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Performance estimation and experimental measurements of a photovoltaic roof

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Abstract

The market for photovoltaic systems is rapidly expanding. Currently, there are a few large utility photovoltaic power plants, thousands of residential systems, and tens of thousands of remote power systems in use. Even if photovoltaics is a technology that has already demonstrated its effectiveness and holds great promise in electrical generation, the costs are still too high to guarantee a commercial competitivity.

The study presented in this paper is part of a European XVII Thermie project entitled "Pilot project for photovoltaic, energetic and biohousing retrieval in a school", the aim of which was to install a photovoltaic plant and solar air collectors coupled with a sun breaker structure at a scientific high school in Umbertide, in central Italy. A 15 kWp photovoltaic power plant was mounted on the roofs of two blocks of the school building in spring 2001. The system consists of 220 modules for a total of 22 arrays, which are connected to inverters to allow conventional appliances to be powered by photovoltaic electricity.

The photovoltaic plant is remotely controlled and data on sun radiation, ambient temperature, modules temperature and power production are continuously acquired by a PC. The measured power plant performances during the year are presented in this paper.

Furthermore, the climate in the area has been simulated through the available experimental data and the system behavior under these conditions is predicted. The experimental data have been used to validate a predicting numerical model for photovoltaic plants performance. © 2003 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Photovoltaic (PV) systems, originally developed for outer space applications, are currently used in many remote applications providing electricity to remote areas for any grid in a manner that uses significantly less primary energy than conventional systems with savings of natural resources and reductions of pollutant emission. Unfortunately, the development of this technology is not yet cost-competitive with conventional energy systems and the current economics are such that the PV market today is very small [1]. The basic reason for the high cost of PV power is the high capital cost for the relatively small amount of power produced: to be economically competitive, the module cost needs to be reduced from about $3.5 \in$ /W to at least $0.5 \in$ /W.

From the 1970s, when some scientists argued that the energy necessary to produce a PV system would never be "repaid" by the system itself [2], many improvements both in economic and environmental terms have been performed. The energy and investment payback time for PV systems have been considerably reduced in the last two decades [3], being now much less than the expected lifetime of the system. Estimated lifetime of panels are in the range of 15–30 years and maintenance, after proper installation, typically involves only minimal cleaning. Assuming a 25-year lifetime for the system, a centralized PV plant payback time is of about 8 years, reduced to 5.5 years for a distributed building integrated PV system (BiPV) [4].

These improvements in the technology, together with the fact that PV systems could have a significant role in offsetting the continuous growth of greenhouse emissions associated with traditional electricity generation, represent the propulsion argument for the worldwide attention to PV applications. Within the 10,000 rooftop PV programs [5–6] activated in most European countries during the 1990s, almost 1 million of PV plants have been installed.

Over 20 MWp PV systems were installed in Italy during 2001, of which 6.3 were for rural applications, 5.3 for domestic off-grid installations, 6.7 on grid in large power plants and 1.7 on grid in distributed applications.

In the Netherlands, where building integrated PV systems started receiving attention in the early 1990s, the total PV installed capacity is predicted to be larger than 250 MW before 2010 [7]. Kurokawa and Ikki [8] describe Japanese efforts through an overview of Japan's basic policies and activities concerning PV systems promotion.

When assessing the convenience of technologies such as PV systems, it is important to include consideration of the way the technology is applied. In light of environmental degradation, it seems wise for architects and engineers to design buildings that maximize the efficient use of renewable energy, such as solar energy, geothermal energy and wind energy. Furthermore, roofs and facades of existing buildings represent a huge potential area for PV system installation, allowing the possibility to combine energy production with other functions of the building or non-building structure. In this scenario, BiPV systems seem to offer the most cost- and energy-effective application of grid connected PV systems [4,9–11].

BiPV systems do not require high-value land and the building on which the system

is mounted provides the access roads and most of the major supports for the modules thus avoiding their costs, since they would be there in any case. Moreover, considering that the building is going to be the electricity user, the costs and the losses associated with transmission and distribution of electricity are minimized. PV systems that are integrated in a building can also provide other functions, such as protecting the building form the weather or reducing solar transmittance to decrease the heat load, while simultaneously producing electricity.

Oliver and Jackson [4] demonstrated the overall benefit of BiPV systems over centralized PV plants in terms of returns on investment, energy payback times and net energy balance.

The study presented in this paper is part of a European XVII Thermie project entitled "Pilot project for photovoltaic, energetic and biohousing retrieval in a school", the aim of which was to install a PV plant and solar air collectors coupled with a sun breaker structure, at a scientific high school in Umbertide, in central Italy. A 15 kWp PV power plant was installed on the roofs of two wings of the school building in spring 2001. The measured power plant performances during one year are presented. Furthermore, the climate in the area has been simulated through the available experimental data and the system behavior under these conditions is predicted. The experimental data have been used to validate a PV plant performance predicting numerical model.

2. System description

The PV system described in this paper has been installed on the roof of the scientific high school "Leonardo da Vinci" (Fig. 1), located in Umbertide, a small town



Fig. 1. Scientific high school "Leonardo da Vinci", located in Umbertide.

Longitude	12.19°	
Latitude	43.18°	
Altitude	247 m	

Table 1 Umbertide geographical coordinates

in the center of Italy in Perugia's province at latitude 43.18° and longitude 12.19° (Table 1). This installation is part of a project for PV, energetic and biohousing retrieval in a school with the objective of reducing the fuel consumption for heating and producing electricity from renewable resources.

The optimal positioning of the PV system would be to the south with an inclination of the modules equal to the latitude of the site. However, the orientation of the school and the geometry of the roof do not allow this target to be achieved, unless using costly and bulky support structures. Therefore, the PV panels have been mounted on the south-east roof of the building with a 20° inclination, which is the best compromise between maximum solar radiation, greatest available surface and minimum costs (Fig. 2). The modules are oriented to the south-east (East 60°) and there are no nearby buildings to cast shadows on the PV panels.

The PV system has a nominal peak power of 15.4 kWp and is composed of two



Fig. 2. System orientation.



Fig. 3. The PV roof.

fields installed on the roofs of two separated wings of the school building (Fig. 3). The overall surface is 169.4 m². The two fields are connected in parallel and consist of 220 modules for a total of 22 arrays, each one connected to its own inverter to allow conventional appliances to be powered by PV electricity. Each array features 10 modules connected in series and is characterized by an open circuit output voltage of 213 V_{DC} and a short circuit output current of 4.4 A. To provide maximum electrical power output, the angle of the PV array should be changed as a function of the solar altitude, but because of safety and costs the arrays were installed at a fixed angle of 22°. The main features of the PV system are summarized in Table 2.

The modules are made up of polycrystalline silicon, which guarantees a conversion efficiency of about 9%. Table 3 shows the modules characteristics at standard conditions (25 °C of ambient temperature and 1000 W/m² of solar irradiance).

The function of the inverters is to statically convert the electricity from a DC input into an AC output, that means without any rotating devices or mechanical switches. The inverters are connected to the 400 V tree-phase circuit in parallel with the ENEL (national electricity distributor) electrical grid. Therefore, the PV energy output is used directly by the school or fed into the grid depending on the produced

Table 2 PV system main characteristics

Nominal power output	15.4 kWp
Net occupied surface	169.4 m ²
Open circuit tension	213 V _{DC}
Number of arrays	22
Modules per array	10

Material	Polycrystalline silicon	
Peak power output	70 W	
Peak power voltage output	17.2 V _{DC}	
Peak power current output	4 A	
Open circuit voltage output	21.3 V _{DC}	
Short circuit current output	4.4 A	
Number of cells	36	
Length	1220 mm	
Width	555 mm	

Table 3		
Modules	main	characteristics

power and on the electricity consumption. This allows the electrical power that is not directly consumed to be exchanged. This is particularly important for this kind of building in that during the period of maximum production (summer) there is minimum electrical demand.

3. Measurement and control system

The system output is monitored at the PV inverters by a data acquisition system controlled by a measurement-and-analysis program (Sunny Boy Control Plus) mounted on a PC. The data acquisition system and the PC communicate with each other by means of a RS232 communication protocol. The data acquisition system features eight digital channels and eight analogical channels.

The measured data are:

- electrical power output of each array;
- voltage of each array;
- each phase current fed into the grid;
- each phase electrical power fed to grid.

Also measured and recorded every 15 min are the global solar irradiance on the modules plane in two different locations of the plant, the modules temperatures and the outdoor temperature.

4. Numerical model

The amount of solar energy reaching a specific location on the surface of the earth at a specific time depends on two main factors. First the geographical coordinates and in particular the changes in the solar position in the sky with latitude. The sun's position is given in terms of solar altitude and azimuth that can be easily determined. Second are the meteorological conditions with the related climate variations which can be considered as sky conditions. If the sun is directly overhead and the sky is

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Fig. 4. Sun-building relative position in June and December.

clear, direct radiation on a generic surface can be calculated from the extraterrestrial radiation by means of the Bouguer law [12]. Suncharts can be drawn through the geographic coordinates of the site (Fig. 4).

The intensity of the direct daily solar radiation received by the system has been calculated knowing the system inclination and orientation and the geographic coordinates of the site [13].

Under clear sky conditions, the system would receive about 2280 kWh/m² of annual solar irradiance against 2390 kWh/m² that would be received in the optimal orientation. The comparison between optimal and actual orientation in terms of clear sky incident solar irradiance during a year is shown in Fig. 5.

Clear sky radiation is an ideal condition that can be calculated in a deterministic manner since it depends only upon sun-earth relative motion. On the other hand,



Fig. 5. Comparison of optimal and actual orientation in terms of clear sky incident solar irradiance.

real solar irradiance spatial and temporal distribution cannot be predicted and can be simulated only through stochastic functions based on meteorological surveys over the past years, which can indicate the prevailing climate conditions of the generic site.

The effective solar radiation $I_{\rm T}$ usually measured at the meteorological stations is the sum of direct solar radiation $I_{\rm d}$, diffuse solar radiation $I_{\rm s}$ and albedo $I_{\rm a}$, which is that fraction of the total irradiance incident on a generic surface which is reflected back in all directions:

$$I_{\rm T} = I_{\rm d}.\cos(j) + I_{\rm s} + I_{\rm a} \tag{1}$$

where j is the angle between the surface normal and the radiation direction. In the following the albedo will be considered to be part of the diffuse radiation.

To predict the performances of the PV system operating on the roof of the school throughout the whole year the following experimental climatic data, available from 1995 to 1998, have been used [12,14–16]:

- average number of days with clear sky;
- average number of days with cloudy sky;
- average effective daylight length;
- global average monthly insolation on a horizontal surface;
- global average daily insolation on a horizontal surface.

The climate indexes indicating the degree of sky clearness are always used as weighting factors to estimate the effective amount of solar radiation. Let us consider the ratio of the direct to clear sky insolation, known as the cloudiness factor, whose average value can be extrapolated by the above-mentioned experimental data (Fig. 6).

The sun's position and the prevailing meteorological conditions are the two essential variables to estimate solar system performance in a certain location.

The predicted cloudiness factor is assigned as the monthly average value. The predicted monthly solar radiation on the module surface, as the sum of the predicted



Fig. 6. Average monthly cloudiness factor.



Fig. 7. Predicted global solar radiation in Perugia: clear vs. cloudy sky.

daily insolation, is shown in Fig. 7, where clear sky and cloudy sky conditions are compared.

The simulation of the system performance under certain climatic conditions has been made through an estimate of the hourly solar irradiance. Since experimental data on hourly insolation are not available, statistical methods have been employed for their prediction.

The method proposed by Liu and Jordan has been used in the present work [12,17–19]. This method allows the determination of the hourly total $I_{h,T}$, diffused $I_{h,s}$ and direct $I_{h,d}$ solar radiations and can be synthesized by the graphs shown in Fig. 8.

With global average daily insolation available, the direct and diffused hourly insolation are correlated to the astronomical daylight length (Fig. 8a), which can be easily determined through the geographic coordinates of the site. The data available allowed fitting the hourly fraction of the daily solar radiation power with a polynomial func-



Fig. 8. Liu and Jordan method.



Fig. 9. Predicted direct solar radiation in Perugia in three representative days.

tion of the daylight length, obtaining for each half hour before and after solar midday the direct insolation and the diffused insolation. Data have been interpolated with a polynomial least squares curve fit.

The ratio of the diffused to global insolation, generally called diffused fraction, is correlated to the cloudiness factor and the data available have been plotted with a least square fifth-order polynomial fit (Fig. 8b).

This procedure allows the determination of the average hourly direct and diffused solar radiation on a generic surface, starting from statistical data on daily clear sky and global insolation. The hourly direct and diffused solar radiations on the system predicted for three characteristic days of the year are shown, respectively, in Figs. 9 and 10.



Fig. 10. Predicted diffused solar radiation in Perugia in three representative days.



Fig. 11. Minimum solar radiation necessary to the PV system to start producing electricity in May 2001.

5. Experimental results

Figs. 11 and 12 show the minimum solar radiation that allows producing electricity in two characteristic months: May and July. The starting production solar irradiance was considerably low, since it ranges between 20 and 80 W/m². The gap between the minimum and the maximum values can be probably attributed to the fact that the period between two consecutive records is 15 min and during this period the solar radiation can vary significantly.



Fig. 12. Minimum solar radiation necessary to the PV system to start producing electricity in July 2001.

The peak energy production is reached in summer. In particular, Fig. 13 shows that the maximum daily power output in July 2001 varied between 10 and 12 kWp, as a conversion of a solar radiation between 900 and 1000 W/m².

The efficiency of a PV system, η , is usually defined as the ratio between the electricity power output for each square meter and the solar radiation incident to the modules. The nominal overall efficiency of the PV system mounted on the roof of the school building, given by the modules manufacturer, is 6.33%. As it will be shown in the following results, this value is very close to the measured average value. Fig. 14 shows the measured daily system efficiency in a characteristic month. The daily system efficiency ranges between 6.24 and 6.65%, giving a monthly average value of 6.46%. The plot in Fig. 15 shows the measured values of the mean monthly efficiency during the whole year. The resulting global mean efficiency is 6.77%, slightly higher than the nominal one.

The daily distribution of the system efficiency and power production for a characteristic day is shown in Fig. 16. The PV system efficiency remains almost constant at around 7% during most of the daylight time. Lower values, below 4%, can be observed in the early morning and in the late afternoon. However, it must be underlined that we are dealing with the efficiency of the whole system, that says nothing about the efficiency of each array. In the last hours of daylight the solar irradiance has significantly decreased and some arrays do not receive the minimum required incident energy to start electricity production. Therefore, those efficiency values of around 4% are due to partial operation of the PV system. Anyway, since the module orientation is fixed, a slight variation of η with time, due to variation of the sun's position, can be observed.

Furthermore, the average daily system performance and power production remain almost unchanged, as shown in Fig. 17, where the average daily efficiency and power production are plotted during the month of July. The summer period was selected for the analysis in order to avoid meteorological effects on the PV system perform-



Fig. 13. Daily peak power production in July 2001.



Fig. 14. Average daily efficiency in July 2001.



Fig. 15. Average monthly efficiency.



Fig. 16. Electricity production, solar radiation and efficiency in a characteristic summer day.



Fig. 17. Electricity production, solar radiation and efficiency in a characteristic summer month.

ance, that are evident during the winter, and enhance the effect of the data acquisition period (15 min) in the production of peaks and valleys in the efficiency trend.

The relationship between the modules temperature, the ambient temperature and the energy conversion efficiency was also analyzed. Fig. 18 shows the ambient and modules temperatures in April. The system efficiency as a function of the modules temperature and of the ambient temperature in two different daily periods characterized by an almost constant solar irradiance are plotted in Fig. 19. The main result is that, as expected, efficiency decreases with increasing temperature. In particular, about 0.025%/°C of efficiency is lost when temperature increases.

6. Measured and computed data comparison

The predicted electricity production has been calculated using the above-mentioned method to compute the solar radiation. The energy conversion efficiency has been fixed to 6.77%, which is the average measured value.

The comparison between predicted and computed solar radiation for a characteristic month is shown in Fig. 20. Considering that the numerical code uses a constant cloudiness factor for each month, the computed and measured trends are completely different. This result is trivial, since there is no way to predict the real daily cloudiness factor. However, at a first glance it is clearly evident how the computed energy production matches the average value of the real one.

The excellent agreement between experimental and numerical data is confirmed by the comparison between real and predicted monthly energy production, shown for the whole year in Fig. 21. The difference between numerical and real electricity production is very low throughout almost all the observation period.

The overall predicted energy production is 18.9 MWh/year against 18.2 MWh/year which was generated. This reveals an excellent prediction potential of the numerical code developed in this work.



Fig. 18. Ambient and average modules temperatures during a characteristic month (April).



Fig. 19. PV system efficiency in function of ambient and modules temperatures.

7. Conclusions

The simulation model presented in this paper allows one to predict with significant precision the energy production of PV power plants, by using geographical and environmental information of the site and the characteristics of the panels.

The results of the simulation model were compared with the measurements of the electricity production of a large PV roof located in central Italy. The measurements also allowed us to calculate the energy conversion efficiency of the panels and the overall production for a whole year of operation.

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Fig. 20. Comparison between real and predicted daily solar radiation in a representative month.



Fig. 21. Comparison between real and predicted electricity production.

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