MODELLING SPECTRAL RESPONSE AND REFLECTIVITY EFFECTS: COMPARISON WITH OUTDOOR MEASUREMENTS ON PV MODULES

A. Spena[1], V. Annoscia[2]
[1]FTA Laboratories, Department of Enterprise Engineering
University of Rome Tor Vergata,
Via del Politecnico 1, 00133 Rome, Italy
[2] Tractebel, Department of Renewable Energy, Bruxelles, Belgium
spena@uniroma2.it

ABSTRACT: Nominal performances measured at STC can't give exhaustive informations about the outdoor real operating behaviour of PV modules due to continuous departures of instantaneous values of the influencing parameters from the reference ones. Also behavioural features of the panels are responsible for a remarkable decrease of the on-field performances when compared with the STC ones. This paper presents a simulation model able to predict, to describe and to justify the outdoor behaviour of PV modules through the use of equations based on few input data. The first results agree satisfactorily with experimental on-field measurements over one entire year.
Keywords: PV module, performance, simulation model

1. INTRODUCTION

Current methods for characterization of the performances of PV modules, based on measurements at STC, don't allows us to predict the effectiveness of the energy collected on field, due to the combined effects of continuous departures, during each day, of values of relevant environmental factors from STC. As a matter of fact, insulation components level (globally mostly lower than 1000 W/m^{2}), spectrum of the sunlight (rarely corresponding to AM=1.5), angle of incidence, operating temperatures (frequently higher than 25°C), when coupled with the glass covers reflectivity and with the spectral selectivity of the PV modules, cause a worsening of the behaviour if compared with predictions based on nominal efficiencies.

The paper deals with a mathematical model built to simulate actual outdoor performances of PV modules. The model has been validated by means of outdoor measurements made on a reference PV panel (see Fig.1) over one entire year of exploitation.

Fig. 1. View of the reference PV panel used for experimental validation of the simulation model.

The model is based on the determination of three corrective coefficients to be applied to the nominal efficiency η_0 in order to calculate the effective instantaneous outdoor efficiency $\eta_{outdoor}$ of a PV module during the day (namely neglecting all the BOS, shadowing and remaining system's effects).

The three corrective coefficients proposed are:

- the air mass and spectral response factor $\eta_{\lambda,m}$
- the angle of incidence factor η_θ
- the module operating temperature factor η_t

The instantaneous efficiency $\eta_{outdoor}$ may then be predicted by multiplying:

$$\eta_{outdoor} = \eta_0 \cdot \eta_{\lambda,m} \cdot \eta_\theta \cdot \eta_t \qquad (1)$$

2. AIR MASS AND SPECTRAL RESPONSE FACTOR

2.1 Air Mass effect

The first corrective coefficient considers the effects of the air mass AM and of the spectral sensitivity of the different cell materials to the solar spectrum. The solar spectrum depends on the Sun's altitude and declination, deterministic parameters which are changing continuously, and on many other additional atmospheric factors.

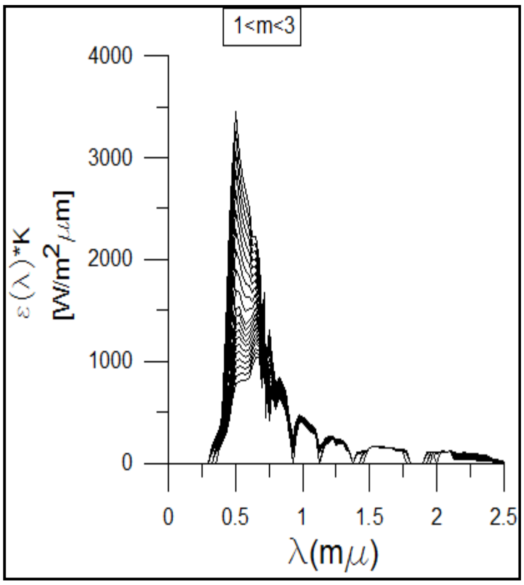

Fig. 2: Corrected values of solar irradiance for 1<AM<3.

In order to characterize the shape of the solar spectrum in a more precise way, we considered the spectral solar irradiance as a function of the wavelength for increasing values of AM. Since the values of the spectral solar irradiance were taken from literature, they were just considered as reference data and therefore, in order to relate these values to reality, we introduced a corrective coefficient K, the ratio between the total irradiance I_c calculated as the sum of the direct and the diffuse components of solar radiation, over the total irradiance evaluated from the reference data of I_g.

The corrected values of the solar irradiance as a function of AM are reported in Fig.2 and in Fig.3.

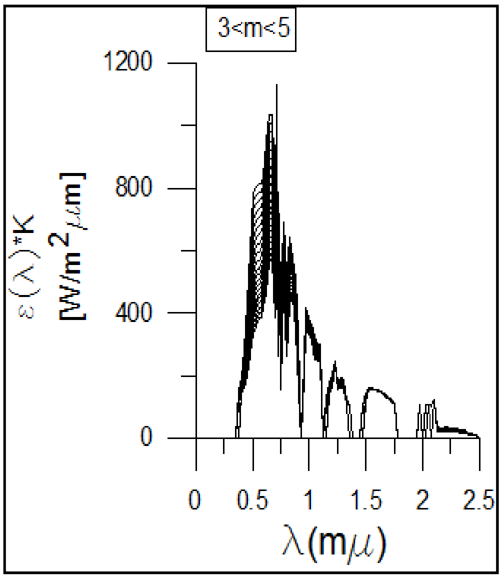

Fig. 3: Corrected values of solar irradiance for 3<AM<5.

2.2 Spectral responsivity effect

As known, every PV material has its own spectral sensitivity which can be represented by the spectral response *SR* describing the performances of any solar cell device related to different wavelengths of sunlight. In order to get the rate of absorption *SR** of each kind of cell as a function of wavelength, the *SR* curves were all related to the ideal case, as shown in Fig.4.

The power that a PV module releases P_{mod} is given by the integral over the whole spectrum of the product of the absorbed percentage of the sunlight by the direct normal simultaneous spectral irradiance, while the maximum power that can be produced at $P_{MAX\,STC}$ is represented by the integral of absorbed percentual of incident radiation by the reference spectral irradiance at AM=1.5.

The ratio between P_{mod} and $P_{MAX\,STC}$ has to be related to actual performance through the corrective coefficient K, so that the expression of the *first corrective coefficient* $\eta_{\lambda,m}$ can be written as:

$$\eta_{\lambda,m} = K \cdot \frac{P_{mod}}{P_{MAXSTC}} = K \cdot \frac{\int SR^{*} \cdot \varepsilon^{\perp} d\lambda}{\int SR^{*} \cdot \varepsilon^{\perp}_{1,5} d\lambda} \qquad (1)$$

where:

$\varepsilon^{\perp}$ = orthogonal solar spectral irradiance occurred during the test

$\varepsilon^{\perp}_{1,5}$ = reference solar spectral irradiance at AM=1.5.

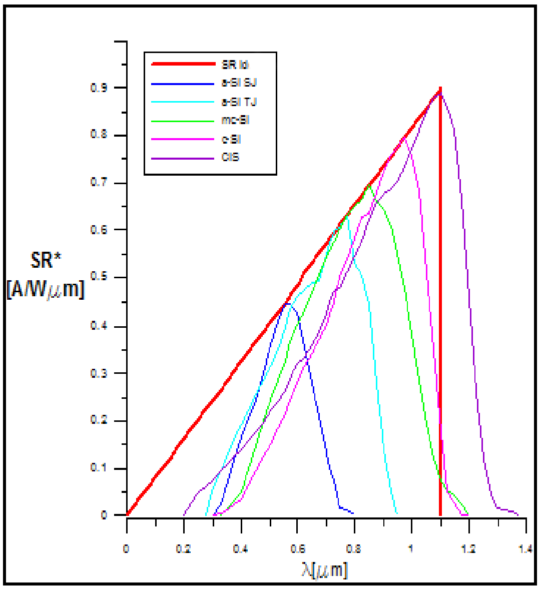

Fig. 4: Spectral response of various cells.

3. ANGLE OF INCIDENCE FACTOR

A PV module's response to the direct irradiance component is influenced by the solar angle of incidence θ and by the optical characteristics of its glass cover. The response of the module to uniformly diffuse irradiance will be here considered independent from the angle of incidence. Furthermore the response of the cell will be here assumed to have no dependence from intrinsic silicon reflectivity, from the spectral sensitivity and the refractive index of the front cell surface. Defining the absorption coefficient only allowing for the reflection characteristics of the glass surface and relating it to the case where the direct irradiance normally hits on the module's front surface, we get the fraction of irradiation which is completely absorbed by the module *a*(θ)*. Once the values of the reflectivity coefficient of the glass front surface as a function of the angle of incidence are known, the absorption rate *a*(θ)* can lead us, through an empirical function f_2 (AOI), to the definition of the *second corrective coefficient*, that considers the effects of the angle of incidence:

$$\eta_{\theta} = \frac{I_D \cdot cos\theta \cdot a^{*}(\theta) + I_d + I_r}{I_{tot}} \qquad (2)$$

where I_r is the reflected irradiance component. The trend of *a*(θ)* is shown in Fig.5.

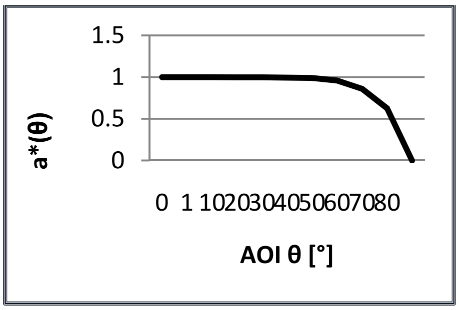

Fig. 5: Absorption rate of the glass cover of a PV module vs angle of incidence.

Plots of η_θ for every month of the year and for different module's inclinations (σ) are reported in Fig. 6.

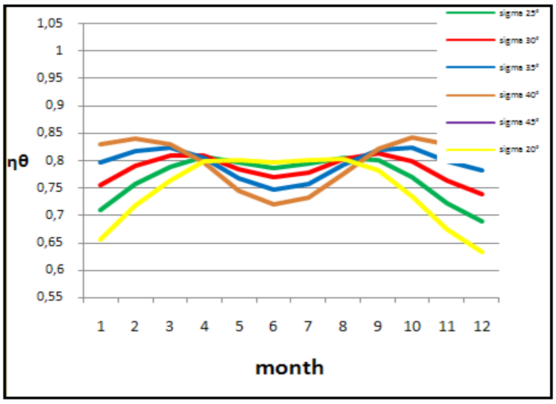

Fig. 6: Monthly average values of η_θ for module's tilt equal to 20°, 25° 30°, 35°, 40° and 45°.

4. OPERATING TEMPERATURE FACTOR

The literature's and practice's most considered parameter influencing the performances of PV modules is the operating temperature. As a matter of fact it influences, through the temperature coefficients, each parameter that characterizes the optoelectronic behaviour of a PV module: and mainly current, voltage and power. Equations from (3) to (5) are currently representative of the phenomena.

$$J(T) = J(T_0) \cdot [1 + \alpha(T_m - T_0)] \qquad (3)$$

$$V(T) = V(T_0) \cdot \left[1 - \frac{\beta}{V_{STC}}(T_m - T_0)\right] \qquad (4)$$

$$P(T) = J(T_0) \cdot [1 + \alpha(T_m - T_0)] \cdot V(T_0) \cdot \left[1 - \frac{\beta}{V_{STC}}(T_m - T_0)\right] \qquad (5)$$

where:

J = current
V = voltage
P = released power
α = temperature coefficient referred to current
β = temperature coefficient as a function of voltage
T_m = module's operating temperature
T_0 = ambient temperature.

A *third corrective coefficient* which considers the effects due to the increases of module's operating temperature is then expressed with reference to the maximum power characteristic parameters (subscribed with the letter M).

$$\eta_t = [1 + \alpha_M(T_m - T_0)] \cdot \left[1 - \frac{\beta_M}{V_M}(T_m - T_0)\right] \qquad (6)$$

5. RESULTS

The model has been validated by means of measurements available from on-field tests on a multicrystalline PV module, Kyocera KC125-GHT, at the outdoor ESTER facility (Fig.7) of the FTA Laboratories of the University of Rome Tor Vergata. Comparisons between simulated and measured data have been extensively carried out over one entire year of exploitation, since June 2008 to May 2009.

Fig. 7. View of the FTA Laboratories facility ESTER used for experimental validation of the simulation model.

Module Type	**Kyocera KC125-GHT**
Technology	Multicrystalline Si
Dimensions [cm]	142,5 x 65,2
Max Power [W]	125
I_{MSTC} [A]	7,2
V_{MSTC} [V]	17,4
I_{scSTC} [A]	8
V_{ocSTC} [V]	21,7
α_M [A/°C]	0,00318
β_M [V/°C]	-0,082

Table 1: Technical features of the Kyocera KC125-GHT.

Technical features of the PV module are given in Table 1. As a first attempt, clear-sky days have been investigated.

The results obtained from simulations appears to agree satisfactorily with the outdoor measurements. In Figs from 8 to 11 are reported the matches between simulated and measured efficiency values, in one clear-sky day per season, for tilts nearly equals to the optimal ones suggested by plots of Fig. 6.

As typical of experimental stands, and also experienced at FTA Laboratories since 2003, atmospheric input data lying close the sun rise and the sun set appear less reliable.

Several aspects of the performance of the PV panel tested, and mainly the concavity of the daily shape of the efficiency, facing bottom in summer and autumn, facing top in winter and spring, may be justified by the plots of the separated coefficients as reported, as an example, in Figs. 12 and 13. Due to the selected tilts, and to the different spans of both azimutal and elevation angles during the year, the result of the conflicting effects of reflection and temperature factors appears strongly influenced by the season's cycling.

For the experienced climatic conditions (Rome, 41.5° Lat North), the main result is that reflective effect rather than temperature effect is the most influencing factor on PV panels performance in clear-sky days during summer time, when the most effective corrective coefficient on the PV performances clearly appears to be $\eta_{\lambda m}$. It may be really observed that in summer time the performances of the PV modules improve even if the module operating temperature increases.

An opposite result appears to occur in winter and mid-seasonal time, though influenced by the different tilt.

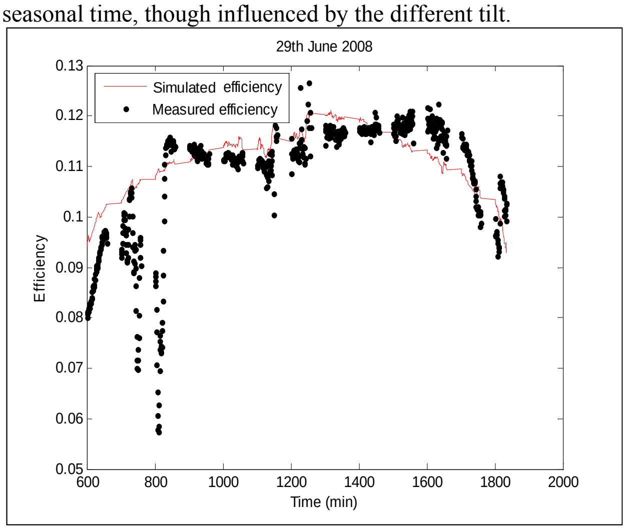

Fig. 8: Comparison of simulated and measured efficiencies, tilt 20° facing South, 29th June 2008.

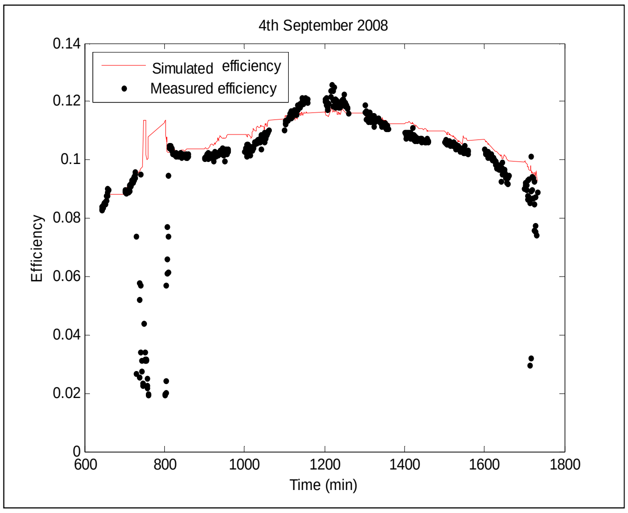

Fig. 9: Comparison of simulated and measured efficiencies, tilt 20° facing South,, 4th September 2008.

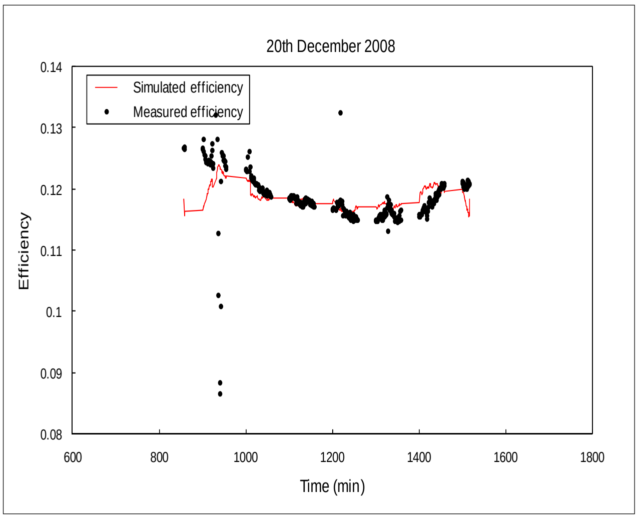

Fig. 10: Comparison of simulated and measured efficiencies, tilt 65° facing South,, 20th December 2008.

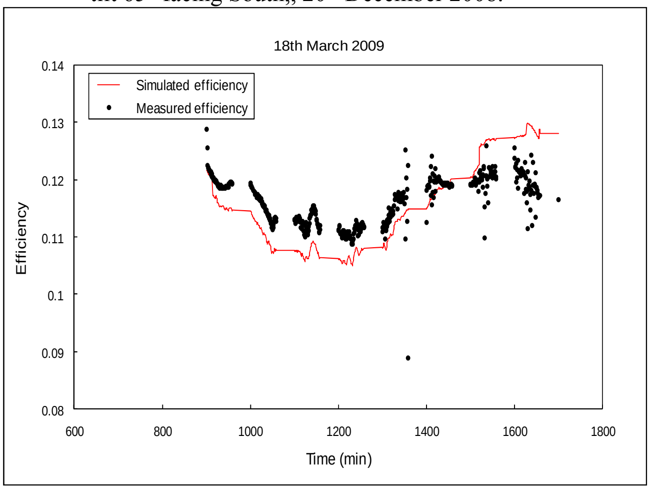

Fig. 11: Comparison of simulated and measured efficiencies, tilt 40° facing South,, 18th March 2009.

6. CONCLUSIONS

Detailed simulation appears well suited to provide a realistic forecast of the outdoor performances of PV modules, to explore ways for optimal coupling of either materials and components with actual climate, to improve system's design approaches, to allow a more correct sizing of plants in the future.

The results obtained from simulations appears to agree satisfactorily with the outdoor measurements.

The main result appears that reflective effect rather than temperature effect is the most influencing factor on PV panels performance in summer clear-sky conditions. This points out that the spectrum of the solar irradiance and the angle of incidence AOI could influence the PV performances more frequently than the operating temperature. Further experiments are needed to investigate if this behaviour could be confirmed in winter season even if keeping fixed the tilt.

The model is also going to be implemented for the forecast of overcast days by means of algorithms obtained from spectral analyses.

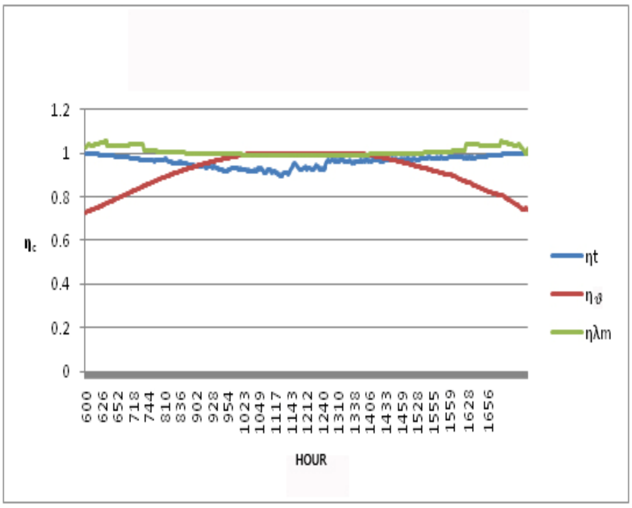

Fig.12: Single effects of the corrective coefficients on the nominal efficiency, 29th June 2008.

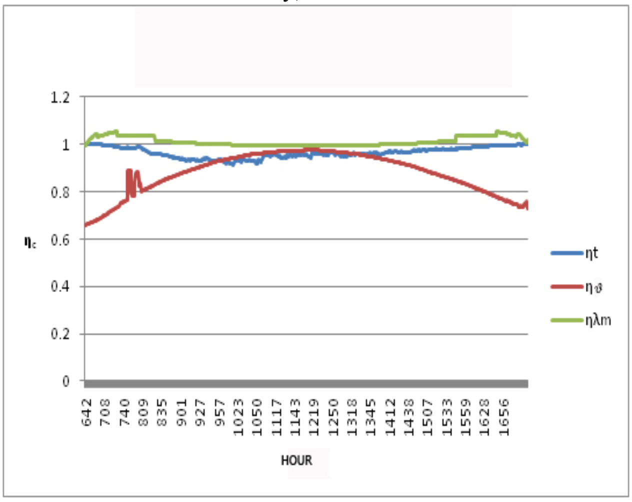

Fig.13: Single effects of the corrective coefficients on the nominal efficiency, 4th September 2008.

7. REFERENCES

[1] Hunter F.A., Davis M.W., Dougherty B.P., King D.L., Boyson W.A., Kratochvil J.A., Comparison of Fotovoltaic Module Performance Measurements, International Solar Energy Conference, Orlando 2005

[2] Sasitharanuwat A., Rakwichian W., Ketjoy N., Yammen S., Performance Evaluation of a 10 kWp PV Power System Prototype for Isolated Building in Thailand, Thailand 2006

[3] Ashrae Handbook, Fundamentals, SI Edition, 1993

[4] King D.L., Kratochvil J.A., Boyson W.E., Measuring Solar Spectral and Angle of Incidence Effects on Photovoltaic Modules and Solar Irradiance Sensors, Sandia National Laboratories Albuquerque, California 1997

[5] ISPRA–JRC, Dati dell'irradianza spettrale in funzione della lunghezza d'onda, Research Report, 1982

[6] LEE-TISO, Centrale di prova per componenti e sistemi per progetti nel campo della tecnologia fotovoltaica, TISO Rapporto finale, periodoVII 2003-2004

[7] LEE-1979-TISO, Cereghetti N., Chianese D., Travaglini G., Behaviour of Triple Junction a-Si Modules, University of Applied Science of Southern Swizerland, 2004

[8] Pèrez-Lòpez F., Fabero F. and Chenlo F., Experimental Solar Spectral Irradiance Until 2500nm: Results and Influence on The PV Conversion of Different Materials, Wiley InterScience 21, Nov. 2006

[9] Ransom S., Wohlgemuth J., Findings from Worldwide Studies of PV Module and System Performance, BP Solar, Chertsey Road, Sunbury On Thames, TW16 7XA, UK, 2001

[10] Spena A., Cornaro C. Serafini S., Outdoor ESTeR Test Facility for Advanced Technologies PV Modules, 33° IEEE Photovoltaic Specialists Conference, San Diego, California, USA, may 2008

[11] Spena A., Fondamenti di Energetica, Cedam, 1996

[12] Spena A., Un metodo generale per la determinazione delle prestazioni di collettori solari disposti in schiere parallele, La Termotecnica, pp. 61-73, aprile 1985

[13] Zdanowicz T., Rodziewicz T., Zabkowska-Waclawek M., Effect of Air Mass Factor on The Performance of Different Type of PV Modules, Optoelectron, Poland, 2004.