Experimental Verification of Thermal Behaviour of Photovoltaic Modules

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Abstract— **The thermal environment that dictates module operating temperature is complex, also being influenced by many variables such as: irradiance, ambient temperature, speed and direction of the wind and module design, orientation, and mounting structure. This paper presents the results of some experiments aimed to verify the thermal behaviour of a photovoltaic module. The study is also based on an analytical electrical and thermal model that has been developed to calculate the cell temperature starting from measured meteorological data.**

Index Terms--**Photovoltaic cell thermal factors, Circuit modeling, numerical analysis, Power measurement.**

I. Introduction

Photovoltaics (PV) probably are the most simple and reliable way to convert solar energy into electricity. However, the technology is not yet commercially competitive for high volume generation of electricity. Nevertheless there are more and more applications for which PVs by far are the best solutions such as the micro and mini distributed generation inside urban and suburban areas.

The future competitiveness of PV depends on many factors, such as technological advances, production volume of PV components, ecological tax on traditional energies, and also on the most judicious use of this new energy technology. The latter point in particular relates to the performances of PV-generator under site-specific climatic conditions. The question is: what energy output of different generators can be expected under actual operating conditions at climatologically different sites? To answer this question, the physical behaviour of solar cells and PV module under varying solar illumination and changing climatic conditions needs to be known. On the other hand the maturity of the photovoltaic industry can be gauged by its ability to design and size arrays for different applications and sites, and then to accurately and cost effectively verify array performance in the field. These abilities will be fully manifested when they can be equitably applied to crystalline silicon, thin-film, and concentrator photovoltaic technologies, with array sizing based on either power or energy production.

It is well-known that most of the solar radiation absorbed by a photovoltaic (PV) module is not converted to electricity but contributes to increase the temperature of the module, thus reducing the electrical efficiency.

In this context, this paper presents the results of some experiments aimed to verify the thermal behavior of a photovoltaic module. In particular the effects of very rapid drop respectively in the irradiance, wind speed and electrical load are presented. The study also compares the experimental results with an analytical electrical and thermal model that has been developed to calculate the PV cell temperature starting from external data.

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II. Behavioural PV module model

The photovoltaic module model, used in this paper, is based on an equivalent circuit with a single diode (single exponential), which is amply described in the bibliography [1]. By means of this model it is possible to explicit, also, the relationships among the electrical variables (V and I) that fix the operating point of the module and the cell temperature (T_{pv}).

In particular it is worth observing how the cell temperature (T_{pv}) and irradiance (G) impact on the efficiency of the module when it is working in its maximum power point (MPP). The related equations, after some simplifying assumptions, are given by:

$$I_{MPP} = \left[I_{MP\,\mathrm{Pr}ef} + \left(\frac{dI_{SC}}{dT_{pv}} \right)\Bigg|_{T_{pv}=T_{pvref}} \left(T_{pv} - T_{pvref} \right) \right] \cdot \frac{G}{G_{ref}} \quad (1)$$

$$V_{MPP} = V_{MP\,\mathrm{Pr}ef} + \left(\frac{\partial V_{OC}}{\partial T_{pv}} \right)\Bigg|_{G=G_{ref}} \left(T_{pv} - T_{pvref} \right) + \left(\frac{\partial V_{OC}}{\partial G} \right)\Bigg|_{T_{pv}=T_{pvref}} \left(G - G_{ref} \right) \quad (2)$$

Where:

G = Solar Irradiance in W/m^2;

T_{pv}= PV cell temperature in °C;

I_{MPP} = Maximum Power Point current in A;

$\frac{dI_{SC}}{dT_{pv}}$ = Derivative of short circuit current versus cell temperature in A/°C;

V_{MPP} = Maximum Power Point voltage in V;

$\frac{\partial V_{OC}}{\partial T_{pv}}$ = Derivative of open circuit voltage versus cell temperature in V/°C;

$\frac{\partial V_{OC}}{\partial G}$ = Derivative of open circuit voltage versus irradiance in V/W/m^2;

Further the parameters with the subscript "ref" refer to the following Standard test conditions (STC):

- ⇒ G = 1000 W/m^2
- ⇒ Atmospheric spectrum corresponding to an air mass ratio of 1.5 (AM)
- ⇒ T_{pv} = 25 °C
- ⇒ Wind speed = 0 m/s

How the cell temperature affects the performances of several photovoltaic modules using various technologies: Crystallin silicon (c-Si), Polycristalline silicon (pc-Si), Cadmium Telluride (CdTe) and, Copper Indium Diselenide (CIS) has been studied in [2], see Tab. I For example for a module made of mono o poli crystalline PV cell, approximately, an increment of 10 °C of the cell temperature determines a module efficiency reduction of about the 3.8÷5.0% referred to the STC conditions.

Tab. I
Effect of the PV cell temperature on the module efficiency [2]

Module technology	c-Si	pc-Si	CIS	CdTe
% °C^{-1}	-0.496÷-0.388	-0.401	-0.484	-0.035

This rough evaluation is crucial to highlight the importance of designing and operating a PV system in such a way to keep the cell temperature as low as possible.
On the other hand the lowering of price of microprocessor ed cards and at the same time the increasing of their calculation capabilities open the possibility to monitor the performances of PV systems so as to put in evidence critical operating conditions (e.g. low ventilation for BIPV systems).

III. PV Module temperature models

The most common manner to determine the cell temperature Tpv consists in using the Normal Operating Cell Temperature (NOCT) [1]. The value of this parameters is given by the PV module manufacturer. Tpv is then dependent on the ambient temperature Ta and on the solar irradiance G according to (3):

$$T_{pv} - T_a = \frac{NOCT - 20}{800} G \qquad (3)$$

NOCT is calculated for a wind speed at a PV module height of w=1 m/s, an ambient temperature Ta = 20 °C and a hemisferical irradiance G= 800 W/m^2 and the module is an open circuit. This simple method works quite well if the ventilation is natural.
Then two other methods have been considered. In the first one the method of Neural Networks was used to analyze the data collected for different PV modules [3]. The objective of the analysis was to obtain a relationship between module temperature and the ambient conditions. In [3] a simple linear relationship between the module temperature and the ambient conditions (ambient temperature, irradiance, humidity , wind speed "w" and wind direction "w^d") has been found, and it is established as shown in (4):

$$T_{pv} = w_1 T_a + w_2 G + w_3 w + w_4 w^d + w_5 \phi + const. \qquad (4)$$

The second method has been developed in Sandia National Laboratories - Photovoltaic Systems Department [4]. This simple experimental model has been found to provide reasonably accurate estimates (±5°C) of module back surface temperature for typical flat-plate modules, near thermal equilibrium, mounted in an open rack structure.
(5) gives the simple relationship used:

$$T_{pv} = T_t + \frac{G}{G_0}\Delta T = \left(T \frac{G}{G_0} \cdot \left(T_1 e^{bw} + T_2 \right) + T_a \right) + \frac{G}{G_0}\Delta T \qquad (5)$$

Where:
T_t = back-surface module temperature in °C
T_a = ambient temperature in °C
G = solar irradiance on module in W/m^2
G_o = reference irradiance, 1000 W/m^2
w = wind speed measured at standard 10-m height in m/s
T_1= empirical coefficient determining upper temperature limit at low wind speeds, in °C

T_2 = empirical coefficient determining lower temperature limit at high wind speeds, in °C
b = empirical coefficient determining the rate that module temperature drops as wind speed increases

Tab. II
Empirical coefficients for module and cell temperature estimation, for two typical module designs [5].

Type	T_1 (°C)	T_2 (°C)	b	ΔT (°C)
Glass/cell/glass	25.0	8.2	-0.112	2
Glass/cell/Tedlar	19.6	11.6	-0.223	3

None of the above methods consider the electrical operating points of the PV module and this is the main point that will be discussed later.

IV. PV MODULE THERMAL MODEL

In section II the effect of the variation of the cell temperature on the efficiency of the module has been shown. Now the effect of the ambient and electrical variables that impact the cell temperature will be considered.
To determine the PV cell temperature it is necessary to study carefully the thermal behaviour of the PV module (Fig.1). This study has been carried out considering the PV modules made of three layers, named respectively front, central and back layer, for each of them a thermal balance has been performed.

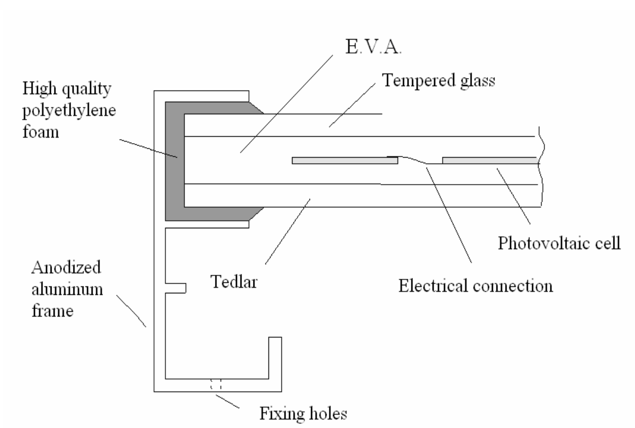

Fig. 1. Photovoltaic module section

$$\alpha_g G + \left(\frac{\lambda_g}{d_g}\right)\left(T_{pv} - T_g\right) = h_{cga}\left(T_g - T_a\right) + h_{rgs}\left(T_g - T_a\right) \quad (6)$$

$$\left(\frac{\tau_g \alpha_{pv}}{\left(1-\left(1-\alpha_{pv}\right)\left(1-\tau_g\right)\right)} - \eta\right) G = \left(\frac{\lambda_g}{d_g}\right)\left(T_{pv} - T_g\right) + \left(\frac{\lambda_t}{d_t}\right)\left(T_{pv} - T_t\right) \quad (7)$$

$$\left(\frac{\lambda_t}{d_t}\right)\left(T_{pv} - T_t\right) = h_{cta}\left(T_t - T_a\right) \quad (8)$$

The parameters and variables are classified as follows:

1) Meteorological data
1.a) Solar irradiance (G)
1.b) Speed (w) and direction of the wind
1.c) Ambient Temperature (Ta)
1.d) Air humidity (ϕ)

2) Data on PV module installation site
2.a) Height on the sea level

3) Thermal characteristic of the PV module materials
3.a) Absorption
3.b) Thermal conductibility
3.c) Heat transfer coefficient
3.d) Transmittance

4) Geometrical characteristic of the module
4.a) Characteristic length
4.b) Module area
4.c) Width of the layers

5) Electrical characteristic of the module
5.a) Voltage of the module
5.b) Current of the module

The set of equations has been implemented in a numerical code developed in Matlab. Starting from the environmental data this software determine the following unknown PV module temperatures: front (glass), PV cell, back (Tedlar).
Varying the electrical working point of the module, from the open circuit state to the short circuit state a parabolic trend of the PV cell temperature is obtained.
When the power supplied by the module is zero (also the efficiency η is zero) the temperature reaches the maximum value. From (7) it is possible to understand that in this case the whole solar energy that remains inside the module is converted in heat.
On the contrary when PV module is on its Maximum power point, i.e. supplying the maximum energy, the cell temperature is minimum. In fact only a fraction of the solar energy inside the module is converted in heat.
Fixing some ambient variables it is possible to calculate by means the electrical and thermal model in [5] the PV cell temperature trend, from short circuit to open circuit.
The proposed model was used to test a polycrystalline photovoltaic module type 125G-2 provided by the manufacturer KYOCERA. Referring to this module, the PV cell, front (glass) and back (Tedlar) temperatures are reported in Fig. 2. PV cell and Tedlar temperatures are very close so as the two curves are overlapped and, of course they are above the glass temperature curve.

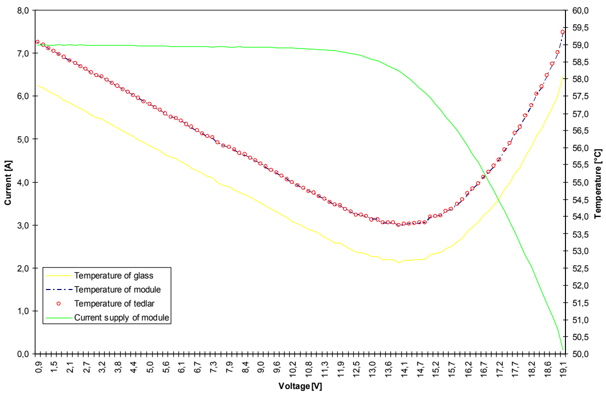

Fig. 2. I-V PV module curve (green line), PV cell and Tedlar temperatures (respectively red and blue lines), glass temperature (yellow line). (G = 800W/m^2, Ta = 25°C; w =1m/s, w_back= 0,5 m/s, ϕ =50%)

Using the mathematical model [5], a sensitivity analysis of PV cell temperature versus the climate variables can be carried out. In particular, under the hypothesis of open circuit (I=0 A) and wind speed on the back of the module equal to 0.5 m/s, the results of the sensitivity analysis for Kyocera 125G-2 have been reported in Tab. III

Tab. III
Sensitivity analysis of PV cell temperature (I=0 A, w_back= 0.5 m/s)

	Inizial value	Δ	ΔT_{pv} (°C)
Irradiance - G	800 W/m^2	+100 W/m^2	+4.4
Ambient temperature - T_a	25 °C	+1 °C	+ 1
Wind speed - w	1 m/s	+1 m/s	- 3.3
Humidity, ϕ	50%	+10%	0.5

V. EXPERIMENTAL RESULTS

From experimental tests, carried out by means of three temperature sensors : on the Glass, on the Tedlar and on the EVA layer. From the analysis of the measured data and the comparison with the results obtained applying the electrical and thermal model, the following considerations can be drawn:

1) the three layers have different temperatures and the central layer has the highest temperature. The same behaviour is predicted by the mathematical model;

2) there is an evident different among measured and calculated values when rapid and wide variations of solar irradiance happen (Fig.3.). This is due to the lacking of thermal capacitances in the mathematical model.

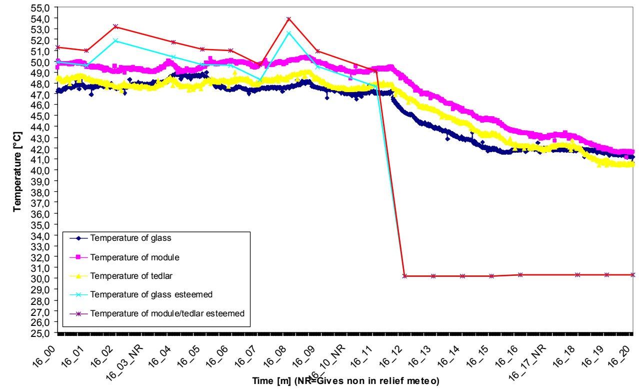

Fig. 3. Front, central and back layer temperatures of the PV module

The Tedlar temperature differs from the cell temperature of about one or two degree whatever irradiance it happens. On the other hand from a practical point of view the Tedlar temperature is the one that is normally monitored in a real pv system so afterwards only the Tedlar temperature will be considered as operating temperature.

The next issue is to determine how this temperature varies moving from the frame to the center of the module. On this regard a set of three temperature sensors (PT100) has been placed in the back of the PV module (see Fig. 4).

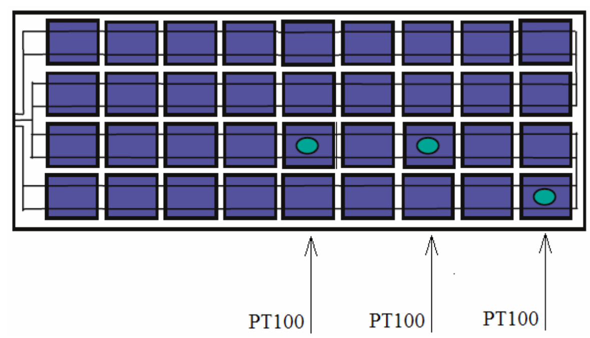

Fig. 4. Position of the three temperature sensors (PT100)

It is worth noticing that the distribution of the temperature along the surface of the module is not uniform but it has a maximum in centre and the minimum along the border. The difference is about five degree (Fig. 5).

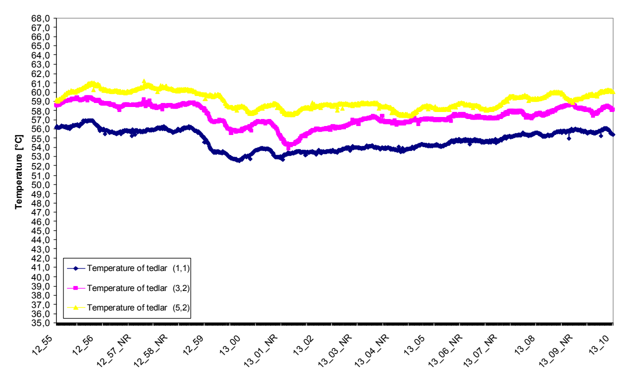

Fig. 5. Temperatures of Tedlar in different positions

A. Thermal time constant of a PV module

The time constant of the thermal module response is defined as the time taken for the module temperature to reach 63% of the total change in temperature resulting from a step change in the irradiance level. To determine such a time constant an experiment has been set: a module was subjected to a step change in the irradiance level from 800 W/m^2 , also to avoid the effect of wind speed on the cell temperature a barrier has been put around the module. According to the literature [6] in the case shown in Fig. 6 the time constant of the module is observed to be about 7 min. Based on this value, during the experiments we wait at least 7 min after a relevant variation of a variable before considering that the system can be considered in steady state condition.

Also it is interesting to evaluate the thermal power keep by the system due to its thermal capacity. During the time interval shown in Fig. 6 (Δt = 22 min), the total drop in temperature ΔT is about 15 K, under the hypothesis of a thermal capacity of the module C_M equal to 2918 J/K [6], thermal power keep by the system $P_{CM} = C_M(\Delta t / \Delta T)$ is equal to 33 W. This value is very low related to the input power G=1000 W/m^2, the percentage ratio P_{CM} / G is only the 3.3%.

As a matter of fact the impact of the variation of the electrical working point of the module (from the open circuit point to short circuit point) if this variation lasts few minutes, has a slight impact on the PV cell temperature. In this case the mathematical model provide results clearly different (Fig. 7).

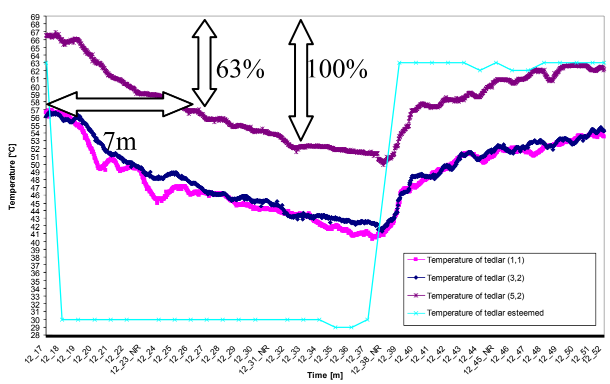

Fig. 6. Thermal time constant of a PV module

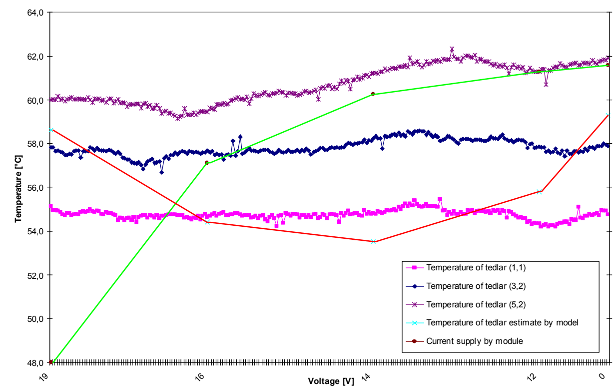

Fig. 7. Measured temperatures of Tedlar in different positions versus calculated Tedlar temperature (red line) varying the electrical working point (green line).

B. Wind speed and electrical load on module temperature

After reaching a thermal steady state condition, for a given electrical load, it has been noticed that, due to the lacking of thermal capacity, the model reacts instantaneously for a variation in wind speed (Fig. 8.a), whereas the experimental results show a damped and delayed answer (Fig. 8.b).

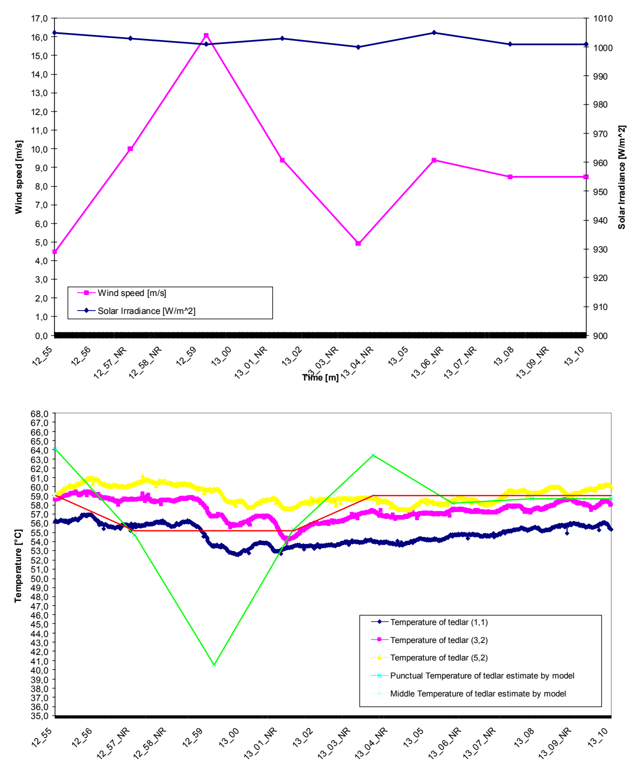

Fig. 8. (a) Solar Irradiance (blue line) and Wind speed (purple line) during size (date 04_07_2007) (b) Temperature of the module varying the wind speed (date 04_07_2007)

The model has been developed under the hypothesis that the wind blows perpendicularly the short side of the module (the length of this side is called characteristic length), under this assumption the heat exchange is optimal. In Fig. 9 the temperature of module versus the characteristic length has been plotted varying the wind speed. This information is useful also to evaluate the impact of the wind direction on the temperature.

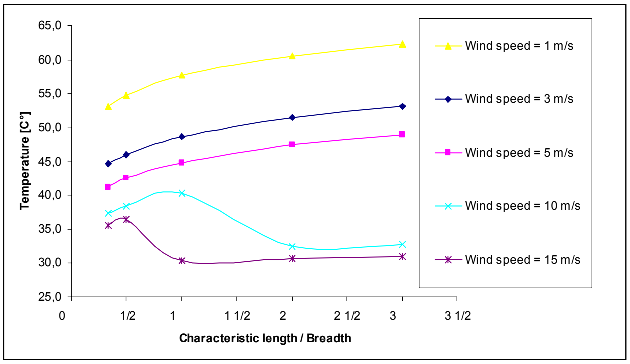

Fig. 9. PV module temperature varying the characteristic length

Further it is to notice that the module temperature depends also on the thermal exchange (i.e. laminar or turbulent wind flow) [7]. In fact for a given combination of both characteristic length and wind speed the transition from laminar to turbulent flow occurs

When it happens the temperature decreases and the characteristic length do not play a rule.

Finally, for stable meteorological conditions, the effects of electrical load have been studied. During the first part of the experiment the load changes, so as to determine the I-V characteristic and the maximum power point (Fig. 10 15:05 ÷15:08). Then the module works at open circuit condition for 7 minutes (Fig. 10 15:08÷15:15); later it works for 7 minutes in maximum power point (Fig. 10 15:16÷15:23).

Also in this case the real system answer is smoothed and delayed compared to mathematical model. (Fig 10).

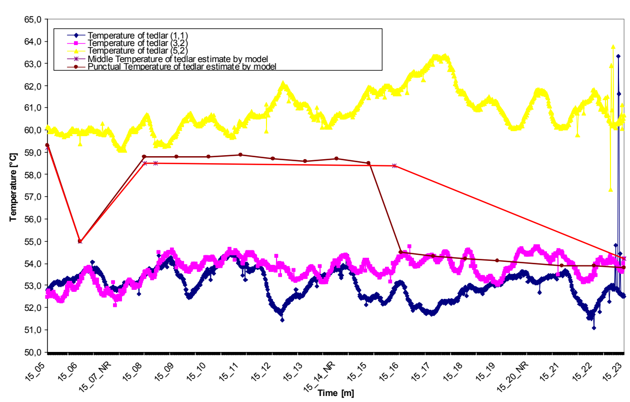

Fig. 10. PV module temperature varying the electrical load (date 09_07_2007)

VI. Conclusions

As far as the thermal behavior of a PV module is concerned, experimental tests have been carried out varying both ambient variables and electrical load. These tests have been used also to validate a thermal and electrical steady state model of a PV module. The results show that the error is not constant in fact it depends on the working conditions, but the variable that mostly affects the results is the wind speed. The comparison with other models, found in the literature, has shown that approximation level is comparable, but when the electrical load is variable the performances are better than other approaches.

VII. References

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