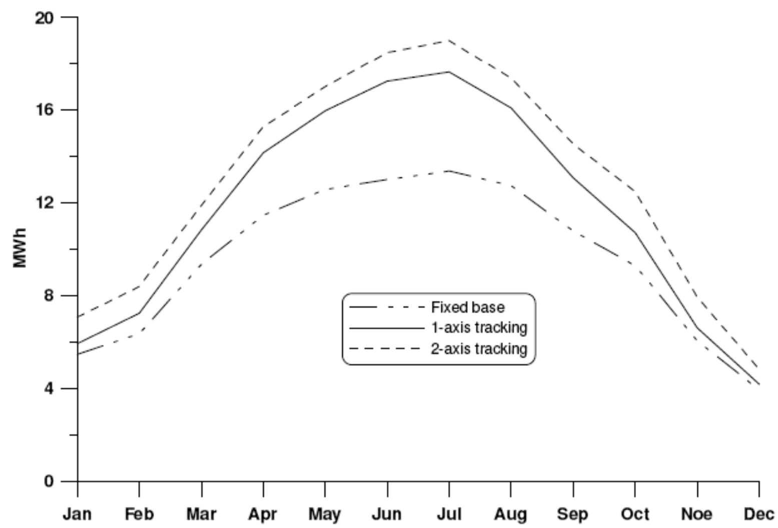

Fig. (11). Calculated annual energy production from the 100 kWp PV system for each of with the three examined sun tracking options.

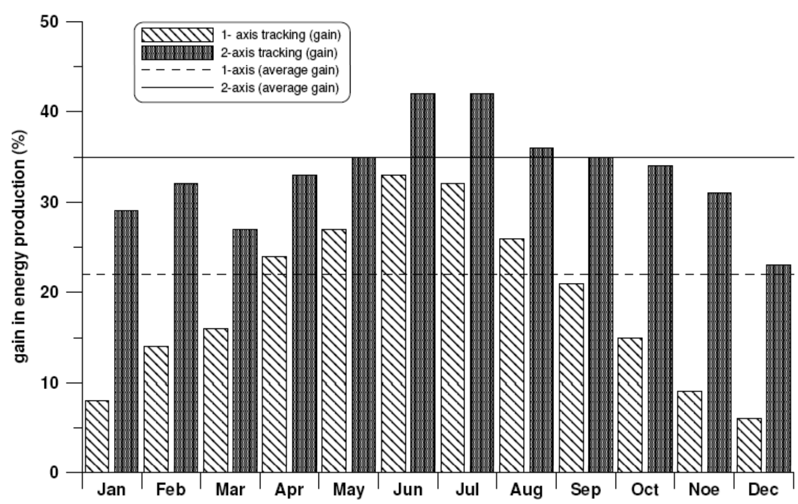

Fig. (12). Calculated gain by using 1-axis and 2-axis trackers in the PV system by comparison to the same fixed base PV system.

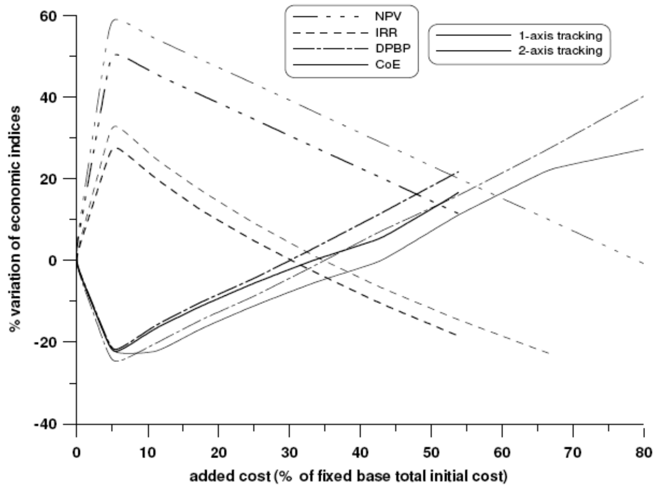

Fig. (13). % variation of the economic indices of the fixed base PV system investment as function of the added cost for the examined sun tracking system (expressed as % of the total initial cost of the fixed base PV system).

the variation of the two and three economic indices, respectively, as function of % loan amount for different levels of subsidy. In any case the own capital amount is [100-(% subsidy)-(% loan)]. As expected the increased % of loan and subsidy lead to more economically attractive investments, due to lower amount of own capital being required. It is to be noted that, due to the applicable high energy feed-in tariff, the examined investment is economically viable even if the total initial cost is to be covered totally by the investor.

For the examined three sun tracking systems: a) with fixed base system, b) with 1-axis tracking, and c) with 2-axis tracking system, the simulation results for the produced annual energy are shown in Fig. (**11**). As expected, the annual produced energy with the 2-axis tracking system is greater than the associated one using 1-axis tracking system. The use of a sun tracking system leads to higher annual energy production by comparison to the associated fixed base system. The annual energy production benefit by using a sun tracking system instead of a fixed base system is calculated and the associated results are shown in Fig. (**12**). As shown in Fig. (**12**) the yearly average increase of energy production by the PV system is about 22% and 35% using 1-axis and 2-axis tracking system, respectively.

For each PV system installation under consideration a practical system investment is to decide about the use or not of a sun tracking system. In the present work a thorough analysis has been conducted by calculating the variation of the values of the economic indices as function of the needed additional cost for the use of a sun tracking system (with the reference PV system being the fixed base one). The computed results for the 1-axis and the 2-axis trackers are shown in Fig (**13**). From Fig. (**13**) it is clear that the use of a sun tracking system is economically attractive only if its cost is smaller than 25-35 % of the total initial cost of the fixed base PV system.

5. CONCLUSIONS

In the present work a systematic procedure was developed and is proposed for the techno-economic-environmental assessment of a PV system with respect to a selected site of installation. The installation of an actual 100 kWp PV system was examined and its energetic, economic and environmental behavior were investigated via commercially available software under different installation, operating and financing conditions.

If a PV system is considered for installation and a thorough pertinent design study is conducted, then the required investment for its installation becomes economically viable. In addition, the availability of relative national economic incentives can make more attractive the wider spreading of this technology, since they enhance significantly the economic viability of a PV system investment and its exploitation. Also an energy balancing and planning analysis of RES penetration to a grid is valuable and necessary for determining the appropriate percentage level to be used.

A significant feature that must be investigated thoroughly is the selection of the mounting option of the PV system. It was demonstrated that the use of a sun tracking system becomes economically beneficial only if its cost is smaller than 30% of the cost of the fixed base PV system. In any case the use of a 1-axis sun tracker increases the energy production of the PV system, whereas the use of a 2-axis tracker system is more beneficial on the basis of annual produced energy.

Finally, the PV system installations lead to significant reduction of otherwise released pollutants to the atmosphere, particularly if they substitute energy produced by lignite power stations (which is obviously the case in the Greek power system). In order to assess in a more detailed way the environmental benefits by the use of PV systems, a life cycle analysis including the produced energy by the PV system and the needed energy for its production process must be taken into account.

NOMENCLATURE

a_i	=	Anisotropy index
a	=	Orientation of surface (degrees)
b	=	Slope of surface with the horizontal plane (degrees)

(b, a)	=	Oriented inclined surface
CoE	=	Cost of energy
DPBP	=	Discounted pay back period
BCR	=	Benefit to cost ratio
f	=	Brilliance of the horizon
f_D	=	Reduction coefficient of diffuse irradiation due to shading
f_{PV}	=	Coefficient of losses of the PV module
G_B	=	Direct component of solar irradiance
G_D	=	Diffuse component of solar irradiance
Gp_g	=	Reflected on the ground component of solar irradiance
G_s	=	Irradiance on Standard Test Conditions (STC), ie 1000W/m2, 25 ^{o}C and 1.5 AM
G_t	=	Diffuse irradiation
H_{hm}	=	Hourly average of global irradiation (kWh/m2)
IRR	=	Internal rate of return
NPV	=	Net PRESENT value
P_{Cu}	=	Copper losses
P_{DC}	=	Input power of the inverter
R_b	=	Ratio of direct irradiance on an inclined surface to direct irradiance in the horizontal plane
Y_{PV}	=	Installed capacity of the PV module
η_{DCnom}	=	Nominal efficiency of the inverter
η_{rel}	=	Relative efficiency of the inverter
ω_s	=	Sunset angle

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