EFFICIENT CONTROL FOR OPERATIONAL ENHANCEMENT OF AN INSTALLED 99,75 kWp GRID-CONNECTED PV SYSTEM AND PV MODULE TEMPERATURE IMPACT CONSIDERATIONS

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Abstract**:** *This paper presents a techno-economic assessment of an installed 99,75 kWp grid-connected photovoltaic (PV) system. The actual site of the system is in the Central Macedonia Region of Greece (city of Katerini area), where a weather station has been installed providing the necessary meteorological data since May 2008 when the system was connected to the electric grid for exploitation purposes. The energy produced by the PV plant is injected to the national electric grid through three central inverters with a feed in tariff of 457€/MWh. The design of the system complies with the national utility code requirements. The system uses MPP tracking and also one-axis sun-tracking system for more efficient and economic operation. The sun-tracking system is programmed properly by using a PLC. In addition, the system is further investigated by maintaining the PV module temperature below a certain value.*

Keywords: *photovoltaic, inverter, module, temperature*

1 INTRODUCTION

Implementation of Renewable Energy Sources (RES) on the electric grid is rapidly growing. Many EU countries etc. have set targets regarding the percentage of power to be produced by RES. Some RES, such as wind power systems, are already considered competitive but they can only be implemented on specific sites. On the other hand, PV power generation is attractive because it is a clean, sound free, and more predictable and inexhaustible energy source (Tsuchiya 1999). For many years the low cost of operation and maintenance (O&M) of central thermal power stations combined with the low prices of fuel, while the increased prices of PV generators (PVGs) and the necessary accompanying power electronics resulted in the extended use of the former to supply almost exclusively electricity to the electric grid, which results in rapid consumption of fossil fuels and in environmental pollution problems. The recent developments of PVs and their related Balance Of System (BOS) have caused a significant decline in their prices. On the other hand, the continuous increasing needs in energy and the utilization of natural resources has caused enormous increase in fuel prices (Papadopoulos and Maltas 2010). These facts have made RES a viable alternative to at least supplement the constant growing needs of electricity (Wies et al 2005).

The advantages of grid connected PV schemes are many since they produce their maximum power at hot summer days when the electric companies must supply their peak loads. They can be dispersed and thus reduce the associated grid losses. Furthermore, modern inverters provide high quality ac power. PV power generation results in reduction of greenhouse gas emissions (Tan et al 2004). The major limitations of PV energy utilization in electric grids, are economical as their prices are still relatively high and there are at times additional costs, inconveniences and management involved which may outweigh the relevant financial benefits (Khouzam 1999). The financial attractiveness of grid connected PV plants depends greatly on the adopted energy policy. The most common policy used to enhance the implementation of grid connected PV plants is the increased feed-in tariff, combined with favorable national investment incentives.

This paper presents a systematic techno-economic assessment for the purpose of system's operational enhancement, and also examines the associated impacts the PV module temperature has on a grid-connected PV system (i.e. the installed 99,75kWp). This PV system has been in operation since May 2008 and relevant meteoroligal data at the actual site are gathered and processed. This data is combined with conducted actual tests on the PV modules and properly analyzed. In addition, an economic analysis and the environmental benefits of the PV system are performed.

2 GRID-CONNECTED PV CONSIDERATIONS

2.1 Energy production by a PV generator

The energy produced by a PV generator (PVG) is proportional to the global radiation and also is related to the existing PV module temperature and the relevant air mass. Other minor factors are the maximum power point dependence on irradiance level, the soiling and possible shading problems, the variation in solar spectrum, and the optical losses when the sun is at high angle of incidence (Markvart and Castaner 2003).

As PV design engineers aim to secure maximum economic return of the required investment, usually global irradiation (G), ambient temperature (T_a), and if possible wind speed at the actual site are extracted and properly assessed for a period of time (i.e. for at least one year). If G and T_a are known, then the PV module temperature (T_c) can be obtained by using (1) (Markvart and Castaner 2003):

$$T_c = T_a + \frac{NOCT - 20}{800} \cdot G \tag{1}$$

where: NOCT (Nominal Operating Cell Temperature) in ^oC and G in W/m^2. If G and T_c are known, then the actual power at G and T_c conditions can be well approximated by (2):

$$P(G,T_c) = P_{STC} \cdot \frac{I_{SC}(G,T_c) \cdot V_{oc}(G,T_c)}{I_{SC_{STC}} \cdot V_{oc_{STC}}} = FF \cdot I_{SC}(G,T_c) \cdot V_{oc}(G,T_c) \tag{2}$$

where: FF is the fill factor of the used module; $P(G,T_c)$, $I_{SC}(G, T_c)$and $V_{oc}(G,T_c)$ are the power, the short-circuit current and the open-circuit voltage of the PV module at (G, T_c) conditions, respectively; and P_{STC}, $I_{SC_{STC}}$ and $V_{oc_{STC}}$ are the power, the short-circuit current and the open-circuit voltage of the PV module at Standard Test Conditions (STC), respectively (given by the manufacturer of the PV module). It is to be noted that FF is slightly altered at various (G, T_c) conditions.
The $I_{SC}(G, T_c)$ can be well approximated by (3):

$$I_{SC}(G,T_c) = I_{SC_{STC}} \cdot \frac{G}{1000} \tag{3}$$

The $V_{oc}(G,T_c)$ can be calculated by (4) (Luque and Hegedus 2003):

$$V_{OC}(G,T_c) = V_{OC_{STC}} - \frac{TKV_{OC}}{1000} \cdot (T_c - 25) + \left(\frac{k \cdot q}{T_C}\right) \cdot \frac{G}{1000} \tag{4}$$

where: TKV_{OC} is the open-circuit voltage drop (in mV/^{0}C) given by the manufacturer.

The effect of temperature on the PVG performance depends primarily on the material being used as temperature coefficients vary for crystalline and amorphous silicon solar modules (King et al 1997). As known the effect of temperature on the PVG is of less importance than the associated effect of the irradiation and is more complicated to be considered. In general the increase of T_c in solar modules causes reduction in their output power production and efficiency.

Since global radiation is the most important factor for the cost-effectiveness of a PV system one or two axis sun-tracking systems may be used to increase their annual energy production. Depending on the latitude the annual energy can be increased by 25-30% by using a sun-tracking system.

2.2 Energy conversion (dc to ac) of a PV system

The output power (dc) of the PVG is transferred to the connecting inverter(s). The inverter(s) convert the dc power into ac power which is then injected at the connection point to the electric grid. The inverter deals also with some principal integration issues. Those issues are safety, power quality, dc injection, and radio frequency suppression. In terms of safety (according to the relevant applied electric codes) the main technical issue has been islanding since it may create hazards for personnel and equipment. Several passive methods (e.g. overvoltage, undervoltage, overfrequency, underfrequency, frequency variation rate, voltage phase jump, third harmonic voltage detection etc.), and active methods (e.g. frequency shift, impedance measurement, harmonic impedance measurement etc.) are used for islanding detection. From these methods the phase criteria, in spite of their simplicity, predict the ranges of loads that lead to detection failure with good accuracy. Additional research has shown that the frequency shift methods which were considered as being the most effective techniques for islanding detection for grid-connected inverters, bear nondetection possibilities for paralleled RLC loads, whereas the automatic phase-shift method is proposed to alleviate this problem (Hung et al 2003). An issue for future anti-islanding schemes is still the avoidance of mutual disturbances by a high number of different types of inverters in an isolated grid section.

Modern inverters perform MPPT of the PVG for the purpose of extracting the maximum possible power. The positions of maximum power on the PVG characteristic depend mainly on the irradiation level and the associated T_c value. MPPT can be achieved directly or indirectly. Indirect MPPT is achieved when some system parameters are measured. For example season-dependent tracking of the PVG voltage leads to more energy production than using a set value of voltage for the whole year. Another indirect MPPT method is the temperature controlled working point voltage, where a temperature sensor is used and the working point voltage is adjusted. Also an indirect MPPT method is based on the measurement of the PVG open circuit voltage, which requires regular intervals of short separation of the load. Direct MPPT is achieved from actually measured current, voltage or power values of the system. Thus, direct MPPT can respond also to unforeseeable modifications in the behavior of the PVG. Direct MPPT also has the advantage that it does not require meteorological sensors, since the necessary measurements are the voltage and current produced, whereas interruption of the normal operation is not required. The MPPT procedure is generally based on a search algorithm. Most algorithms vary the PVG current and decide about the working point. If by increasing the current the injected power to the grid increases or decreases and then is decided how the inverter control must be changed in order to move the operating point in the direction of the maximum power point. Recent studies suggest that voltage based MPPT has several advantages over current based MPPT since it is more efficient and has less circuit losses, whereas current based MPPT provides more accurate approximation of the non linear PV characteristics. More sophisticated MPPT algorithms compute the sign of the PV power derivative vs. voltage and may indicate if the control system has good performance and thus the knowledge of the PV panel model is not required (Casadei et al 2006). Most grid-connected inverter manufacturers use direct voltage-based MPPT algorithms which can be performed at a specific dc input voltage range.

The nominal ratings of the inverters determine the PVG design. Several PV modules connected in series form a string which provides the required voltage value for the inverter to perform MPPT and its current is equal to the current of a single solar module. Each string goes through a string control device which compares the power of each string to that of the other ones. Then several strings are connected in parallel in order to give the total input current of the inverter (see Fig.1).

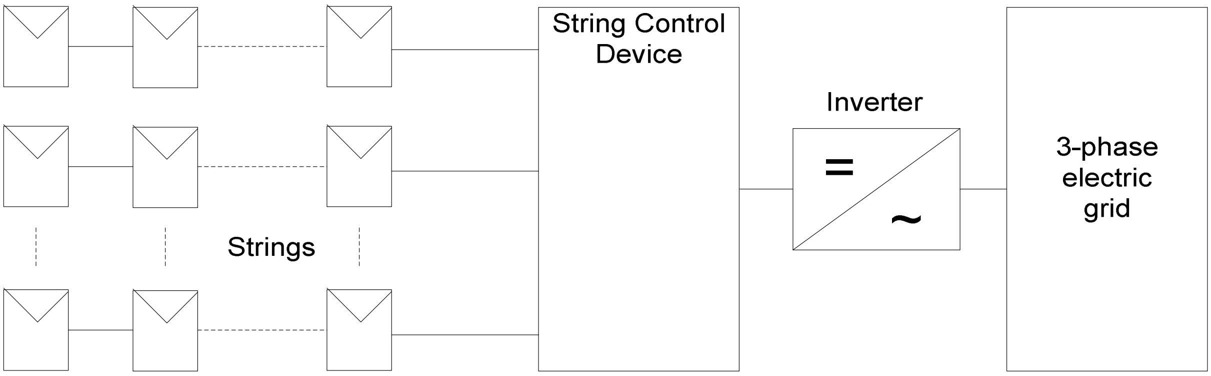

Fig.1. PVG schematic using central inverter configuration

3 CONTROL OF A PV SYSTEM

The complete PV system is fully controlled by a PLC. The PLC's inputs are dealing with the time of the day, which when combined with the season provide outputs to the motors moving the sun-tracking devices and thus the PV modules capture the most possible global radiation. The wind speed and direction are also inputs to the PLC, since severe damage may occur to the PV modules and the sun-tracking systems if the wind speed exceeds a critical value. Under such conditions the tracking system places the PV array in parallel with the wind direction to avoid damage (see Fig.2).

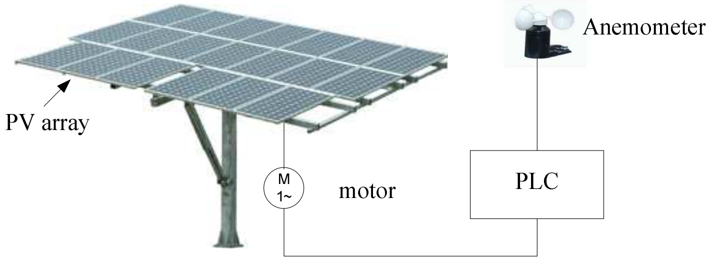

Fig.2. General schematic of sun-tracking system control

The string control is a device that is located between the PV modules that form strings and the central inverter. This device compares the power produced by each string to that of the others. If a string does not produce almost the same amount of power as the others, then an alarm is set and the string is identified so that the faulty PV module(s) may be repaired.

4 CASE STUDY

The installed 99,75kWp grid-connected PV power system (being composed of 570 monocrystalline PV modules of 175 Wp each) is assessed technically and economically in a systematic way. The PV modules are mounted on one axis sun-tracking system. Ten PV modules compose one string and each string is connected to the string control device. Nineteen strings are connected in parallel and provide the input power to each of the three central inverters with nominal power 32 kW. The PVG power is 97% of the inverters' maximum power.

The PV power system has been in operation since May 2008 with applicable feed-in tariff of 457€/MWh. Its measured data are its produced ac power and energy, the grid voltage, the dc current and voltage. The recorded meteorological data are the temperatures T_c and T_a, the G on the modules' inclination, and the wind speed.

The performed economic evaluation is based on the measured and recorded data. In addition energy production tests were held to PV modules of the same type keeping the T_c value constant. The financial benefits by keeping the T_c value below a certain limit are thoroughly examined.

4.1 Meteorological data of the site of the PV system

The statistical solar data of the selected site for the year 2009 were measured-recorded from a meteorological station installed at the mentioned site, which collects all necessary data for the assessment of the installed PV system. The measured monthly daily mean irradiation $(G_d)_m$ for the surface of the one-axis sun-tracking system and the associated theoretical values for a tilted surface at 32^o are shown in Fig.3.

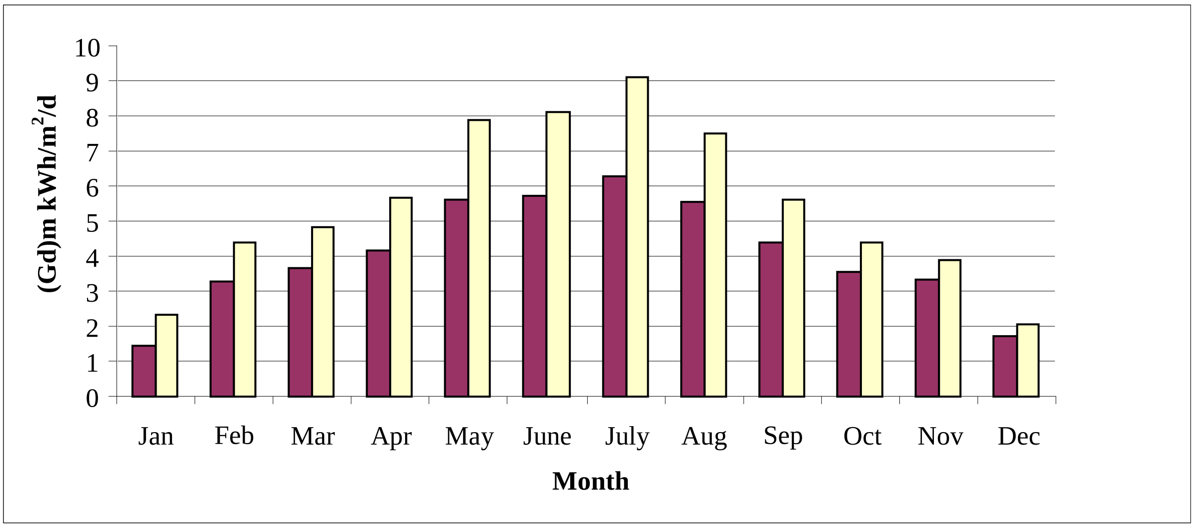

Fig. 3. Monthly daily mean irradiation $(G_d)_m$ for the examined site (Katerini area in Greece for data of year 2009): ■ without sun-tracker and with 32^o angle, and □ with sun-tracker

4.2 PV system design

Using Fronius Solar.Configurator the proposed design of the PV system is shown in Fig.4. The specifications of each PV module and inverter(s) used are summarized in Table 1 and Table 2, respectively.

Generally, PV design engineers aim to connect as many PV modules as possible in one string in order to form the least possible number of strings. This principle results in reduced cabling (that reduces also the requirements for the connection devices between the PVG and the inverter) and enhances the efficiency of the inverter as its input voltage falls mostly in the MPPT range.

Each of the three central inverters has as input 190 PV modules (divided in 19 strings and with 10 PV modules in each one). Each string is mounted on each of the sun-tracking systems. This PVG design forms the input power of each inverter 33,25kWp which is the 97% of its maximum power (see Fig.4). Thus, for the given site, the design results with a maximum PV current of 100,7A, a 299V MPP voltage at 65^oC, a 358V MPP voltage at 25^oC, and a 495V open-circuit voltage at -10^oC. These calculations show that the inverter's voltage is always in its MPP range when it injects power to the grid, resulting in improved efficiency without running the risk of damage. Further efficiency improvement may be achieved when the inverter is operating at its nominal power ratings. The proposed central inverter(s) accomplishes this by dividing its overall power in twelve sub circuits all of which are connected in parallel. If one of these sub circuits appears to be faulty, it can easily be replaced without affecting the operation of the others. At the beginning of the day, when the PV modules produce enough voltage and power for the inverter to start its operation, the latter activates randomly one of its twelve sub circuits. Some time later, and if the weather conditions are suitable, another sub circuit may be activated etc. This results in less operating hours for each of the inverter's sub circuits, with the end result being the extention of its lifecycle, minimization of inverter's losses, and improvement of the overall efficiency of the inverter.

Model	**SW175 mono**
Power [W]	175 Wp
Open circuit Voltage [V_{OC}]	44,4 V
MPPT voltage [V_{MPP}]	35,8 V
Short circuit current [I_{SC}]	5,30 A
MPPT current [I_{MPP}]	4,89 A

Tab.1. Technical specifications for SolarWorld SW175 mono PV module

Model	**Fronius IG 400**
AC output power	32 kW
MPP voltage range	210-420 V
Maximum input voltage	530 V
Maximum DC input power	34,4 kW
Maximum input current	164 A
Maximum efficiency	94,3%
Euro efficiency	93,4%
Mains Connection	3~NPE,400/230VAC, 50Hz
THD	<5 %

Tab.2. Technical specifications for Fronius IG 400 central inverter

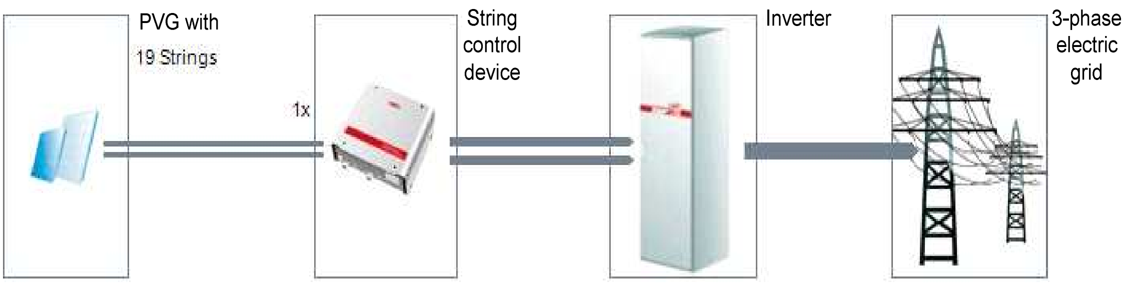

Fig.4. Design schematic of the PV system for one of the three used central inverters

The PV string with 10 PV modules (which refers to one-axis sun-tracking structure, is led to the central inverter via a string control device) and its power is calculated and compared to each other. Such action may trigger the string control device, not only in the case of a faulty PV module, but also in the case of a fault in the sun-tracking motor, which will result in wrong positioning of the sun-tracking structure. For the safety of the equipment each PV string is protected not only by the fuse (set in the string control device to prevent overcurrent to the string control) but also by a suitable varistor which is set before the fuse to prevent overvoltages which may be a result of a thunder strike. Similar actions are taken in the ac side of the inverter to avoid its possible damage from large disturbances occurring in the electric grid side.

4.3 Economic analysis of the PV system

An economic analysis is performed taking into consideration the Greek market prices at the beginning of the installation of the system (January 2008) for the used equipment. The feed-in payment earnings of the system are calculated based on its operation during the year 2009 (see Tab. 3). Based on the one year (2009) and on the life-cycle (20 years) operation of the PV system, the associated avoided CO_2 emissions to the environment are shown in Tab.4. The main data for the economic assessment are shown in Tab. 5, whereas the computed results of the relevant indices NPV, IRR, DPBP, BCR, CoE are shown in Tab. 6.

From Tab.4 it is obvious that the CO_2 avoided emissions to the environment are really significant.

Month	Produced Energy (kWh)	Monthly Earnings (€)	Daily Earnings (€)
January	6716	3069,21	99,01
February	11821	5402,20	192,94
March	13844	6326,71	204,09
April	15121	6910,30	230,34
May	21243	9708,05	313,16
June	21327	9746,44	324,88
July	23925	10933,73	352,70
August	19789	9043,57	291,73
September	14777	6753,09	225,10
October	12331	5635,27	181,78
November	10844	4955,71	165,19
December	5924	2707,27	87,33
Total	**177662**	**81191,55**	**222,44**

Tab.3. Actual energy production and associated earnings of the 99,75 kWp PV system for the year 2009

Alternate production with	2009 operation	Life-cycle operation (20 years)
Lignite	183,738	3674,761
Oil	134,998	2699,965
Natural gas	94,459	1889,187
Generation mix of Greece	153,008	3060,157

Tab.4. Avoided CO_2 emissions in tons for a year (2009) and for life-cycle (20 years) operation of the 99,75 kWp PV system

Parameter	**Value**
Total Initial Cost (€)	595000
Subsidy on Total Initial Cost (%)	50
Self-Capital on Total Initial Cost (%)	25
Loan on Total Initial Cost (%)	25
Annual Loan Interest (%)	6
Discount Rate (%)	7
Economic Life Cycle (yrs)	20
Feed –in Payment (€/kWh)	0,457
Increase of Feed –in Payment (%/yr)	1,1
Operating Cost (€/yr)	1500
Increase of Operating Cost (%/yr)	2
Tax Rate (%)	25

Tab.5. Main economic data of the PV system applicable for the year 2009

It is clear from the computed result of Tab.6 that the investment of the PV system is very attractive in both examined cases (i.e. with total initial cost and with self capital cost).

Indices	Value	
	Based on Total Initial Cost	Based on Self Capital Cost
NPV (€)	170065	417422
IRR (%)	10,1%	24,2
DPBP (yrs)	13,4	6,6
BCR	1,29	1,7
CoE (€/kWh)	0,32	0,16

Tab.6. Computation of economic indices of the PV system

4.4 PV module temperature impact considerations

High T_c values affect negatively the efficiency of the PV modules. At the given site the maximum recorded T_c value for the year 2009 was 60^{o}C, much higher than the 25^{o}C used for the STC case. Experiments were conducted on the same type of PV modules used in the 99,75kWp grid-connected PV system, while the T_c value was maintained constant at 25^{o}C and changing the irradiance (see Fig.5). Based on the information of Fig.5 and taking into account the 570 PV modules of the PVG, its computed expected energy production and the associated earnings for the year 2009 are calculated and presented in Tab. 7.

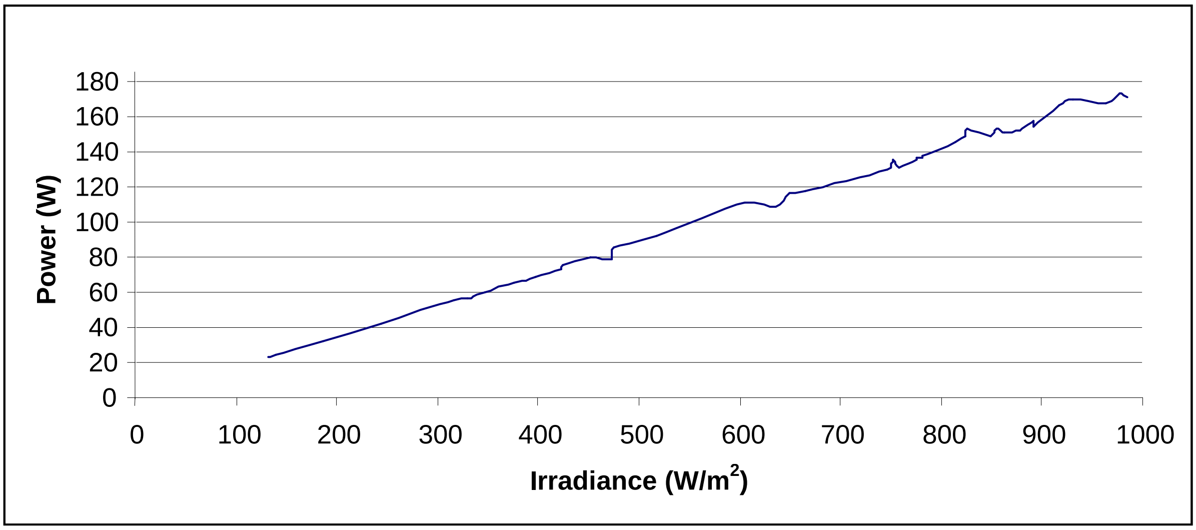

Fig.5. Output power as function of irradiance of one PV module (175Wp)

5 CONCLUSIONS

In this paper an installed 99,75 kWp grid-connected PV system is thoroughly investigated and assessed techno-economically. The recorded data, from the beginning of the system's operation, are used to also assess the economic impact the T_c values have on the PVG energy production performance. The obtained computed results show that the relatively high ambient temperature, during the summer period, affects adversely the efficiency of the PV module and consequently that of the PV system.

Experiments conducted on the same type of module (175Wp) at constant T_c value (25^{o}C) are used in combination with recorded data of the PV system (of this work) to assess the financial impact the high T_c values, recorded during summer period have on the system's efficiency. From Tab.7 it is seen that when T_c<25^{o}C an additional 11820 kWh (6,65%) would have been produced by the PV system for operation of year 2009 providing additional associated earnings of 5401,74€.

Finally, it is pointed out that with the operation of the PV system a significant amount of CO_2 emissions are avoided, and the economic analysis of the PV system clearly demonstrated the attractiveness of its investment.

Month	Optimized energy produced (with T_c<25°C) (kWh)	Actual energy produced (with free T_c value) (see Tab.3) (kWh)	Monthly optimized earnings (€)	Daily optimized earnings (€)
January	6737	6716	3078,81	99,32
February	11865	11821	5422,31	193,65
March	13994	13844	6395,26	206,30
April	15706	15121	7177,64	239,25
May	22957	21243	10491,35	338,43
June	23405	21327	10696,09	356,54
July	26901	23925	12293,76	396,57
August	22049	19789	10076,39	325,04
September	15907	14777	7269,50	242,32
October	12904	12331	5897,13	190,23
November	11060	10844	5054,42	168,48
December	5994	5924	2739,26	88,36
Total	189479	177662	86591,92	237,24

Tab.7. Optimized energy production and associated earnings of the 99,75 kWp PV system by maintaining T_c below 25°C for operation of year 2009

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