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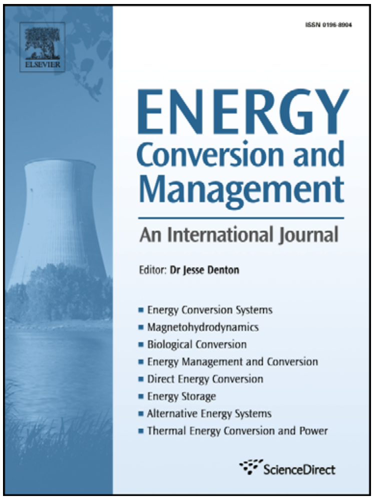

Performance Analysis of PV plants: Optimization for improving profitability

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Performance Analysis of PV plants: Optimization for improving profitability

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ABSTRACT

A study is conducted of real PV production from two 100 kW_p grid-connected installations located in the same area, both of which experience the same fluctuations in temperature and radiation. Data sets on production were collected over an entire year and both installations were compared under various levels of radiation. The installations were assembled with mono-Si panels, mounted on the same support system, and the power supply was equal for the inverter and the measurement system; the same parameters were also employed for the wiring, and electrical losses were calculated in both cases. The results, in economic terms, highlight the importance of properly selecting the system components and the design parameters for maximum profitability.

Keywords: System Performance, PV System, Grid-Connected, optimization.

1. Introduction

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Over the last decade, global market penetration of photovoltaic (PV) technology has increased tremendously. This trend is not only driven by the environmental benefits that characterize this technology, but also by the incentive mechanisms developed in various countries; the most common of which, the feed-in tariff, has been introduced in many countries and regions in recent years. In this model, electricity companies are obliged to purchase electricity from renewable energy sources at a minimum price fixed by law. Feed-in tariffs have been adopted in many countries including: Austria, France, Denmark, France, Germany, Greece, Italy, Netherlands, Portugal, Spain, Switzerland and the state of California (USA), among others. Table 1 summarises the electricity price of PV kWh in different countries [1] in 2009.

High demand and an exponential increase in the supply of components for photovoltaic systems have led to a very significant price drop per kW installed, and economic incentives have encouraged a large number of small investors to enter the photovoltaic market. PV module prices have fallen by 22 % each time the cumulative installed capacity (in MW) has doubled [2]. For large ground-mounted systems, the generation costs in 2010 ranged from approximately €0.29/kWh in the north of Europe to €0.15/kWh in the south of Europe and were as low as €0.12/kWh in the Middle East. According to EPIA (European Photovoltaics Industrial Association) estimations, these rates will fall significantly over the next decade. Expected generation costs for large, ground-mounted PV systems in 2020 are likely to be in the range of €0.07 to €0.17/kWh across Europe[2].

In the Spanish case, this has meant more than 3,350 grid connected MW distributed across more than 50,000 installations. Spain is a world leader in solar penetration per capita (75.19 W / person) and coverage of electricity demand by this technology was 1 % in 2008 and approximately 1.5 % in 2009. The technology has already won widespread social acceptance, is no longer marginal, and will be the basic standard in a very short time. The Spanish PV market in 2008 reached a value in excess of 16,000 M€, with over 40 identified companies engaged in the manufacture of components, many installation companies and more than 15,000 direct permanent jobs and a further 25,000 casual jobs at peak activity[3]. However, mechanisms to ensure the quality of facilities in Spain, from an energy standpoint, have not been implemented in any single instance. The economic returns are guaranteed even if the installation is not optimized.

The profitability of the investments made so far has become a priority for both government and industry. In Spain, this is evident from the changing scenario brought about by Royal Decree (RD) 1578/2008[4], which introduced a significant decline in production premiums, and by Order ITC/3353/2010[5], which placed limitations on production times at feed-in tariff prices and introduced the obligation to produce at the ordinary tariff at other times. The same situation occurs in other countries like France[6], Italy [7] or Germany [8]where the entry into force of the new regulated rates was a major turning point in the profitability of the facilities.

Studies of PV systems in Germany [9], California [10] and Japan [11], have revealed performance problems associated with such issues as shading, equipment and installation defects, inverter failure, and deviations from manufacturer’s specifications in the PV modules.

In this work, the importance of an appropriate choice of elements for the installation is studied. The influence of the quality of the panels used, the location of the protection and measurement system, the design of the wiring and the choice of the inverter system have all been analysed in economic terms, using real production data taken from two 100 kW_p grid-connected installations.

2. The facilities.

Both facilities (System 1 and System 2) in this case study are located at Torquemada (Palencia), at the centre of the autonomous region of Castilla y León in Spain. Their geographical coordinates are 42º 01'28'' N latitude and 4º 18'28''W longitude, situated at an altitude of 740 m above sea level. The facilities are located in neighbouring plots, with no barriers between them, occupying a total surface parcel of 8000 m^2. They stand on a gentle, south-facing slope that is conducive to natural air circulation, one of the most beneficial aspects for improving the panels' electrical production in summer time.

Hence, the two facilities are subject to the same environmental conditions in terms of temperature, radiation, humidity and wind speed. The area benefits from very favourable atmospheric conditions. Solar irradiation is estimated at approximately 1,450 Kwh/m^2year[12]. The ambient temperature range is between 4ºC and 20ºC and the number of cloudy days is very low[13]. Figure 1 presents an aerial photograph of both installations.

2.1. Description of the PV-panels

System 1 can generate 101.01 kW_p with 546 PV panels (model BP-7185S[14]), the technical specifications for which are 185 W_p, 5.1 A of I_{PM} and 36.5 V for V_{PM}. Electrical performance is between 14 % and 15 % and the tolerance value is ±2.5 %. The panels integrate IntegraBus technology, which limits partial shading losses. They are arranged in groups of 14 panels in series to work with a voltage of 511 V, (within the voltage range of the inverter). The current for each group is 5.1 A. Panels are arranged in twelve rows with three groups in each one and a further two rows with two groups and one group, respectively. This means that the distance between the first and the last row is 60 m and the width is approximately 42 m, as portrayed in Figure 1.

A mobile structure was designed which adjusts the position of the panels according to the time of year, in order to optimize electrical production, which also helps to minimize the visual impact of the facilities. The maximum height of the panels (1.80 m) usually occurs during winter time and they can be lowered at other times of the year, using a manual system that allows the angle of inclination of the panels to be varied between 5º and 50°. This modification is performed approximately every 26 days. Figure 2 presents the panel support system and Figure 3, their highest and lowest positions.

The second facility, System 2, can generate 108.36 kW_p with 602 panels (model CEEG-180 24/s[15]). Their technical specifications are 180 W_P, 5 A of I_{PM} and 36 V for V_{PM}. Electrical performance is 16.8 % and the tolerance value is ±5 %. They are arranged in groups of 14 panels in series functioning at a voltage of 504 V, (valid range for the inverter). Current for each group is 5 A. The plot distribution has been arranged in 10 rows with different numbers in each group as presented in Figure 4. The distance between the first and the last row is 50 m with a maximum width of 100 m.

The mobile structure on which to place the panels is the same as in System 1 and panel adjustments are performed simultaneously.

2.2. Description of the Inverters

Only one 100 kW inverter was selected for System 1: Ingecom Sun 100 Model [16]. Its technical specifications are 100 kW nominal power and 110 kW maximum power, input voltage range of 405 V to 750 V and input current of 286 A; output voltage is 3 x 400 V and output current 187 A; harmonic distortion is less than 3 % and energy efficiency is higher than 96 %. The working temperature range is -10ºC to 65ºC. In order to prevent unwanted disruptions due to any adverse effects of temperature, a ventilation system that eliminates warm air in summer has been designed and installed alongside the inverter in a stall, located 5 m from the front row.

As in System 1, an SMA Sunny Central inverter (100kW Indoor) [17] was the sole choice for System 2. Its technical specifications are 100 kW nominal power and 110 kW maximum power, input voltage range 480 V to 820 V and input current 235 A; output voltage is 3 x 400 V and output current 145 A; harmonic distortion is less than 3 % and energy efficiency higher than 97.6 %. The working temperature range is -20ºC to 50ºC. The stall of the inverter is located 10 m from the front row and has been fitted with the same type of cooling installation as employed in System 1.

2.3. The Protection Boxes

The protection system for System 1 is structured in rows. One box, containing the protection elements -fuse and switch- for each group in the row is placed in its respective position. The protection system structure is as follows: the fourteenth row, at the northernmost point of the facility, formed of a single group, within the enclosure, consists of a fuse and a 10 A switch. Output from this box goes to the box in the adjacent row, (the thirteenth), where there are two 10 A switches and two 10 A fuses. Each group goes through the fuse and the switch, and the output is added to the previous row. The output wiring of the thirteenth row protection box contains the necessary section for the three groups. Following the same design philosophy, the output wiring section of each protection box is sufficient to carry the current from the groups of previous rows. Thus, the output section of the first line, the southernmost and closest to the inverter location, supports a current of 198.9 A, coming from the 39 groups of the installation. This output wiring is attached to the DC input inverter, located approximately 5 m from the enclosure of the first row.

Distribution of System 2 is as follows: the wiring for each of the 43 groups in System 2 runs along the tables into a ditch that crosses the centre of the installation from north to south. There are only three protection boxes, in the first, fifth and seventh rows. Fifteen groups are wired into the first box (row 1) and fourteen groups are wired into each of the other two boxes (rows 5 and 7). All wiring has a cross-section of 10 mm^2. Two wires emerge from each protection box to the inverter conducting a maximum current of 70 A. There are three positives and three negative input wires to the inverter, which facilitate this type of connection.

2.4. The Measurement System

For System 1, the connection to the measurement system is a 6 m long section of wire able to conduct a maximum current of 146 A, corresponding to the maximum output of the inverter. For System 2 the connection is 50 m long. The section of wiring is the same as that employed in System 1, since the maximum output current of the System 2 inverter matches that in System 1. The electrical company which buys and distributes the electricity stipulates a requirement that the signal should pass through a standard fuse and switch and three current transformers with the values that are sufficient for the measurement system, at the point at which production measurement occurs. The measurement system is the same for both Systems, 1 and 2, since technical and mechanical specifications are common to both.

Since its start up on 5th July 2006, until 30th June, 2010, System 1 has produced 518,076 kWh, which amounts to €240,000, surpassing its expected performance by more than 5 %. Since 25th September 2008, until 30th June, 2010, System 2 has produced 258,028 kWh, the estimated cost of which, at €121,273, is 2.6 % higher than predicted. Table 2 summarizes the technical specifications of both installations.

3. Factors influencing the performance of PV plant

In recent years, PV-plants in Spain have become a very attractive investment product, almost within reach of any small investor. The economic incentives for PV production, soft loans and subsidies for small power plants have meant that facilities of up to 100 kW proliferate throughout the country. There have been a number of installation companies that offer turnkey solutions in order to cover the high demand. They handle all administrative procedures, carry out the project, install the plants, and even participate in their maintenance. But mechanisms have not been implemented which would ensure the quality of installation, neither has optimal plant design and the best conditions for their operation been assured.

Several recent works [18-21] have studied the influence in the PV-plant performance of different elements. PV module technology [22], inclination [23], inverter and control systems [24], sun tracker system [25] and wiring influence have been determined for experimental and real facilities, demonstrating that all these elements play a more or less important role, in the overall performance of the system.

Sizing of a PV-plant usually commences with an analysis of solar radiation at site level. Data, on the basis of daily or monthly averages, are gathered from regional or national meteorological data bases. Some of the sources used most often are PV-GIS [12], NASA [26], S@tel-ligh [27], and Meteonorm [28]. Simple calculations are applied for PV panel maximum current and voltage and some coefficients, which are functions of a tilted position of the modules.

PV-panels are the next element to choose for the facility. The main part of on-ground mounted installations with crystalline silicon technologies have a market share of over 80 % [29]. There are mono-crystalline modules with up to 14 % efficiency and polycrystalline modules with approximately 12 % efficiency on the market. Thin-film cells based on amorphous silicon, Cadmium telluride (CdTe) or copper-indium-diselenide (CIS) technologies have not gained a significant market share. The decision to use one technology or another (mono-Si or poly-Si) depends more on price differences (10 % lower for poly-Si) than performance. In addition, during the period in which the market peaked -2007 to 2008-, the decision was taken on the basis of current market offers rather than any other parameter.

The electrical power output from a photovoltaic panel depends on its incident solar radiation, cell temperature, solar incidence angle and load resistance. Manufacturers usually only give limited operational specifications for photovoltaic panels, such as their open circuit voltage (V_{oc}), short circuit current (I_{sc}), maximum power current (I_{PM}) and voltage (V_{PM}) and their nominal operating cell temperature (NOCT). These specifications are only given at standard rating conditions (SRC), for which irradiance is 1000 W/m^{2}V and cell temperature (T_c) is 25ºC (except for the V_{NOCT} which is determined at 800 W/m^2 at an ambient temperature of 20ºC) [30]. Superficially, specification sheets for different panels might suggest very similar characteristics, although this does not guarantee similar behaviour under real conditions. Responses in order to address diffuse components of radiation, low levels of insolation, or ambient temperature influence, can differ considerably within the same PV-module technology.

The choice of an inverter system for a PV-plant is based on price criteria and ease of maintenance, because most technical criteria, including efficiency, harmonic distortion or even consumption, weight and operating temperature ranges are usually very similar in all the available models. Often the most controversial decision is whether to use a single full power inverter, the sum of which is equal to or more than the nominal power of the plant. Most facilities have chosen a single inverter, thereby avoiding additional problems related to the maintenance of this piece of equipment.

Nowadays, all inverters have a module which seeks the Maximum Power Point (MPP) of the PV generator, because if the inverter does not operate at the MPP, the installation will present production loss [31]. However, manufacturers do not disclose the MPP algorithm that they use. Nevertheless, there are other operating parameters that can have an important influence on inverter performance which do not appear in the technical specifications of the system. Starting and stopping threshold points indicate shorter or higher daily operating times, which lead to differences in annual production. Reset and test times following unscheduled stops due to the injection of energy into the grid can also lead to major differences in total production.

Wiring is a commonly overlooked factor in the analysis of PV-production. Panel distribution in the parcel and the location of protection boxes and inverter systems play an important role in the PV-plant performance, decreasing electrical losses. Moreover, a successful design can be crucial in order to minimize the cost of installation and improve the quality of electrical transportation.

4. The study case

4.1. Data analysis and classification

The two facilities under study -System 1 and System 2- are the property of SOLARSAN S.L., which provided the data to the research group for this case study: total electric production, measured by the inverter and by the measurement system from both facilities over one year. An analysis of data from 2009 revealed some discrepancies in their electrical production, in contrast to the anticipated return from both installations, which had been expected to reveal very similar results, since the plants are in the same geographical position and have the same structural characteristics.

The study began by comparing electrical production at two available points, inverter and measurement system, reducing all data to 100 kW_p. Differences between both measurements are explained by electrical losses in wiring and inverter efficiency. Wiring losses were calculated as a function of the wiring and the distance between the inverter and the measurement system and the distance between the panels and the inverter for the maximum value of the electrical current flowing from the facilities. Technical characteristics of wiring of System 1 and System 2 for these calculations are shown in Table 3. The results are 0.03 kW and 0.058 kW for System 1 and System 2, respectively. Taking into account the estimated annual operating time for the area where the facilities are situated[12], total wiring losses were 77 kWh/year and 134.62 kWh/year for System 1 and System 2, respectively.

Inverter performance was estimated at 96 % for System 1 and 97.6 % for System 2. The different starting thresholds of the two inverter systems should be considered. The System 2 inverter functions for an average of 10 minutes more per day than System 1. Taking into account average insolation in the area and the number of sunny hours[12], it has been calculated that the inverter of System 2 produces 14 kWh/day more than the System 1 inverter. Simple calculations put total inverter losses at 6,572 kWh/year for System 1 and 3,698 kWh/year for System 2. This accounts for 4 % and 2 % respectively of total losses at the facilities.

Each panel’s total electrical production is calculated by taking all these differences into account. Calculated electrical production for System 1 panels throughout 2009 was 162,376 kWh while production from System 2 panels was 148,475 kWh. This indicates a total difference of 8.56 %. The resulting data reveals the panel's electrical production and allows a comparative analysis between both technologies. Monthly results are presented in Figure 5.

The second stage in the study was to classify the resulting differences (calculated electrical production from the inverter system) between each system's electrical production based on the amount of electricity generated by System 1. These results are grouped into intervals in Table 4.

4.2. Results

As a first result, Table 4 indicates that the area experiences very good atmospheric conditions that are conducive to PV production. Electrical production was higher than 500 kWh for over 50 % of 2009. The differences in production at both installations are accentuated when the radiation level is higher, which indicates that the panels in System 1 (European technology) outperform those of System 2 under high levels of isolation. However, the response to diffuse radiation was similar, and low levels of solar radiation produced insignificant differences in production. Figure 6 highlights this fact.

Ambient temperature is a further parameter which influences PV production. A seasonal classification of results allows us to relate the differences in ambient temperature and to study the thermal behaviour of the panels' technology. The results are outlined in Figure 7.

The greatest differences were observed in summer, when temperatures and hours of sunshine are higher. System 1 panels also performed better under higher temperatures. It

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may be observed that, in colder months, including February and March, there were significant differences in electrical production between both facilities. This highlights how the panels in System 1 also performed better when ambient temperatures were low. In economic terms the differences in production account for 6375 €/year.

An exhaustive study was undertaken of the flash report of the PV modules provided by the manufacturer, in order to understand the behaviour of both types of panels. These documents present the electrical parameter values of the panels, tested at standard rating conditions: nominal power, (W_P), open circuit voltage (V_{oc}), short circuit current (I_{sc}) and maximum power current (I_{PM}) and voltage (V_{PM}). In some cases, they also specify the Fill Factor (FF). The results of the study are presented in Table 5. The quality of a manufacturing process is directly related to the homogeneity of the technical specifications for the final product. As demonstrated in Table 5, the average values and the standard deviations (σ) of the electrical parameters reveal better results in the System 1 PV modules, which demonstrate that the manufacturing process for this technology is of higher quality. The cost of the panels used in System 1 was 3.8 €/w as opposed to 2.5 €/w for the System 2 panels. It is important to take into account the fall in the price of PV panels of both facilities over the two years [3]. However, as confirmed by this study, any investment can rapidly be recouped.

Losses in wiring are an important factor to be considered. A study of these losses was made from the length and section of the wire and the electricity current in the different parts into which the facilities have been divided.

For System 1, four sections were considered: the length from the panels to the protection boxes, the length between protection boxes of different rows, which is designed as a telescopic system; the length from the first row to the inverter system and the connection of the inverter to the measurement system. System 2 has been divided into three sections: the length from the panels to the protection boxes, the length between the protection boxes and the inverter system and the length of the connection of the inverter system to the measurement system. Technical specifications and loss calculations for each section are outlined in Table 3.

5. Conclusions

This study has demonstrated that the System 1 panels perform better from every perspective. Although the PV panels of both facilities have the same nominal power, a higher dispersion was observed in the technical characteristics of the PV modules that were used in the facility with lower production levels. The homogeneity of the characteristic curves of the panels in use appears to be an indicator of their quality. Panel behaviour under high and low temperatures also differs as well as the response experienced under different levels of radiation. PV panels' production differs by more than 8 % and this signifies the main contribution to the differences in production between both facilities.

Although the System 2 inverter behaves better than the System 1 inverter, their performance is not able to compensate the disequilibrium caused by the PV panels.

Wiring losses have been calculated for both installations. Preliminary studies were performed of wiring, panel distribution in the parcel and the location of protection boxes and inverter systems, demonstrating the best options. As tested, wiring losses represent less than 1 % of the electrical production of the systems.

Total production for both facilities, in 2009, was 155,803 kWh and 144,777 kWh, respectively: a difference of 11.026 kWh, which represents a cost of €5,080, within the actual tariff system. If the installations were to function at full capacity for 25 years, these differences would account for 7 % of total revenue, 21 % over the total investment and 2 further years in the payback time.

Exhaustive studies on the arrangement of the panels in the parcel, a meticulous wiring design and the correct siting of the protection and measurement system are all crucial to improving the profitability of the PV installation, decreasing the price of generated kWh and the payback time. As this paper has highlighted the performance of PV plants is directly related, in economic terms, to improvements of all their critical components.

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Figure Caption

Figure 1: Aerial photograph of System 1 and System 2, at Torquemada (Palencia, Spain), portraying the panels and the inverter systems of both facilities.

Figure 2: Panel support system. Detail of mechanical support

Figure 3: Panel support system. High and low panel positions.

Figure 4: Panels distribution in System 2.

Figure 5**:** Monthly electrical production of System 1 and System 2 (kWh), and average of ambient temperature (ºC) in the area.

Figure 6: Differences in electrical production (kWh) between System 1 and System 2 as a function of total production (kWh) at the facilities.

Figure 7: Average differences in the electrical production by month, at pre-defined production intervals), and average of ambient temperature (ºC) in the area.

Figure 1

Figure 2

Figure 3

Figure 4

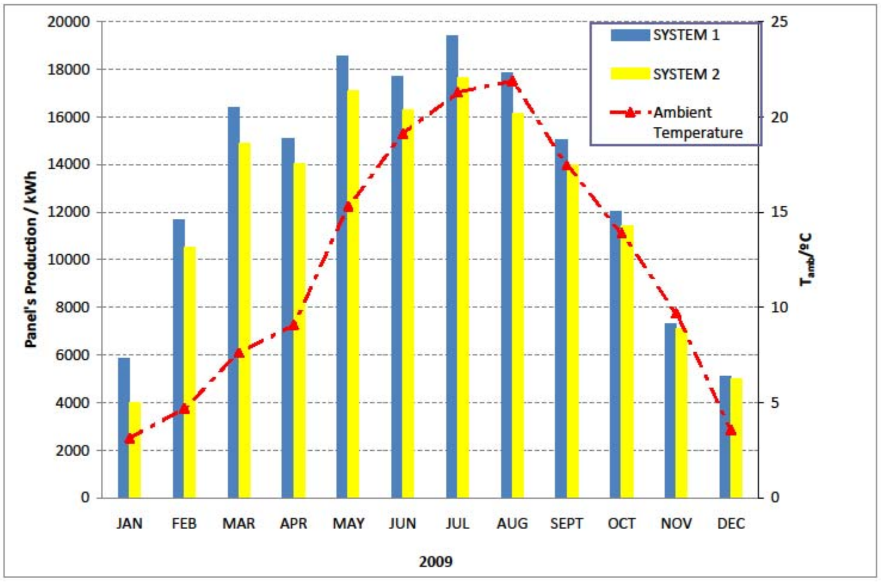


Figure 5

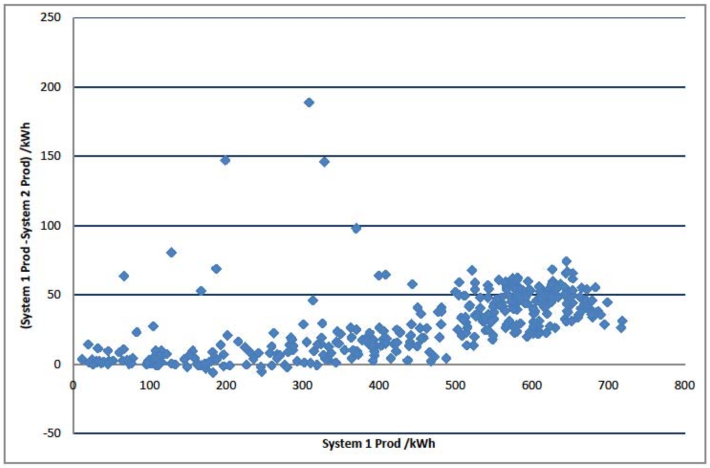


Figure 6

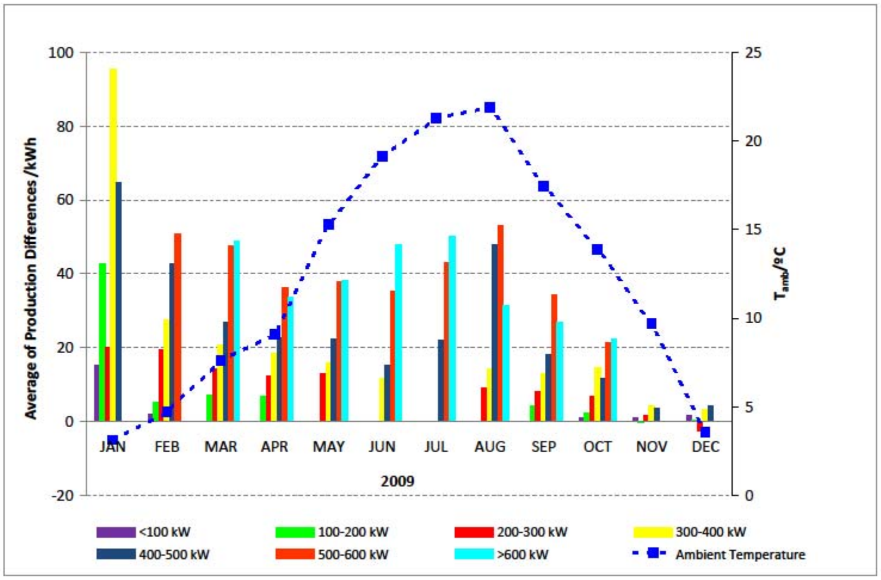


Figure 7

Table 1: Indicative installed PV prices per kWh in various countries in 2009. Tariff depends on type and installed power of facilities. Data from [32]

Country	**Price (€/kWh)**
Austria	0.46 - 0.30
Canada	0.82 - 0.42
France	0.57 - 0.32
Germany	0.43 - 0.31
Greece	0.45 - 0.40
Italy	0.40 - 0.36
Japan	0.22 - 0.20
Portugal	0.45 - 0.32
Spain	0.30 – 0.24
Switzerland	0.56 - 0.30
USA	0.24 - 0.18

Table 2: Technical specifications of panels and inverter used in System 1 and System 2

Panels	System 1 BP-7185S	System 2 CEEG-180
V_{PM} (V)	36.5	36
I_{PM} (A)	5.1	5
W_P (W)	185	180
Performance (%)	14-16 %	16.8 %
Tolerance value (%)	±2.5 %	±5 %
Nº of panels	546	602
Nº of groups	39	43
V_{group} (V)	511	504
Facility Power (kW)	101.01	108.36
Inverter	Ingecom Sun 100	SMA- Sunny Central 100 Indoor
V_{cc} (V)	405-750	480-820
I_{cc} (A)	286	235
V_{ca} (V)	3x400	3x400
I_{ca} (A)	187	145
Temperature Range	-10-65 ºC	-20-60 ºC
Performance (%)	>96	97.6

Table 3: Technical characteristics of wiring of System 1 and System 2

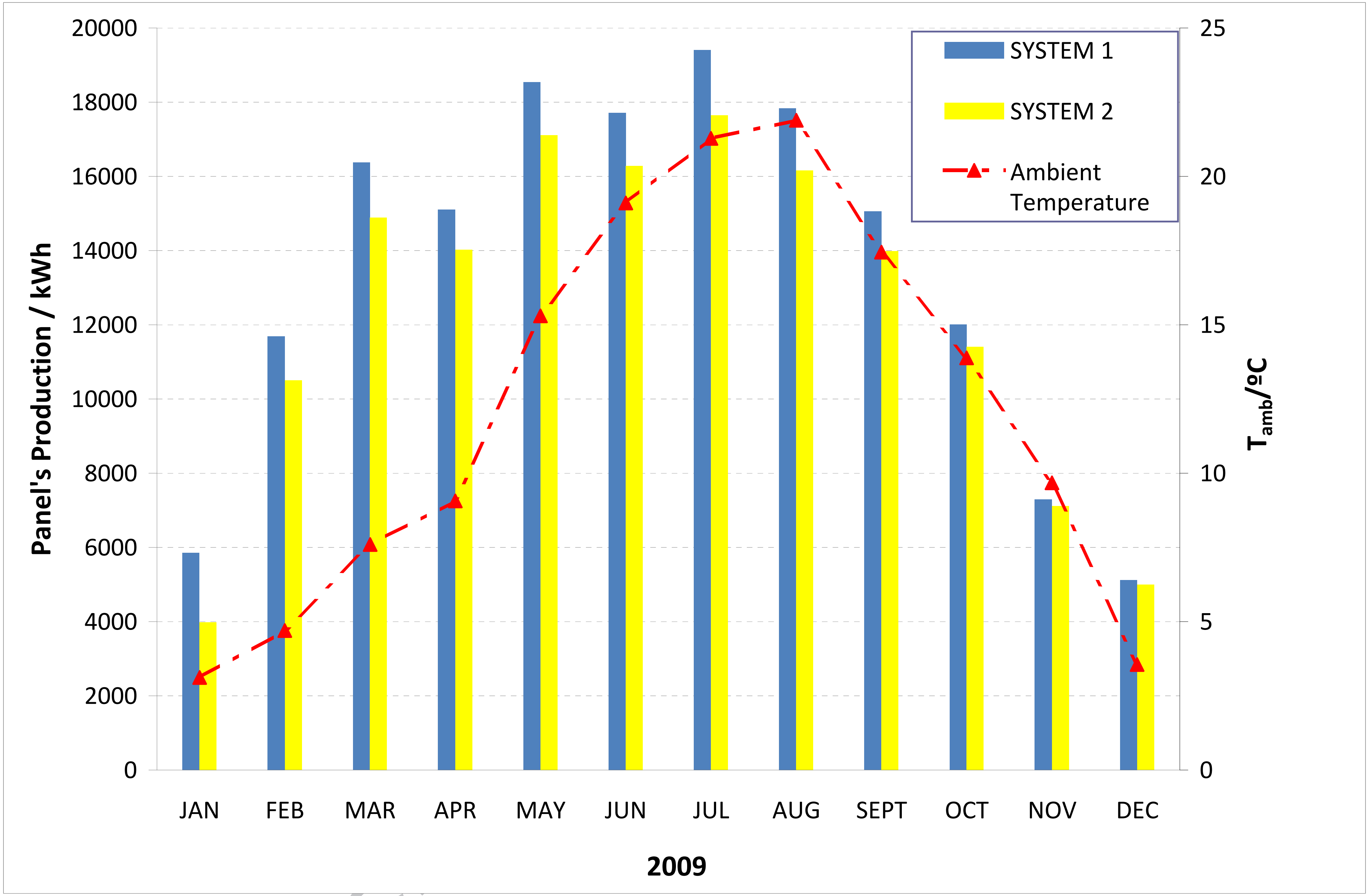
		Length	Section	Max. current	Total losses
System 1	Stretch 1	2-30 m	10 mm^2	5.1 A	77.04 kWh/year
	Stretch 2	Telescopic	25-50-75 mm^2	5.1 A-183.6 A	
	Stretch 3	5 m	95 mm^2	183.6 A	
	Stretch 4	6 m	95 mm^2	144.3 A	
System 2	Stretch 1	3-108 m	10 mm^2	5 A	134.6 kWh/year
	Stretch 2	35, 25, 2 m	50 mm^2	70, 70, 75 A	
	Stretch 3	50 m	150 mm^2	144.3 A	

Table 4: Average differences in the daily electrical production of both installations based on System 1 production: N is the number of days that production in System 1 is within a defined interval, and $(P_1-P_2)/N$, is the average electrical production difference (kWh) over the same period.

P_1 (kWh)	N (days)	$(P_1-P_2)/N$ (kWh)
<100	31	7.25
100-200	42	14.59
200-300	26	12.48
300-400	46	30.04
400-500	39	42.21
500-600	97	51.95
>600	84	55.53

Table 5: Average and standard deviation (σ) of the PV module electrical parameters calculated from flash reports

	System 1 panels BP-7185S		System 2 panels CEEG-180 24/s	
Parameter	Average	(σ)	Average	(σ)
W_P / W	186.51	1.18	176.59	3.40
V_{oc} / V	5.58	0.14	5.26	0.08
I_{sc} / A	44.15	0.03	44.80	0.32
V_{PM}/ V	5.11	0.24	4.92	0.11
I_{PM} / A	36.47	0.03	36.23	0.30



20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Panel's Production / kWh
25
20
15
10
5
0
T_{amb}/ºC
SYSTEM 1
SYSTEM 2
Ambient Temperature
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEPT
OCT
NOV
DEC
2009

Highlights

Real PV production from two 100 kW_p grid-connected installations is conducted.

Data sets on production were collected over an entire year.

Economic results highlight the importance of properly selecting the system components.

Performance of PV plants is directly related to improvements of all components.