# A PV Temperature Prediction Model for BIPV Configurations, Comparison with Other Models and Experimental results

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## *Abstract*

*The temperatures of c-Si and pc-Si BIPV configurations of different manufacturers were studied when operating under various environmental conditions. The BIPV configurations formed part of the roof in a Zero Energy Building, (ZEB), hanged over windows with varying inclination on a seasonal basis and finally two identical 0.5kW$_p$ PV generators were mounted on a terrace in two modes: fixed inclination and sun-tracking. The PV and ambient temperatures, $T_{pv}$ and $T_a$, respectively, the intensity of the global solar radiation on the modules, $I_T$, and the wind velocity on their surface, $v_w$, were monitored for 2 years. The effect of the intensity, $I_T$, the PV module inclination and $v_w$, on $T_{pv}$ was investigated. The values of the coefficient f relating $T_{pv}$ and $I_T$, were determined and argued for the configurations studied. A theoretical model was elaborated to predict $T_{pv}$ and f for the cases of PV modules embedded on a roof, hanging over the windows and in free standing configurations. The effect of $v_w$ on f dominated for PV modules mounted on the terrace compared to the BIPV configurations in wind protected areas.*

**Keywords:** PV temperature prediction, PV inclination, BIPV, wind effect, PV roofs

## INTRODUCTION

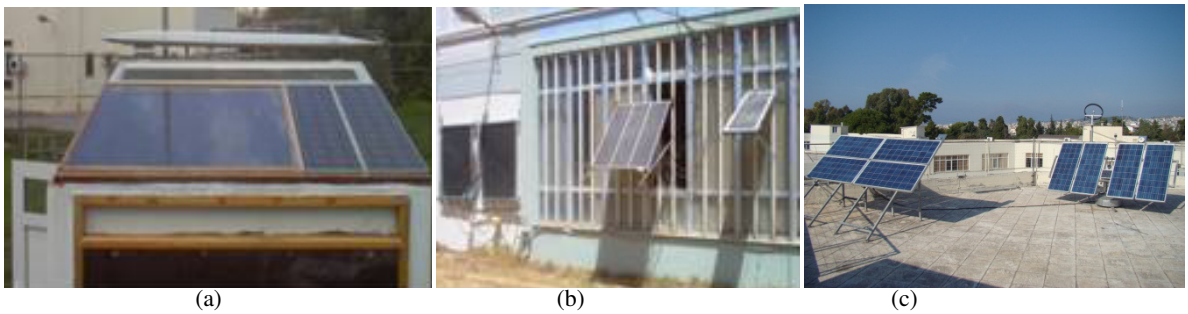
The issue of PV module temperatures, $T_{pv}$, developed when operating under field conditions was investigated in a number of projects where different formulas for its determination were provided [1-8]. The $T_{pv}$ profiles were well understood by building the Energy Balance Equation for transient and steady state conditions taking into account the power and heat generated in a PV module operating under global solar radiation intensity on it, $I_T$, in ambient temperature, $T_a$, and wind speed, $v_w$ [9-11]. Figs.1(a),(b),(c) show the various BIPV configurations monitored and studied in this project. In other ZEB configurations, the PV modules are either embedded in facades being part of the building structure through sophisticated designs operating as PV/T power and heat co-generation systems [11] or the PV modules are placed at a small distance about 10-15 cm from the roof tiles. Published works deal with the $T_{pv}$ functional dependence on $I_T$ and $v_w$ in various environments like in [5-8,11,12]. Especially, $v_w$ strongly affects the heat convection coefficients, $h_{c,f}$ and $h_{c,b}$ in the front and back side of the module and therefore $T_{pv}$. However, the equations proposed take the $v_w$ effect on $h_{c,f}$ and $h_{c,b}$ to be in a linear form, while other parameters, too, are very important for consideration such as the geometry of the module, the air flow details as for example air free flow, forced flow, laminar and turbulent modes, the wind direction with respect to the PV module and also the inclination of the module with respect to horizontal, as was investigated in [13]. In some works, the type of PV cell, Si or CdTe was specified in the formulas proposed for the $T_{pv}$ prediction along with the BIPV configuration which resulted in slight modifications [5,6]. It is underlined that the wind speed, $v_w$, and the solar irradiance on the modules, $I_T$, have a 2$^{nd}$ order effect on $T_{pv}$ through their effect to $\eta_{pv}$. The $T_{pv}$ as a notion has to be clarified as the temperature in the front, the back side of the module and the semiconductor temperature differ. Thus, there is a need for more systematic and comparative analysis as it regards the effect of the environmental conditions in the BIPV performance where the explicit and implicit inter-relationships between, $T_{pv}$, $I_T$, $v_w$ and the PV module inclination should be included. An approach to estimate $T_{pv}$ for PV systems in facades was presented in, [14], using the relationship given in [5]. A wider analytic approach for the *f* factor and $T_{pv}$ prediction is presented in this paper for various BIPV configurations using:

1. a set of co-related equations which fully describe the heat propagation from the PV inner core to the environment, and
2. a relationship, taking as a reference the ambient temperature, $T_a$, and an elaborated mathematical expression for the factor $f$=f($v_w$, $T_{pv}$, $I_T$,$\eta_{pv}$), as discussed below,

$$T_{PV} = T_\alpha + f \cdot I_T \qquad (1)$$

*f* may not be given by a closed mathematical formula due to its implicit dependence on the above quantities. Instead, an empirical function of *f* applicable to any conditions was determined in this paper through regression analysis of measured values, $T_{pv}$, $I_T$, $v_w$, $T_a$. In

another approach a theoretical model might be developed with a set of equations to be used for the determination of the $f$ and $T_{pv}$ by means of a complete set of heat transfer and IR radiation expressions associated to the PV module energy balance equation, as analytically elaborated in [13] taking into account all possible environmental condition and geometries. In this research project the values that $f$ takes up in various types of BIPV installations were determined experimentally analyzing systematically a time series of $I_T$, $T_a$, $T_{pv}$ and $v_w$ data on the basis of eq.(1), for $f=f(v_w, T_{pv}, I_T, \eta_{pv})$. An algorithmic approach to predict $T_{pv}$ is outlined in the next Section using expressions through which $f$ may be estimated as an implicit function of the environmental conditions. Conclusively, $T_{pv}$ experiences explicit and implicit dependence on the environmental conditions. Its impact to PV power performance may be estimated through eq.(1) from the $f$ values theoretically produced or experimentally developed as functions of $v_w$, $\eta_{pv}$ and $T_{pv}$, in a second order effect [4,5,11,15].



(a) (b) (c)

Fig. 1(a) BIPV embedded in a roof, (b) BIPV as shadow hangers, (c) BIPV fixed and sun-tracking on a terrace

## THE THEORETICAL MODEL TO PREDICT $f$ and $T_{pv}$ in BIPV CONFIGURATIONS

It is important to provide good estimates of the power performance of PV modules integrated into ZEB structures taking into account $I_T$, $T_{pv}$ $v_w$, $T_a$, and where appropriate the inclination of the PV modules. The PV modules, as shown in Figs.1(a),(b) have their back side fully or partially wind protected. An insulated back cover below the PV plane stands for the ceiling, Figs.2(a),(b). Heat is extracted via air free flow in laminar mode through an orifice pattern. The warm air is self-pumped through the orifice and is self-circulated by free convection within the room for space heating or in warm days it is self-pumped out of the building through the solar chimney, Fig.1(a), [11]. The room temperature inside the building plays the role of $T_a$ in eq.(1). The front side of the PV modules faces the free environment and heat may be extracted by air free flow or air forced flow either under laminar or turbulent mode to be determined from the environmental conditions prevailing each time. The front PV side may experience higher heat rate extraction than its back side which forms part of the internal building structure. The natural ventilation inside the ZEB test cell reduces the $T_{pv}$ rise at the PV back side and hence limits the drop in $\eta_{pv}$, thus attaining a partial recuperation. This solar roof design is advantageous over the design where the PV modules are mounted upon the roof with an air gap of about 10-15cm from the tiles, as it operates as a PV/T. In both cases, the PV back side is wind protected contrary to the front one. For the BIPV configuration where the PV modules are deployed over windows, their inclination, $\beta$, with respect to the horizontal, Fig.1(b), changes seasonally so that the direct solar radiation to be normal on the PV plane, satisfying the condition, $\beta=\varphi-\delta$, where $\varphi$ is the latitude of the site and $\delta$ is the sun's declination angle, easily calculated.

The heat convection coefficients $h_{c,f}$ and $h_{c,b}$ for the inclined front and back sides, should be determined by proper expressions as those in sub-sections 2.1.1 and 2.1.2 in [13] which cover the entire range of $Ra$ values, including the transition from laminar to turbulent flow through the estimation of the critical Grashof number $Gr_c$ included in the $Nu$ expression, [16,17]. The inclination effect enters through the determination of the $Nu$ number at air flow modes from both the front and back PV sides. The 3rd and 4th BIPV examined have the form of small PV generators 0.5 $kW_p$ aesthetically mounted on a terrace as fixed and sun-tracking. The estimation of the $h_{c,f}$, $h_{c,b}$ and $h_{r,f}$, $h_{r,b}$ coefficients, dependent on $T_{pv}$, $v_w$, inclination and orientation of the modules follows the analysis in [13].

### An outline of the proposed model to predict $T_{pv}$ based on the determination of the $f$ coefficient

The energy balance equation for steady state conditions, shown in eq.(4), takes into account the solar radiation on the PV module, the power produced, the heat losses due to conduction, convection, and the net IR radiation exchange with the environment. $U_f$ and $U_b$ below stand for the sum of heat and radiative loss coefficients for the front and back sides, respectively, where:

$$\boldsymbol{U_f = h_{c,f} + h_{r,f}} \quad \text{and} \quad \boldsymbol{U_b = h_{c,b} + h_{r,b}} \qquad (3)$$

(a)

(b)

Fig.2 (a)The back side of the PV modules which make part of the roof in a ZEB cell. (b) The wooden case forms the ceiling. The higher end of the case ends to a number of air orifice for the heated by the module air to expand.

A theoretical model is developed based on eqs.(4)-(9) to predict effectively $T_{pv}$ and determine $f$ for any PV configuration at steady state conditions.

$$I_T = \eta_{pv} I_T + U_f(T_f - T_\alpha) + U_b(T_b - T_\alpha) \qquad (4)$$

For $T_f = T_b + \delta T$ (5)

$$T_b = T_\alpha + \frac{(1-\eta_{pv})I_T}{U_f+U_b} - \frac{U_f}{U_f+U_b}\delta T \qquad (6)$$

$T_b$ is chosen instead of $T_f$ as it was measured and recorded by the monitoring system during this project.

A considerable effort has been made to develop easily handled expressions to determine $T_{pv}$ by means of the $f$ coefficient. The combination of eqs.(1) and (6) gives that $f$ may be expressed by:

$$f = \frac{1-\eta_{pv}}{U_f+U_b} - \frac{U_f}{(U_f+U_b)I_T}\delta T \qquad (7)$$

The first term above is considered as the first approach value of $f$, $f_o$, where,

$$f_o = \frac{1-\eta_{pv}}{U_f+U_b} \qquad (8)$$

$$f = f_o - \left[\frac{U_f}{(U_f+U_b)I_T}\right]\delta T \qquad (9)$$

For low wind speeds $U_f$ and $U_b$ take values around 10W/m$^2$K, while the temperature difference in the front and back side, $\delta T$, experimentally measured was around $\pm$2-3$^o$C. The sign changes due to wind velocity direction either forward or leeward. Therefore, for $I_T$ in the range of 800-10$^3$W/m$^2$ and $\eta_{pv}$ =0.15, $f$ falls as easily calculated in the range of [0.040, 0.044] m$^2$K/W which is the region of $f$ values experimentally determined in BIPV cases, such as those in Figs.1(a),(b). For $v_w$ of about 2.5m/s, $U_f$ and $U_b$ values increase and $f$ reduces to values of about 0.028m$^2$K/W and for $v_w$ >5m/s to values in the range of 0.015-0.020 m$^2$K/W, as this is the case of PV systems in Fig.1(c).

The $f$ factor was investigated as a product of 2 functions shown in eq.(10) and validated comparing its values with experimentally produced ones and also with those from other 2 well known model functions [4,5].

$$f = \frac{1-\eta_{pv}}{U_f+U_b} - \left[\frac{U_f}{(U_f+U_b)I_T}\right]\delta T = f(v_w)f(\eta_{pv}, T_{pv}, I_T, v_w) \qquad (10)$$

The first one is a function of $v_w$, and the second of $\eta_{pv}$ implicitly dependent on $T_{pv}$, and in second order on $I_T$ and $v_w$. Expanding $f$ in Taylor series around the point v=v$_w$ and estimating the first derivative for the average values of the recorded environmental data ($T_a$ =20$^o$C and $I_T$=800W/m$^2$) at that point, the following expression is obtained.

$$f = f(v_w) + \left(\frac{df}{d\eta_{pv}}\right)_m \delta\eta_{pv} = f(v_w) - \delta\eta_{pv}/(U_f + U_b) = f(v_w)(1 - \delta\eta_{pv}/(1-\eta_{pv,m})) \qquad (11)$$

The $f(v_w)$ value obtained from the rational expression, eq.(12) whose coefficients were obtained by regression analysis of the 2 years recorded data $T_b$, $v_w$, $I_T$, $T_a$, corresponds to the average values of $T_a$ and $I_T$.

$$f(v_w) = \frac{a+bv_w}{1+cv_w+dv_w^2} \qquad (12)$$

where, a= 0.0375, b=0.0081, c=0.2653, d=0.0492.

Finally, the $f$ coefficient is estimated by:

$$f = f(v_w)\left(1 - \frac{\frac{d\eta_{pv}}{dT}\delta T_{pv}}{1-\eta_{pv,m}}\right) \qquad (13)$$

$\delta T_{pv}$ may be expressed through the differences between the environmental conditions during the experiment and the average environmental conditions, as said above.

The above formula may be used for the prediction of $T_{pv}$ and especially in this case $T_b$ for any environmental conditions, $I_T$, $T_a$, $v_w$. Eq.(11) is also used for PV modules other than c-Si or pc-Si with different $\eta_{pv}$ as it modifies the constants in the rational expression for $f$.

## EXPERIMENTAL RESULTS - DISCUSSION

1. BIPV configuration with the PV modules making part of the roof, Fig.1(a).

$f$ for clear sky, almost clear sky or partly cloudy conditions during the 2 years data monitoring even with $v_w$ up to 5m/s for any day of the year takes values in the domain $0.0420 \pm 0.006$ $m^2K/W$ which differ considerably from the cases of PV mounted on terrace as to be shown below.

Such values are also valid for PV modules serving as shadow hangers over windows with very low angle of inclination, e.g. $0^o$-$15^o$, in wind protected areas at low wind speeds <1.0 m/s, as given in Table 1 and in Fig.5 for several inclination angles.

2. For PV configurations with the modules in the free environment, and not in wind protected areas, $f$ may be obtained from eqs.(11)-(13), taking into account the operating conditions each time.
The proposed expressions of eqs.(11)-(13) hold for any BIPV with PV modules mounted on fixed or sun-tracking frames or in solar roofs. Based on the above, for the BIPV of Fig.1(a), for $I_T$ =800W/$m^2$ on a PV roof with $\eta_{pv}$ =0.15, the uncertainty in the estimation of $T_{pv}$ equals to $\Delta T_{pv}$=±0.006 x 800=±4.8°C. For, $\delta\eta_{pv}/\eta_{pv}$ = -0.4% $\Delta T_{pv}$ it becomes $\delta\eta_{pv} = \eta_{pv}$ x 1.92% =0.15 x 0.0192 =±0.3% which in fact is a relatively narrow domain in which $\eta_{pv}$ values were estimated.

Figs.3(a)-(d) show the $T_{pv}$ vs $I_T$ for an embedded PV roof for several days within a year. The slope, $f$, lies in the range theoretically predicted above. Fig.3(c) shows slight deviations from the linearity due to changes in the sky conditions and the environment. Such cases were also observed in [18,20]. However, the general linear form still holds and the slope is kept within the interval of values specified above. In general, the abscissa is equal to $T_a$, at the time the PV starts running, while the slope i.e. the rate $T_{pv}$ changes is higher in cold environment rather than warm, in agreement to the theoretical model outlined. $f$ decreases with increasing $v_w$ according to eq.(12) for PV modules either in a free environment or for PV integrated into a façade or roof.

Figs.4(a),(b),(c) show $(T_{pv}$-$T_a)$ vs $I_T$, $v_w$ vs hour and the $f$ vs the hour of the day for free standing pc-Si PV modules fixed and sun-tracking on a terrace for July. In both PV systems, $f$ experiences considerable changes, mainly due to the $v_w$. The $f$ values in the fixed and sun-tracking systems at the same hour differ due to the different wind speed direction with reference to the PV plane.

$(T_{pv}$-$T_a)$ vs $I_T$ for free standing PV for the representative day of July shows sub-linear behaviour and this is due to the higher $v_w$ values around 3-4m/s for the period after 10am when $I_T$ takes values higher than 500 W/$m^2$ for the fixed system and 850W/$m^2$ for the sun-tracking. The wind effect decreased the slope of the $T_{pv}$ vs $I_T$ curve. The $f$ values are about 0.035$Km^2$/W for the fixed system and 0.030 $Km^2$/W for the sun-tracking at 10am when $v_w$ is 2.5m/s. During that period the angle of wind direction with respect the sun-tracker is 30-60° on the back side, where $T_{pv}$ is measured, while for the fixed system the wind strikes the front surface in around 80-90°, which implies lower rate to heat extraction [13]. For higher $v_w$ in the range of 2.5-4m/s the $f$ coefficient takes values of about 0.022-0.025 $Km^2$/W very close for both configurations as the front side is the windward side for both. When $v_w$ is low, see Figs.4(b) morning hours, the $f$ value for the fixed system is higher due to the dependence of the $Ra$ number on the inclination which in this case is lower for the fixed system, 38° compared to the sun-tracking system inclination around 50-60° for the morning hours. The difference in $f$ for both systems vanishes as $v_w$ >2.5m/s.

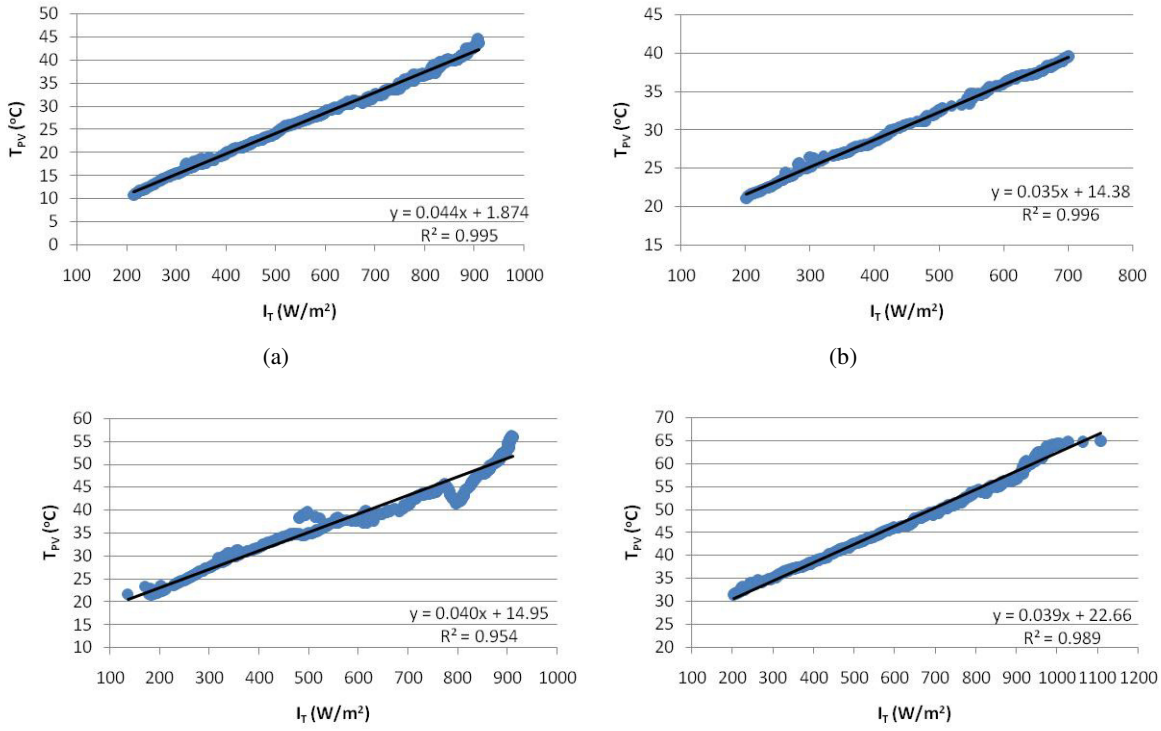
On the other hand, $(T_{pv}$-$T_a)$ vs $I_T$ may change to super-linear when low $v_w$ values prevail during noon compared to the morning and afternoon $v_w$ values. That was verified with the experimental data analyzed.

BIPV configurations with PV modules mounted in wind protected zones or hanging over windows for shadowing and power production were monitored. The data analysis of $T_{pv}$ $vs$ $I_T$ for cases $v_w$<1m/s gave the results for $f$ coefficient shown in Table 1. Fig.5 shows $(T_{pv}$-$T_a)$ vs $I_T$ for various inclinations. The $f$ coefficient decreases as $\beta$ increases from 0° as argued before. It is very interesting to realize that for $\beta$ around 45° $f$ takes its lowest value due to the fact that the air flow past the PV module back side reaches the stage to turn into turbulent, while its highest value is for small nearly horizontal inclinations. For inclination higher than 45° $f$ increases slowly.

Table 1. Values of the f coefficient for PV modules as shadow hangers in wind protected areas for various inclinations

| **β** | **f ± σf** |
|---|---|
| **0°** | 0.044 ± 0.004 |
| **16°** | 0.040 ± 0.002 |
| **26°** | 0.033 ± 0.003 |
| **36°** | 0.025 ± 0.002 |
| **47°** | 0.023 ± 0.002 |
| **>70°** | 0.034 ± 0.005 |

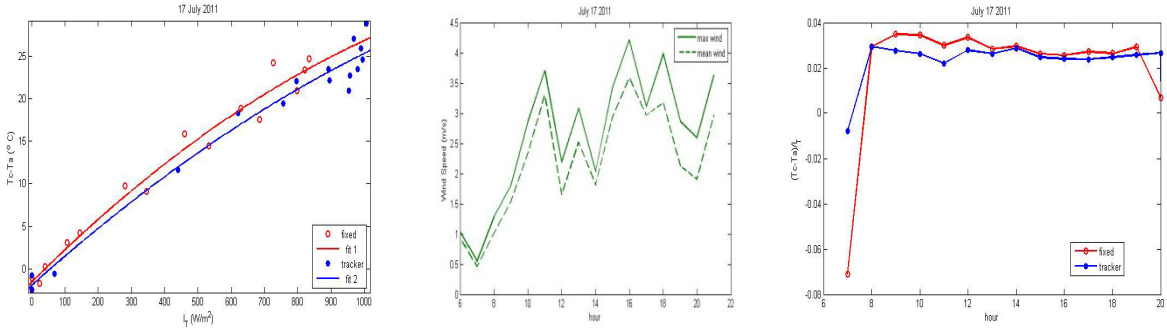
The results of $T_{pv}$ prediction given by the proposed model through the determination of the $f$ coefficient were compared for validation with measured values during the representative days of the months of the year and also with the $T_{pv}$ provided by the models [5,6]. The results for July for both BIPV configurations are given in Table 2 where it is obvious that the proposed model has an overall very good prediction performance compared to the other models.




(a) (b)

(c) (d)

Fig.3 $T_{pv}$ vs $I_T$ in an embedded PV roof for the (a) 18-3-17, (b) 17-5-16, (c) 4-10-16, (d) 9-7-16




(a) (b) (c)

Fig.4 (a) $T_c$ -$T_a$ vs $I_T$ for the month July for pc-Si PV modules on the terrace. For both fixed and sun-tracking frames the function is sub-linear due to the high $v_w$ after 10am when $I_T$ takes values above 400W/m$^2$, (b) provides the $v_w$ vs hour of the day and (c) shows the changes in f from 0.038 morning hours when $v_w$ is low to 0.022 for the rest of the day when $v_w$ > 2.5m/s. The lines correspond to fixed and sun-tracking frames.

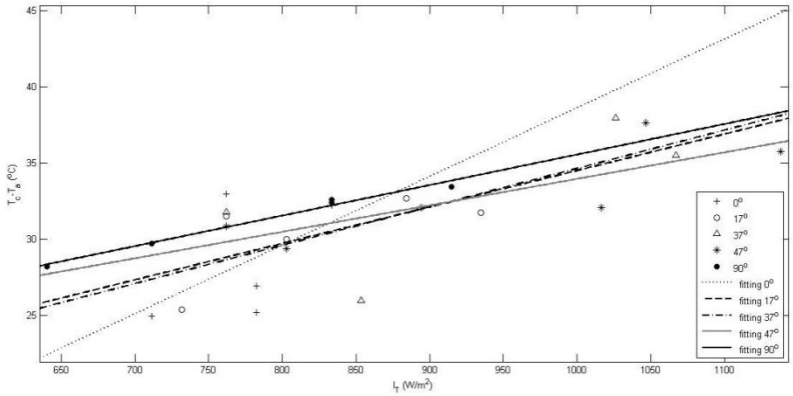



Fig.5 *($T_{PV}$-$T_a$) vs $I_T$* for different PV inclination angles, for c-Si PV modules operating in free space -wind protected.

Table 2. Comparison of predicted $T_{pv}$ values by this model, and those in [5,6] with measured ones in July from a fixed and a sun-tracking PV system on a terrace.

| **Time hour** | **Model [6] $T_{pv}$ ($^o$C)** | | **Model [5] $T_{pv}$ ($^o$C)** | | **Measured $T_{pv}$ ($^o$C)** | | **Proposed Model $T_{pv}$ ($^o$C)** | |
|---|---|---|---|---|---|---|---|---|
| | Fixed | Tracking | Fixed | Tracking | Fixed | Tracking | Fixed | Tracking |
| **10** | 10.1 | 19.8 | 12.1 | 23.7 | 14.0 | 22.5 | 13.0 | 26.2 |
| **12** | 17.3 | 23.3 | 19.9 | 26.8 | 23.0 | 27.0 | 21.5 | 28.1 |
| **14** | 22.2 | 27.0 | 21.0 | 25.3 | 24.0 | 29.0 | 24.9 | 31.0 |
| **16** | 15.2 | 21.5 | 16.0 | 21.5 | 17.0 | 23.0 | 19.0 | 26.8 |

## CONCLUSIONS

The paper outlines a theoretical model developed for the PV module temperature, $T_{pv}$, prediction taking into account the environmental conditions, i.e. ambient temperature, $T_a$, solar irradiance on the module, $I_T$, and wind speed, $v_{w,}$ on the PV module and their effect to the PV efficiency. A set of equations fully simulate the heat propagation from the PV module to the environment and through iterations give the front, back side and Si temperatures. To predict $T_{pv}$ a regression analysis of recorded data of c-Si and pc-Si modules gave a formula to determine the correlation factor between $T_{pv}$ and $I_T$ . The formula is split in 2 functions, the first with argument the wind speed in a rational function and the second the efficiency change due to the effect of the environmental factors. The values of this factor differ according to the BIPV configuration. BIPV serving as roofs and PV generators gave high $f$ values in the range $0.040 \pm 0.006 m^2K/W$. Same values were obtained experimentally and theoretically for BIPV systems acting also as shadow hangers over windows placed in wind protected zones with small inclination $<16^o$. For small BIPV systems of $0.5kW_p$ placed on the terrace either in fixed position or on sun-tracking frames the predicted $T_{pv}$ values through the determination of $f$ were compared with other 2 known models and the experimental results and showed very good prediction for both BIPV modes. The formula for $f$ is applicable to other types of PV cells. The $f$ coefficient ranges from almost 0.01 $m^{2o}C/W$ for free standing PV arrays at strong wind speeds, $v_w$>7m/s, up to around 0.05 $m^{2o}C/W$ for the case of flexible PV modules which make part of the roof in a BIPV system. In addition, $f$ depends implicitly on $I_T$, the inclination angle, $\beta$, the type of heat convection; that is, natural or forced flow, the pattern of air flow past the PV panel, i.e. laminar or turbulent, the relative wind direction with respect to the PV module surface and the type of the BIPV configuration. The effect in $f$ is bigger for free standing systems rather than for wind protected systems where only the front side is directly subjected to the wind.

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