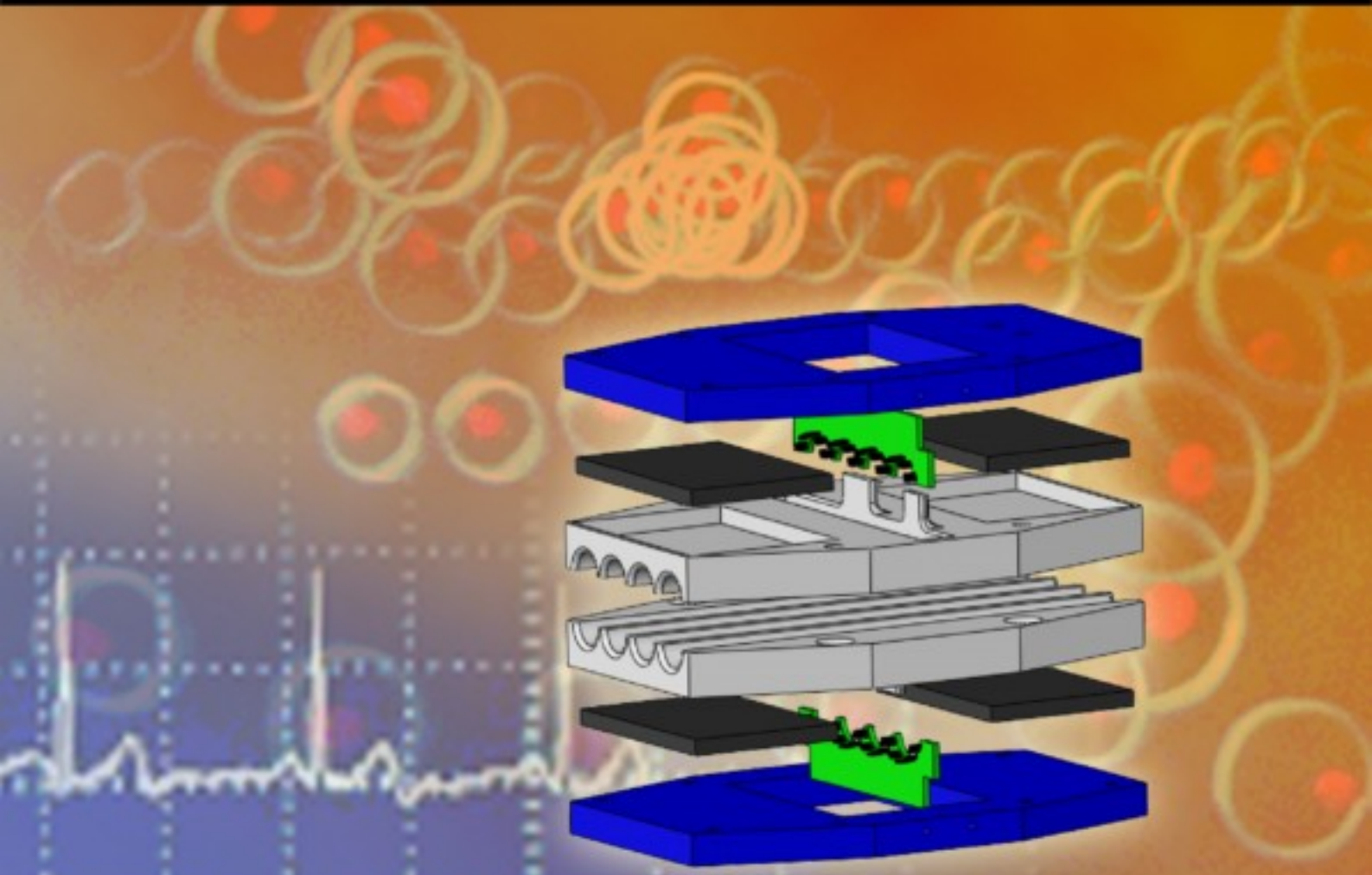


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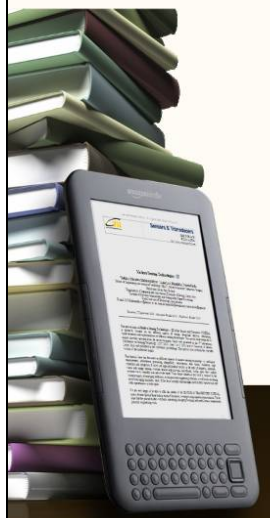
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- Biodevices
- Biomedical technologies
- Biological technologies
- Biomanufacturing

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Submission (full paper)	January 10, 2011
Notification	February 20, 2011
Registration	March 5, 2011
Camera ready	March 20, 2011

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- EDNA: Emergency Services and Disaster Recovery of Networks and Applications
- IPv6DFI: Deploying the Future Infrastructure
- IPDy: Internet Packet Dynamics
- GOBS: GRID over Optical Burst Switching Networks



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Notification	October 20, 2010
Registration	November 5, 2010
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Experimental Performance Measurements of Home Photovoltaic Plants: A Case Study

¹C. Calò, ¹C. Chiffi, ¹G. D’Aniello, ²A. Lay-Ekuakille, ²P. Vergallo, ³A. Trotta

¹Roam 2000 S.r.l., Via della Transumanza, 5, 74100 Taranto, Italy

²DII, University of Salento, Via Monteroni, Lecce, 73100 Lecce, Italy

Tel.: +39.0832.297822, +39.0832.297827,

²DEE, Polytechnic of Bari, Via Orabona 4, Bari, 70100 Lecce, Italy

E-mail: aime.lay.ekuakille@unisalento.it

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Abstract: Many researches generally encompass experimental and dedicated plants for scientific purposes. They display outputs with limited uses. On the contrary, measurements performed on real plants could be very significant because they reflect the reality and the milieu where the plants are located. This paper illustrates a method of characterizing a real plant based on a pre-characterization of a sample of photovoltaic module and on an “ex-post” characterization of a general plant where the same photovoltaic module is used. The photovoltaic pre-characterization is an outdoor one performed in several months in order to know the response of the module due to solar exposure. Outdoor characterizations are necessary beside flash test with sun simulator. Power matrixes are a useful method for predicting and verifying the performances of a photovoltaic module. The research offers the opportunity to calculate the efficiency and the energy production for a 50 kWp plant. *Copyright © 2010 IFSA.*

Keywords: Irradiance sensing, Photovoltaic system, Solar efficiency, Measurements, Power matrix

1. Introduction

Shade has a significant impact on PV module can significantly lower the module output current. It is important to choose a site for a PV system where the PV array will remain unshaded for as much of the day as possible. This is easy if there are no obstacles and no objects that might shade the array, but it is probably more likely that a site will have objects nearby that shade the array at some time of the day on some day of the year. The PV system designer must be able to use his knowledge of sun position to

determine the times at which a PV array might be shaded [1]. Shading can be monitored thanks to different sensing instruments. Since all calculations and approximations in the world cannot yield exact predictions of the amount of sunlight that will fall on a given surface at a given angle at a given time at a given day in a given place, the design of a photovoltaic power systems is dependent upon the use of data based on measurements averaged over a long time. However, depending whether it is desired to measure global, beam, diffuse or albedo components of irradiance, or whether it is simply desired to measure when sunlight exceeds a certain brightness level, different types of instrument are used: black and white pyranometer, pyrheliometer with tracker, and pyranometer mounted on a shadow band stand. Moreover, a sustainable development has to respect certain guard rails. With respect to the energy supply system, these are mainly determined by the global warming/ CO_2 problem. A global warming of more than $2\text{ }^\circ\text{C}$ (with respect to the pre-industrialised period) and a warming rate of $0.2\text{ }^\circ\text{C}$ per decade seems to be the upper limits for a development that may be kept under control. These settings are in accordance with the results of recent studies of the International Panel on Climate Change [2].

2. The Physical Basis of Photovoltaic

Solar cells are made of semiconductors, which have weakly bonded electrons occupying a band of energy, called the *valence band*. When energy exceeding a certain threshold, called the *band gap energy*, is applied to a valence electron, the bonds are broken and the electron is somewhat “free” to move around in a new energy band called the *conduction band* where it can “conduct” electricity through the material. The free electrons in the conduction band are separated from the valence band by the band gap (measured in units of electron volts or eV). This energy needed to free the electron can be supplied by photons, which are particles of light. Fig. 1 shows the idealized relation between energy (vertical axis) and the spatial boundaries (horizontal axis).

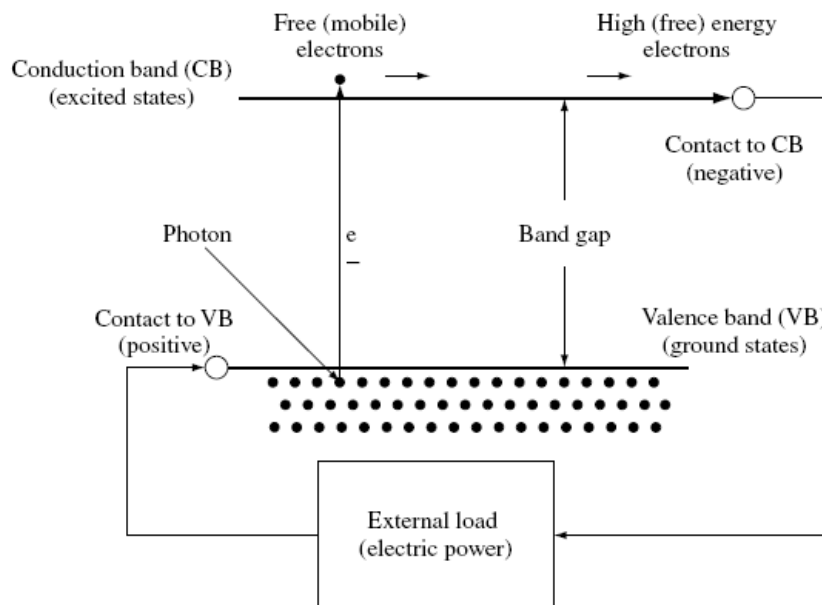


Fig. 1. Schematic of a solar cell.

When the solar cell is exposed to sunlight, photons hit valence electrons, breaking the bonds and pumping them to the conduction band. There, a specially made selective contact that collects conduction-band electrons drives such electrons to the external circuit. The electrons lose their energy by doing work in the external circuit such as pumping water, spinning a fan, powering a sewing

machine motor, a light bulb, or a computer. They are restored to the solar cell by the return loop of the circuit via a second selective contact, which returns them to the valence band with the same energy that they started with. The movement of these electrons in the external circuit and contacts is called the *electric current*. The potential at which the electrons are delivered to the external world is slightly less than the threshold energy that excited the electrons; that is, the band gap. Thus, in a material with a 1 eV band gap, electrons excited by a 2 eV photon or by a 3 eV photon will both still have a potential of slightly less than 1 V (i.e. the electrons are delivered with an energy of 1 eV) [3].

Sunlight is a spectrum of photons distributed over a range of energy. Photons whose energy is greater than the band gap energy (the threshold energy) can excite electrons from the valence to conduction band where they can exit the device and generate electrical power. Photons with energy less than the energy gap fail to excite free electrons. Instead, that energy travels through the solar cell and is absorbed at the rear as heat. Solar cells in direct sunlight can be somewhat (20–30°C) warmer than the ambient air temperature. Thus, PV cells can produce electricity without operating at high temperature and without mobile parts.

3. Efficiency through Power Matrix

The matrix method is a simple system of prediction of the energy produced by the photovoltaic panels based on direct measurements performed in real operating conditions. It is one of the methods used for determining module efficiency, as indicated in Fig. 2.

name of method	from	power or efficiency equations	temperature coefficient(s)
SSE	CREST	$\eta(G, 25^\circ) = C_0 + C_1 G + C_2 \ln G$	TC@1000W/m ²
Yield Simulator	ECN	avg $\eta(G, 25^\circ)$	average TC (250, 500, 750, 1000W/m ²)
Somes	UU	$P_r = P_{nom} \cdot \frac{\Theta(G)}{\Theta(1000)} \cdot \frac{G}{1000}$	TC=0.4%/°C (default value)
MotherPV	INES	avg $\eta(G, 25^\circ)$	TC(G)
PV-SAT	H2M	$\eta_{3pp}(G, T) = a_1 + a_2 G + a_3 \ln(G \cdot m^2 / W) \cdot (1 + \alpha \cdot (T - 25))$	
Matrix method	SUPSI	$I_m = I_{m,sto} \cdot G/1000 \cdot [1 + \alpha_{Im} \cdot (\Delta T + T - 25)]$ $V_m = V_{m,sto} + C_0 \cdot \ln(G/1000) + C_1 \cdot (\ln(G/1000))^2 + \beta_{Vm} \cdot (\Delta T + T - 25)$	
ESTI-ER	JRC	$P(G, T) = I_{m,sto} \cdot G/1000 \cdot [1 + \alpha_{Im} \cdot (T - 25)] \cdot (V_{m,sto} + C_0 \cdot \ln(G/1000) + C_1 \cdot (\ln(G/1000))^2 + \beta_{Vm} \cdot (T - 25))$	
ZENIT	ISE	$P(G, T) = a \cdot G^2 + b \cdot \log(G + 1) \cdot G + c \cdot \left(\frac{(\log(G + e))^2}{G + 1} - 1 \right) \cdot G + d \cdot (T - 25)$	

Fig. 2. Power efficiency method.

The energy produced in a year by a device is obtained simply by multiplying the elements of power matrix $P=\{P(G_i, T_a)\}$ by the elements of the matrix of the climatic events $N=\{N(G_i, T_a)\}$ and adding the elements of the resultant matrix:

$$E = \sum_{G_i, T_a} P(G_i, T_a) N(G_i, T_a) [kWh / year] \tag{1}$$

The P power matrix describes the power produced by a special device depending on the incident radiation on the panel plan (G_i) and on the room temperature (T_a). The elements $P(G_i, T_a)$ of the P matrix are obtained through the average of the powers produced by a panel during a year of monitoring for every single climatic situation (G_i, T_a):

$$P(G_i, T_a) = 1/N \left(\sum_{i=1, N} P_i(G_i, T_a) \right) \quad (2)$$

Each power $P(G_i, T_a)$ is obtained by multiplying I_{mpp} and V_{mpp} measured in the climatic situation (G_i, T_a). At the end, the matrix is "filtered" excluding the points obtained by an average on less than 3 measurements ($N < 3$; rare events) or measurements with excessive standard error ($StDev/Avg > 20\%$; measurement errors). The matrix of the climatic events N counts the number of times that in a year given climatic event (G_i, T_a) occurs. This can be obtained through the hourly data of radiation and temperature obtained from standard software like METEONORM, or through the direct acquisition of (G_i, T_a) by a climatic station in the installation site. In this last case, it is necessary, however, to normalize the matrix by dividing it by the number of acquisitions made in an hour. The procedure for the matrix creation consists in a separated interpolation of the current $I_m(G_i, T_a)$ and the voltage $V_m(G_i, T_a)$ obtained by the measurements. The power matrix is yielded by multiplying the current matrix by the voltage one. The equations are described below:

$$I_m = I_{m, stc} \cdot G_i / 1000 \cdot [1 + \alpha_{I_m} \cdot (\Delta T \cdot G_i / 1000 + T_a - 25)] \quad (3)$$

$$V_m = V_{m, stc} + C_0 \cdot \ln(G_i / 1000) + C_1 \cdot (\ln(G_i / 1000))^2 + \beta_{V_m} \cdot (\Delta T \cdot G_i / 1000 + T_a - 25) \quad (4)$$

where:

$I_{m, stc}$ current at maximum power point at STC condition;

α_{I_m} coefficient of temperature of I_m to $1000W/m^2$;

ΔT difference of $T_{cell} - T_a$ temperature to $1000W/m^2$ and working of the panel at the maximum power point;

$V_{m, stc}$ tension at maximum power point at STC condition;

C_0 and C_1 parameters of panel;

β_{V_m} coefficient of temperature of V_m to $1000W/m^2$;

T_a room temperature;

G_i incident radiation on the panel.

Fig. 3 and Fig. 4 depict the power matrix yielded from the developed modeling while Fig. 5 illustrates the ideal and real power matrixes got from the implemented modeling.

Performing outdoor test [4, 5], one wants to have the possibility to study the behaviour in real conditions of working of various device typologies, in climatic situations of Lecce. Using two panels mono-Si, of Top-Ray manufacturer, with different tolerance, it was possible to monitor the power produced in MPP and build the power matrixes and the matrix of the climatic events. Through the analysis of the monitored data it was possible to study the response in temperature and the response in radiation of the different devices, trying to evaluate the typology most suitable for the local climatic situation, that is, the typology that produces the biggest amount of energy. It was also possible to study the effects of the change of spectral output on the different devices. We are working, together with TISO laboratory, to turn the matrix method into true and real software for the prediction of the energy produced by the photovoltaic systems, including corrective factors in the method which considers the effect of cloud and the other system power losses (mismatch between the panels, losses in the cables and efficiency of inverter). Once data are available, it is possible to calculate the total efficiency of a photovoltaic system, given from the product of the photovoltaic modules efficiency η_{module} by BOS

(Balance Of System) system efficiency η_{BOS} , as follows:

$$\eta_{PV} = \eta_{module} \cdot \eta_{BOS} \quad (5)$$

where the photovoltaic modules efficiency, which expresses the part of the solar power incident on the module surface that is converted in electric power, is given by:

$$\eta_{module} = \frac{P_{el}}{G \cdot A} \quad (6)$$

where:

G is the radiation in STC [W/m^2];

A is the generic module area [m^2];

P_{el} is the maximum electric power provided form module [W].

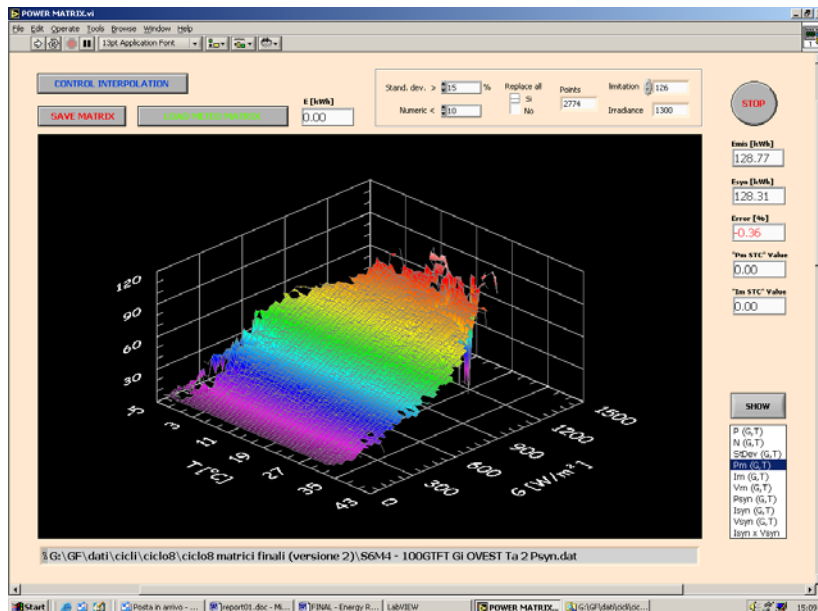


Fig. 3. Power matrix.

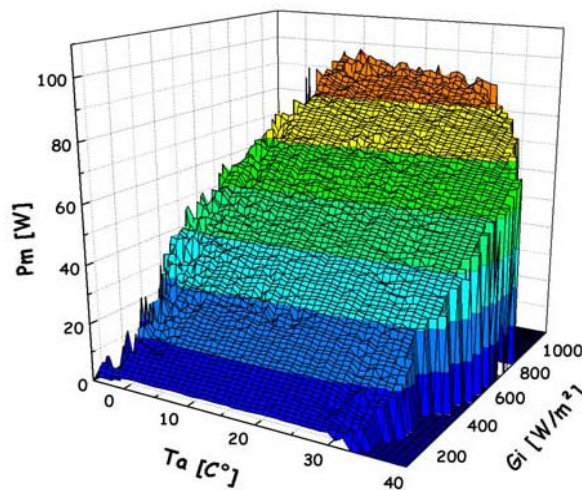


Fig. 4. Power matrix representation.

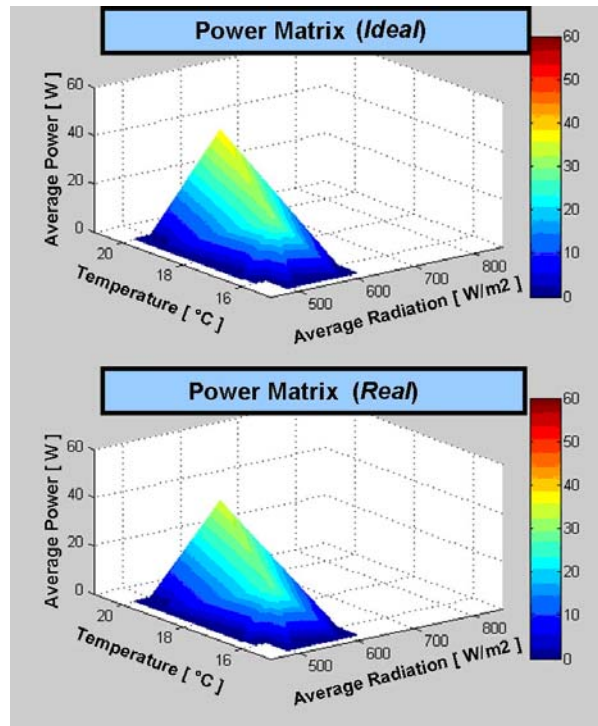


Fig. 5. Ideal and real power matrixes a photovoltaic.

4. Home PV Plant

In the end of the month of April 2009, a 50 kWp of power photovoltaic system was installed on the flat roof of an institute of Taranto, the “Salesiano Don Bosco”, showed in Fig. 6 and in Fig. 7. In the first phase of design, several information pertaining to environmental, technical and logistic conditions of the future system installation site has been collected.



Fig. 6. General view.



Fig. 7. Partial view.

During the inspection, the site conditions, the available area, the optimal system orientation and the shading zones have been estimated. Therefore, we decided that the photovoltaic system would be exposed with an azimuth of 0 degrees with respect to south and would be a tilt of 30 degrees with respect to horizon. Such exposure is the most suitable in order to maximize the energy yield. A verification of the system has been performed to help company to install the plant. A shadow factor

equal to 0.85 m, assuring in this way that the energy losses resulting from shading are not longer than 15 % on yearly basis. The general board and the inverters are depicted in Fig. 8 and Fig. 9 respectively.



Fig. 8. General board.



Fig. 9. Inverter system.

Before installing the plant on the roof, it was appropriate to use measurements performed at the University of Salento for the specific solar module “Top-Ray”. The solar module has been exposed in open air for outdoor characterization, by measuring irradiance, atmosphere and module temperatures, wind speed, etc.. The measurements have been recorded for many months and bring to the following results [6]: matrix of interpolated power (Fig. 10) which explains the power that the module would produce if it were exposed for long time with respect to the current one even if all data were not available; the weather matrix (Fig. 11), necessary to correlate sensed irradiance with temperature; and the energy production (Fig. 12). A concise description of the results is shown in Table 1 and Table 2. Table 2 demonstrates the difference between the measured energy and the calculated one that is around 0.80 that indicated the adopted method of power matrix yields good estimates.

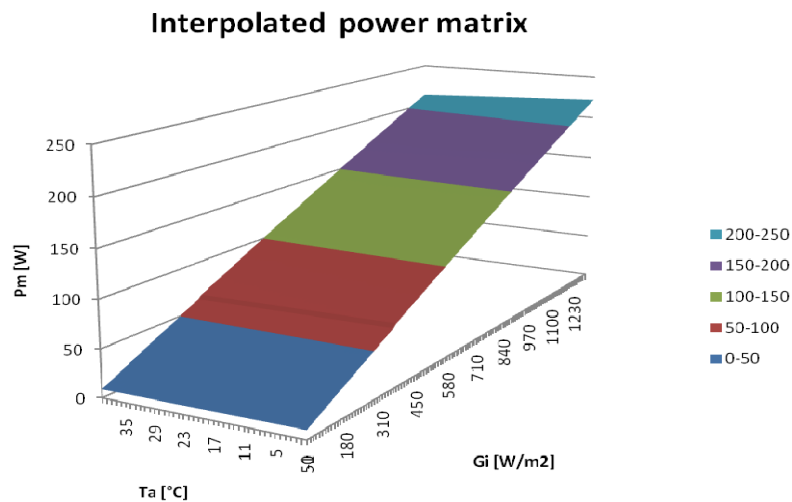


Fig. 10. Power matrix.

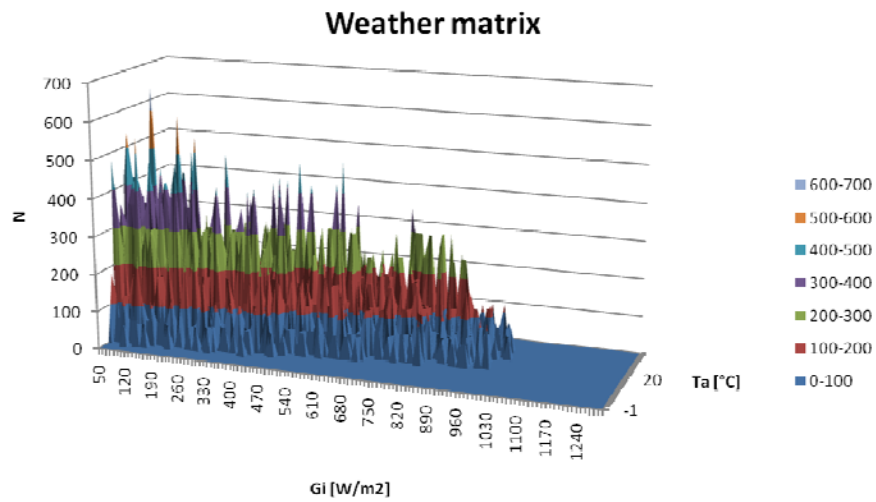


Fig. 11. Weather matrix.

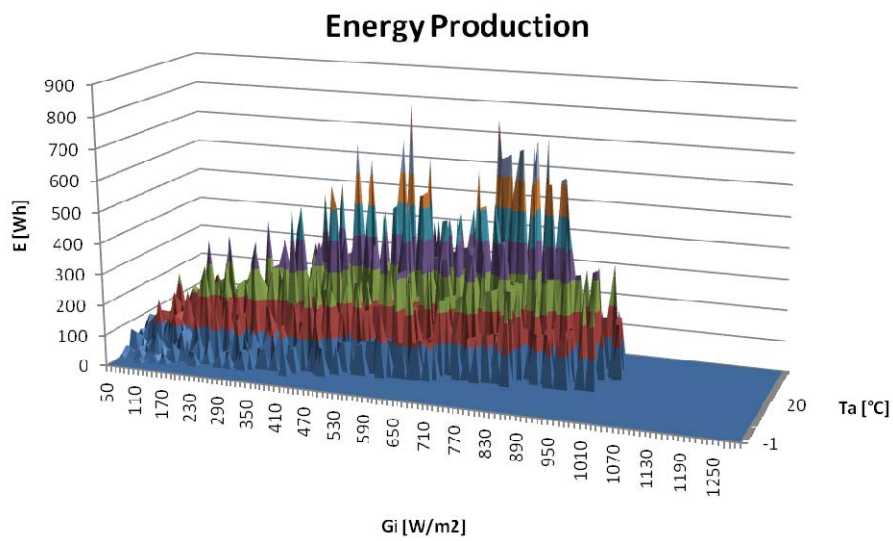


Fig. 12. Estimated energy production.

Table 1. PV module main data.

Manufacturer	TOPRAY	Serial Nr.	
Module Name	TPS-105-175W	Material	mono-LGBC
Annual Energy Production			Power
30° south	[kWh]	[kWh/W]	Pm 175
Lecce	265.0577326	1.514616	

Table 2. PV module outputs.

Module & technology		E(real)	E(calc)	$\Delta E(\text{real})-E(\text{calc})$
		year	10x1	
		[kWh]	[kWh]	[kWh]
TPS-105-175W	mono-LGBC	270.85	265.0577	0.7923

After determining the performances of the PV module, making a comparison with manufacturer datasheet, the modules of the same characteristics have been installed and the plant completed for producing energy as illustrated in the previous figures. Obviously, a specific characterization of the location has been performed in terms of shadows, irradiance, temperatures etc using references according to current legislation (Table 3 and Fig. 12)

Table 3. Solar radiation table in Taranto on the basis of UNI 10349 protocol calculated with an orientation (azimuth) of module of 0 degrees with respect to south and with a tilt of 30 degrees with respect to horizon. Chosen Albedo factor: Green grass.

Month	Daily				Monthly
	Direct Radiation (Wh/m ²)	Diffuse Radiation (Wh/m ²)	Reflected Radiation (Wh/m ²)	TOTAL (Wh/m ²)	TOTAL (kWh/m ²)
Jan	2189	774	35	2998	93
Feb	2772	1032	51	3855	108
Mar	3318	1393	73	4784	148
Apr	3935	1702	101	5738	172
May	4325	1883	123	6331	196
June	4948	1806	140	6894	207
July	5553	1573	145	7271	225
Aug	5224	1522	125	6871	213
Sept	4493	1367	94	5955	179
Oct	3663	1083	65	4811	149
Nov	2560	825	41	3426	103
Dec	2026	696	31	2753	85
Annual Tot.					1879

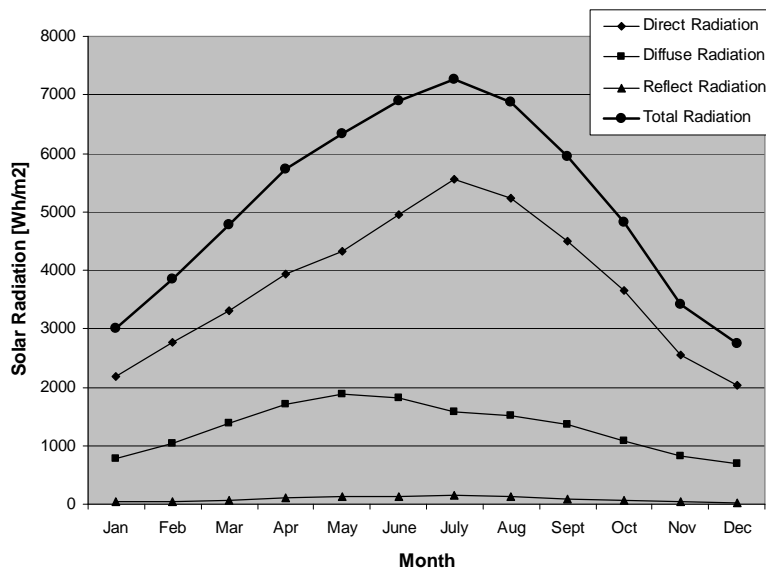


Fig. 13. Solar radiation chart.

The photovoltaic system has been mounted using 294 monocrystalline silicon photovoltaic modules, with a total surface of 383,41 m². Each monocrystalline silicon photovoltaic module has 170 W

nominal power, hence the whole system has about 50 kWp nominal power. Moreover, the system is made up of 24 strings of 11 modules each and of 3 strings of 10 modules each. The voltage values at the operating temperatures (minimal, maximum and operating one) fall within the ranges of inverter's recommended operating condition. The photovoltaic modules are provided with by-pass diode. Each string is provided with block diode necessary to isolate each string from the others in event of shading, faults, etc. The power line coming from photovoltaic modules is grounding by means proper surge protection, in order to guarantee the protection from thunderbolts. The converting group is made up of nine static inverters. The calculation of requirement, executed in the basis of energy consumption pertinent to the last three years previous to the system installation (provided by Enel Energia, Italian national grid), is about 55000 kWh/year.

4.1. Electric Power Yield Prediction

On the basis of UNI 8477-1 and UNI 10349 [7] protocols, the radiation, calculated on modules exposed to 0 degrees with respect to south, with a tilt of 30 degrees with respect to horizon and with a chosen Albedo factor of green grass, is equal to 1879 kWh/m². The photovoltaic system power, in STC (i.e. module radiation of 1000 W/m² and temperature of 25 °C) is in 2009:

$$P_{STC} = P_{\text{module}} \times \text{number of module} = 170 \times 294 = 49980 \text{ Wp} \quad (7)$$

Considering an η_{BOS} equal to 80%, the power in AC side will be about:

$$P_{CA} = P_{STC} \times 80\% = 39984 \text{ Wp} \quad (8)$$

The yearly yielded energy by the photovoltaic system will be:

$$E [\text{kWh/year}] = (I \times A \times K_{\text{shading}} \times \eta_{\text{module}} \times \eta_{BOS}), \quad (9)$$

where:

- I : yearly mean radiation = 1879 kWh/m²;
- A : total area of modules = 383.4 m²;
- η_{module} : conversion efficiency fo modules = 13.2 %;
- K_{shading} : shadows factor = 0.85;
- η_{BOS} : B.O.S. efficiency = 80 %;

Therefore, applying formula (9):

$$E = 1879 \times 383.4 \times 0.132 \times (0.85 \times 0.80) = 64663.8 \text{ kWh/year} \quad (10)$$

The value 64663.8 kWh/year is the energy that the photovoltaic system will annually produce without failures.

4.2. Electric Power Yield Sensing

In phase of planning, the predicted power yield has been of 64663.8 kWh/year. Against this value, there is the yield really obtained by the photovoltaic system. Following meters have been used to learn the effective values of yielded energy.

An electric meter which measures the total yielded energy by the photovoltaic system put immediately after inverters (UTF meter); An electric meter provided by ENEL. Moreover, data can directly be displayed in remote control thanks to web site <http://salesiani.sytes.net>

It has been therefore possible to monitor the system and to obtain a data survey for the first eight month of the system life. This is a sufficient sample for establishing the system efficiency and for valuating reliability of performed predictions. The UTF meter, from 1st of May to 31st of December 2009, surveyed almost 47500 kWh of yielded electric power ¹. If a valuation on an entire year want to be done (in order to compare predicted power yield with the effective one), it can be carried out a projection for the only four months left. Referring to data in the table, it can be observed that the radiation of months from January to April would be analogous to the four-month period September – December radiation, where have been globally produced 17300 kW of electric power. If these predictions would be true, the one year yield, from 1st of May to 30st of April 2010, will be the same of the predicted one. In year 2010, the energy produced assume the same trend as shown in Table 4 and in Fig. 14.

Table 4. Example of date.

Month	Energy Yelded [kWh]
Jun 2009	7728
Jul 2009	8586
Aug 2009	7797
Sept 2009	6411
Oct 2009	4209
Nov 2009	3891
Dec 2009	2742
Jan 2010	2823
Feb 2010	3984
Mar 2010	5490
Apr 2010	6774
May 2010	7632
Jun 2010	7824
Jul 2010	7938
Aug 2010	8490

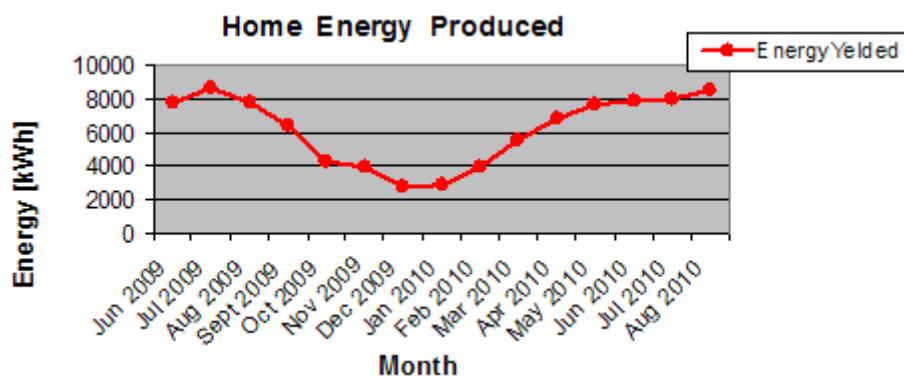


Fig. 14. Energy produced in 2009.

¹ These data, daily surveyed and transcribed on “UTF register”, has official value.

5. Results and Conclusions

The 50 kWp photovoltaic system was designed in order to obtain the maximum yield in terms of electric power. For this system, in preliminary step a production of 64663.8 kWh/year was estimated. Then, during the system first eight months of live, the production data have been daily monitored. Considering these data and making a short projection, it can be affirmed that, at 30th of April 2010, the photovoltaic system will produced 64.580 kWh, so an extremely close value to the predicted one.

It can be concluded that predictions, based on the calculation of subsection 4.1, are truthful so they have been estimated in accurate way and that the photovoltaic system has been designed in such way to consider all the possible losses [8, 9] capable of invalidating [10] the system efficiency (shading, azimuth, module tilt, etc.).

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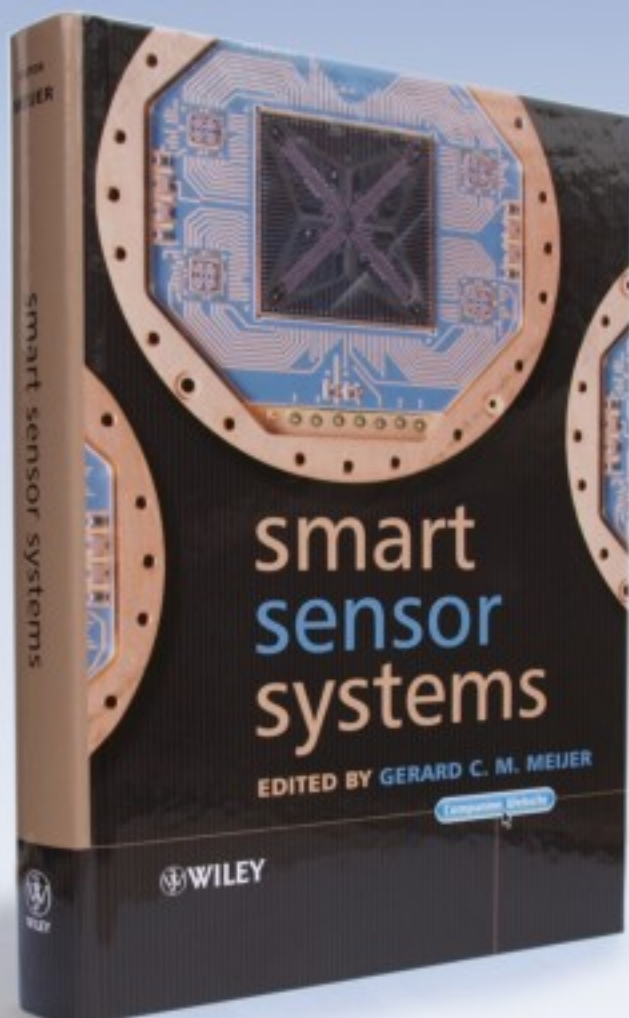
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