PV temperature and performance prediction in free-standing, BIPV and BAPV incorporating the effect of temperature and inclination on the heat transfer coefficients and the impact of wind, efficiency and ageing

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PII: S0960-1481(21)01292-1
DOI: https://doi.org/10.1016/j.renene.2021.08.124
Reference: RENE 15935

To appear in: Renewable Energy

Received Date: 10 December 2020
Revised Date: 4 August 2021
Accepted Date: 30 August 2021

Please cite this article as: Kaplanis S, Kaplani E, Kaldellis JK, PV temperature and performance prediction in free-standing, BIPV and BAPV incorporating the effect of temperature and inclination on the heat transfer coefficients and the impact of wind, efficiency and ageing, Renewable Energy (2021), doi: https://doi.org/10.1016/j.renene.2021.08.124.

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**S. Kaplanis**: Conceptualization, Methodology, Investigation, Resources, Writing-Original draft preparation, Writing- Reviewing and Editing. **E. Kaplani**: Methodology, Software, Validation, Formal Analysis, Investigation, Data curation, Writing- Original draft preparation, Writing- Reviewing and Editing. **J. Kaldellis**: Investigation, Validation, Resources, Writing- Reviewing and Editing.
PV temperature and performance prediction in free-standing, BIPV and BAPV incorporating the effect of temperature and inclination on the heat transfer coefficients and the impact of wind, efficiency and ageing

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Abstract

A novel compact model is developed to predict the PV temperature \( T_{pv} \), coefficient \( f \) which relates \( T_{pv} \) with the in-plane solar irradiance \( I_r \), and power output \( P_m \). The \( T_{pv}, I_r, \) ambient temperature \( T_a \), and wind velocity \( v_w \) on a sun-tracking pc-Si PV and c-Si BIPV were monitored. \( f \) depends explicitly on \( v_w \), PV efficiency, heat losses coefficient, and implicitly on \( T_{pv}, I_r, T_a \) loosely on the module inclination at low \( v_w \), while this effect weakens at high \( v_w \). \( T_{pv} \) prediction is provided by means of 5 functions, which cater for the deviation of the environmental conditions from the Standard Operating Conditions, the operating efficiency, the natural ageing, PV geometry and cell technology. The \( T_{pv} \) prediction for the sun-tracking system has relative error 2.6% for PV operating temperatures around the NOCT, and may overestimate by up to 1.4°C. Similarly, the relative error for the BIPV system is -2.1% for PV temperatures around the NOCT, with underestimation up to 1.6°C. The model predicted \( P_m \) with relative error 1.9% for PV operating near its nominal value. The model is compared to 3 well-known models and also applied to other BIPV/BAPV configurations in various countries proving its wide applicability, high accuracy and universality.

Keywords: PV temperature prediction, PV power prediction, BIPV, temperature and wind effect, inclination effect, PV ageing

Nomenclature

<table>
<thead>
<tr>
<th>BAPV</th>
<th>Building Adapted PV</th>
<th>( T_{sk} )</th>
<th>sky temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIPV</td>
<td>Building Integrated PV</td>
<td>( U_f )</td>
<td>heat losses coef. due to convection and IR radiation at the front side of the PV module (W/m²K), equal to ( h_{c,r}+h_{r,f} )</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>F_{pv-sky,f}</td>
<td>View factor of the front PV surface to sky and to ground, respectively</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F_{pv-gr,f}</td>
<td>View factor of the back PV surface to sky and to ground, respectively</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F_{pv-sky,b}</td>
<td>View factor of the back PV surface to sky</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F_{pv-gr,b}</td>
<td>View factor of the back PV surface to ground</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U_b</td>
<td>heat losses coeff. due to convection and IR radiation at the back side of the PV module (W/m²K), equal to (h_{c,b}+h_{r,b})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U_{pv}</td>
<td>The overall heat losses coefficient from a PV (W/m²K), equal to (U_f+U_b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gr</td>
<td>Grashof number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U_{pv,SOC}</td>
<td>The overall heat losses coefficient from a PV at SOC (W/m²K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number of the air flow either in the front or back side of the PV module, to be stated</td>
<td></td>
<td></td>
</tr>
<tr>
<td>k_i</td>
<td>thermal conductivity of material (i) (W/m²K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p_m</td>
<td>maximum power output at operating conditions (W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(r_{ageing})</td>
<td>percentage of overall degradation due to ageing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{m,STC}</td>
<td>maximum rated power at STC (W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(v_w)</td>
<td>wind velocity (m/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta T)</td>
<td>Temperature difference between PV and air bulk temperature, (T_{pv}-T_o)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\Delta T_{c-b})</td>
<td>Temperature difference between cell and back, (T_c-T_b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\delta T_{pv})</td>
<td>Difference between the PV temperature and its temperature at SOC, (T_{pv}-T_{SOC})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ra</td>
<td>Rayleigh number, (Ra = Gr Pr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\delta x)</td>
<td>Layer thickness (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF</td>
<td>Scaling factor multiplied with (f) to adapt the model to BIPV/BAPV configurations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\varepsilon_{sky},\varepsilon_{pv},\varepsilon_{b},\varepsilon_{gr})</td>
<td>emissivity coefficients for the sky, the PV glass, the back surface and ground respectively</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOC</td>
<td>Standard Operating Conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\eta_{pv})</td>
<td>PV module nominal efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\eta_{pv,SOC})</td>
<td>module efficiency at SOC in the year of operation for the module used in the development of the model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\eta_{pv,STC})</td>
<td>module efficiency at STC in the year of operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\eta_{pv,n})</td>
<td>efficiency at SOC for the module to be tested</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{pl}</td>
<td>the indoor plank/plaster temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{a}</td>
<td>ambient temperature (°C or K as specified)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{pl}</td>
<td>film temperature of the air boundary layer at the PV module side front or back (K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T_{gr}</td>
<td>ground surface temperature (K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\nu)</td>
<td>kinematic viscosity of the air (m²/s)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 1. Introduction

The development of temperature profiles, \(T_{pv}\), in PV modules operating in field conditions was studied since many years due to its importance on the PV performance studies. Various formulas have been...
proposed as outlined in [1] as it concerns the $T_{pv}$ and the power output, $P_{m}$, prediction. The $T_{pv}$ profiles
are well understood by building a simulation model based on the Energy Balance Equation (EBE), for
transient and/or steady state conditions, taking into account the power and heat generated within a PV
module operating under a global solar radiation intensity on it, $I_r$, at ambient temperature, $T_s$, and wind
speed, $v_w$ [2-9]. A large number of research articles deal with the prediction of the PV module or PV
cell temperature $T_{pv}$ and $T_c$, respectively, for cell types such as mc-Si, pc-Si, a-Si, CIS, CdTe [10]
providing comparisons with other models and with measured values and investigating the effect of
various external factors, as discussed below. In [11-14], the differences between $T_{pv}$, $T_c$, $T_b$ and $T_f$ which
stand for the module temperature, the cell semiconductor layer temperature, and the module's back and
front side temperatures, are argued. $T_b$ is measured in the experiments and is usually referred as $T_{pv}$ or
$T_{m}$. Finally, $T_c$ is estimated [11]:

$$T_c = T_b + \frac{I_r}{I_{ref}} \cdot \Delta T_{c-b} \quad \text{where} \quad \Delta T_{c-b} = T_c - T_b \quad (1)$$

$I_r$ is the intensity of the global solar radiation on the module and $I_{ref}=10^3$ W/m². The value of $\Delta T_{c-b}$ is
taken equal to 2-3°C according to [11,12], while in [6] the $\Delta T$ difference was defined instead as ($I_r - T_b$)
equal to 3°C. Based on the heat flow continuity from the semi-conductor to the PV back side the
following formulas may be used to determine $T_c$ from $T_b$ which is the temperature usually measured.

$$T_c = T_b + \dot{Q} \cdot \Sigma(\delta x_i/k_i) = T_b \left( 1 + \frac{\Sigma(\delta x_i/k_i)}{U_b^{-1}} \right) - T_a \frac{\Sigma(\delta x_i/k_i)}{U_b^{-1}} \quad (2)$$

$\dot{Q}$ (W/m²) may be assumed to a good first approximation as half of the heat rate generated in the
semiconductor, in glass-glass or glass-tedlar module technology, estimated equal to 0.5(1-$\eta_{pv}$)$/I_r$
neglecting a small fraction of reflected radiation. This assumption is valid because the heat conduction
resistance from the cell to the front and to the back side and the corresponding convection and radiative
heat coefficients do not differ so much to each other. $\Sigma(\delta x_i/k_i)$ is the total resistance per m² due to heat
conduction in the layers from the semiconductor to the back surface and $U_b$ is the heat losses coefficient
(convection and radiated heat) from the PV back surface. For insulated PV back surfaces or low $U_b$ both
expressions in eq.(2) result to $T_c=T_b$. Giving appropriate values to the physical quantities [5,6], in eq.(2)
results to $\Delta T_{c-b} = T_c - T_b = 2^\circ C$ for $I_r = 10^3$ W/m². This value depends also on the material of the cell layers,
i.e. their conductivity coefficients and their thickness and also on the wind speed which strongly affects
$U_b$. The assumption $T_c = T_b = T_f$ in [15] is a gross approximation which has to be argued on the basis of
the difference between predicted and measured $T_b$ which for most models is higher than the expected
intra-cell temperature difference, $\Delta T_{c-b}=2-3^\circ C$.

In the group of physics-based models for the $T_c$ prediction a set of equations is formulated including
the EBE at steady and/or transient conditions coupled with equations on heat propagation from the
semiconductor layer to the front and back surfaces and then to the environment [3,7,16,17]. It is
important to take into account the radiated heat exchanged between PV surface and sky/ground. Such a set of equations which take into account all the environmental conditions constitute a complete simulation model [2,3,8,9,18-20]. However, the heat convection and the radiated heat coefficients used do not cover sufficiently the whole range of the environmental conditions. More elaborated analysis was outlined in [3,17,21,22] and provided better $T_c$ predictions. In a second group, the so called grey models, electric and heat transfer parameters associated to the operating PV module are introduced into an EBE and a regression analysis of recorded data from monitored quantities is applied for the development of semi-empirical models for $T_c$ prediction. Those (semi)–empirical $T_{pv}$ prediction models are categorized as explicit and implicit ones. Implicit models are the ones which provide $T_{pv}$ through variables which depend on the $T_{pv}$ itself as it is the PV efficiency, $\eta_{pv}$ and the heat losses coefficients, $U_f$, $U_b$ or $U_{pv} = U_f + U_b$. The latter coefficients are $T_{pv}$ dependent mainly due to the radiative heat coefficients, $h_{r,f}$ and $h_{r,b}$ for the front and back PV side and strongly dependent on $v_w$ through the heat convection coefficients, $h_{c,f}$ and $h_{c,b}$, for the front and back PV module sides, respectively. $h_{c,f}$ and $h_{c,b}$, are loosely dependent on $T_{pv}$ and $T_a$. The most common $T_c$ or $T_{pv}$ prediction empirical formulas of explicit and implicit structure which appear in PV performance model comparisons [1,12,19-24] take the forms summarized in Table 1.

### Table 1: PV temperature prediction explicit and implicit empirical models

<table>
<thead>
<tr>
<th>Model</th>
<th>Reference</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_c = T_a + \frac{I_T}{I_{T,NOCT}}(T_{NOCT} - T_{a,NOCT})F(U_{pv})F'\left(\frac{\eta_{pv}}{T_a}\right)$</td>
<td>[13,14,25,26]</td>
<td>(3)</td>
</tr>
<tr>
<td>$T_c = T_a + \frac{I_T}{I_{T,NOCT}}(T_{NOCT} - T_{a,NOCT})\frac{U_{pv,NOCT}}{U_{pv}} \cdot \left(1 - \frac{\eta_{pv}}{(\tau_a)}\right)$</td>
<td>[1,13]</td>
<td>(4)</td>
</tr>
<tr>
<td>$T_c = T_a + f I_T$</td>
<td>[27-29]</td>
<td>(5)</td>
</tr>
<tr>
<td>$T_c = T_a + a I_T(1 + \beta T_a)F(v_w)F'(\eta_{pv})$</td>
<td>[30]</td>
<td>(6)</td>
</tr>
<tr>
<td>$T_c = T_a + \frac{I_T}{(U_0 + U_1 v_w)}$</td>
<td>[31,32]</td>
<td>(7)</td>
</tr>
<tr>
<td>$T_c = T_a + I_T \exp(a + b v_w)$</td>
<td>[11, 33]</td>
<td>(8)</td>
</tr>
</tbody>
</table>

In the above models, the thermal radiation exchanges between the PV module and the environment were not adequately considered despite the considerable temperature difference between the PV module and the sky-ground environment. The assumption argued in [13], by which a $T_c$ prediction model, eq.(3), might be converted from implicit to explicit, by dropping the factors $F(U_{pv})$ and $F'(\eta_{pv}/(\tau_a))$ as not essentially affected by $T_c$ and $v_w$, is not always valid because $v_w$ and $T_c$ may take values which substantially affect the $T_c$ result. Deviations between the predicted $T_c$ values by various models and measured ones are shown in [23,24,34]. It was concluded that the NOCT model outlined in [35] deviates more as it does not take into account the $v_w$ effect, while the rest of the aforementioned models consider
a linear dependence of $h_{c,f}$ and $h_{c,b}$ on $v_w$. However, these do not fit well in the whole range of $v_w$ values as discussed in [17], where the PV module geometry and the wind speed and direction have to be taken into account in order to predict the parameter $f$ introduced in eq.(5), which is known as the Ross coefficient and relates $T_c$ with $T_a$ and $I_T$ [27].

A third group of methodologies applies ANN for the $T_c$ prediction resulting in eq.(9), [22,36,37]. $T_c$ is predicted as a function of $T_a$, $I_T$, $v_w$, wind direction and humidity. In the ANN approach it is necessary to train the model to the site environmental conditions, the specific mounting scheme, the structural details, geometry and the type of PV cell, in order to obtain suitable parameters for the $T_c$ prediction, independent, if possible, of the site and the technology type, as claimed in [36].

$$T_{pv} = 0.943T_a + 0.028I_T - 1.528v_w + 4.3 \tag{9}$$

In [24], a $T_c$ prediction formula different to eq.(9) has been derived through ANN for the floating PV modules. This justifies the argument on the specific training requirements for the ANN methodologies applied for the $T_c$ prediction and that a general purpose $T_c$ prediction model is absolutely required.

An investigation of the $v_w$ effect on $T_{pv}$ (practically equal to $T_b$ and $T_c$), $\eta_{pv}$ and $P_m$ was outlined in [34,38-41] where the models [13,14,32,33] and the NOCT were applied in mc-Si, pc-Si, a-Si and CdTe modules. The factors $U_a$ and $U_f$ used in [32] were adopted from [31]. The NOCT model provided higher values as it does not take into account the $v_w$ effect in the module cooling, as mentioned above. The other models exhibited coefficient of determination, $R^2$, between predicted and measured $T_c$ from 0.85 to 0.96. However, the implicit nature expressed by $T_{pv}(I_T,T_a,\eta_{pv}(T_{pv},I_T,v_w),U_{pv}(T_{pv},I_T,v_w))$, the module inclination, and the wind direction have not been considered adequately enough. Indeed, $v_w$, and $I_T$, have a 2nd order effect on $T_{pv}$ through their effect mainly on $\eta_{pv}$ and $U_{pv}$ and this has to be accounted for. In [42], the role of $I_T$, $v_w$, $T_a$ and the solar spectrum in the PV performance, as well as their impact on $T_{pv}$ in c-Si and CdTe cells have been studied taking into account the coefficients $U_a$ and $U_f$ [31,32]. A simpler $T_{pv}$ implicit formula was developed [14] based on the EBE taking into consideration $T_{pv}$ dependent PV coefficients and not the NOCT as it was done in [11,25]. In the above referenced models, the PV heat losses coefficient $U_{pv}(v_w)$ was assumed to be linearly dependent on $v_w$ which does not hold for natural heat air flow as it was analytically presented in [17,21].

Additionally, Building Integrated PV (BIPV) in roofs or facades attracted a lot of research interest, since they behave as distributed clean energy sources towards zero energy buildings, presented in review papers [43-45]. Similarly, Building Adapted PV (BAPV) design configurations have been studied for roofs and sunshades [46-48]. Fig. 1 shows BIPV and BAPV designs on roofs and facades, the former representing fully integrated PV solutions into the building structure and the latter building adapted solutions with a naturally ventilated air gap between the PV modules and the building elements.

The $T_{pv}$ prediction is one of the main objectives in the design of BIPV and BAPV because it affects
significantly the PV performance. Also, BIPV/T configurations have been investigated [49-51]. Several simulation models have been developed for the various BIPV, BAPV, BIPV/T configurations per case, and comparisons of predicted $T_{pv}$ values with experimental data gave very good results [50-52]. However, an extended validation process applying those simulation models to any other environment and BIPV design has been limited mainly due to the complexity of the simulation models and their use of parameters specific to the particular BIPV design studied. In most of the BIPV, BAPV, BIPV/T works published [15,46, 53-54] the experimental results and the models developed have been compared to widely accepted and applicable simple formulas and software such as [11,13,53,55]. While the benefit of a general formula for $T_{pv}$ prediction is obvious, there is a great necessity for increasing the accuracy of $T_{pv}$ prediction taking into account important parameters, which are missing from simple widely accepted models.

Fig. 1. (a) BIPV at the South facing façade and rooftop of ZICER building at the University of East Anglia, UK, (b) an interior view of the BIPV façade and rooftop of ZICER building shown in (a). The BIPV façade and rooftop consist of glass/glass pc-Si and sc-Si PV modules respectively, (c) BAPV on the SW facing façade with 10cm wide air gap between the c-Si PV modules and the building wall at the Czech Technical University in Prague, (d) BAPV mounted on the rooftop with a small air gap between the PV modules and the roof tiles at a residential building in Norwich, UK.
This research study aims to fill in this gap and develop a rigorous, innovative, flexible and compact model and integrate the effect of the $v_w$ on $T_{pv}$ and $U_{pv}$, the effect of $T_{pv}$ on $\eta_{pv}$ and $U_{pv}$. Also, the effect of $I_T$ on $\eta_{pv}$ and the effect of the PV inclination $\beta$ on the $U_{pv}$. The latter is essential especially in the study of BIPV facades. All these important effects have not been previously considered in a generalized compact model for $T_{pv}$ and $P_m$ prediction. An additional parameter of importance is the PV mounting design, either for free standing, or BIPV, BIPV/T and BAPV as it significantly affects $T_{pv}$ and the air flow past one or both PV sides. The model developed in this study integrates all the above and takes into account the module efficiency and its natural ageing which are responsible for deviations observed between predicted and measured $T_{pv}$.

In Section 2, the PV configurations used in this study for the model development and validation are described along with the experimental details, while in Section 3, heat transfer issues of the PV configurations are discussed along with a short analysis to derive the formulas for the coefficients of heat convection and radiated heat from the PV modules to the environment and the estimation of their rates of change with respect to temperature $T$ and inclination $\beta$. In Section 4, a detailed analysis for the development of the $T_{pv}$ prediction model is presented. The mathematical expressions which take into account the above mentioned conditions are provided. In Section 5, results of the proposed model for free-standing and BIPV are presented and discussed while the model itself is validated by comparing the predicted $T_{pv}$ and $P_m$ values with experimental ones and with results from other models [11,31,36].

2. PV configurations and experimental procedure

Two main PV configurations were used in this study, a free-standing and a building integrated PV operating in the RES Lab, University of Peloponness in Patra, Greece. The first one is a double axis sun-tracking PV system 480W$_p$ shown in Fig.2(a-b) together with an identical fixed –angle PV array South facing and inclined at $\beta=\phi=38^o$ which was additionally used for model development. The fixed and sun-tracking PV systems consist of 4 pc-Si Energy Solutions modules, each 120W$_p$ with dimensions 1.490m x 0.674m, and 9 years of operation. The parameters monitored for a period of 2 years include the $T_{pv}$ measured at the back side of the modules with Cu-Const thermocouples, the solar irradiance on the PV plane $I_T$ measured with Kipp & Zonen CM11 pyranometers mounted on the plane of the PV modules, the ambient temperature $T_a$ measured via means of a MP101A sensor, the wind velocity $v_w$ and wind direction monitored using a R.M. Young 05103 anemometer 4m above the PV system. The wind speed was converted to the level of the modules by using the Justus and Michail formula [56]. The sun-tracking PV system was monitored via an in-house developed system including an electronic load and capturing the I-V characteristic of the PV generator during 4 cycles at the beginning of every
hour. The peak power $P_m$ was then extracted from the I-V characteristic. The PV related parameters were monitored for a period of 4 min at the beginning of every hour with sampling rate 500ms and were combined with the corresponding recordings of the environmental parameters monitored in 1 min intervals with the synchronized meteo-station in the laboratory. The recordings were logged via means of 2 synchronized Campbell Scientific CR1000 data loggers, and 4 min averages were calculated. The data were previously screened for clear sky days for a more reliable representation of the $f$ coefficient as the generalized model developed is steady-state. The range of conditions recorded are: $T_a$ from 3.8 to 37°C, $I_T$ from 94 to 1104 W/m$^2$, $v_w$ from 0 to 8.5m/s. The wide range of inclination and orientation angle achieved by the sun-tracking system throughout the days and year allowed the robust validation of the model.

For the sun-tracking PV system with 9 years of operation in the field, data from the 8th year of operation were used for the model development for which a 9% degradation and a 0.11 efficiency at STC were considered, while data from the 9th year of operation were used for the model validation considering a 10% PV degradation experimentally determined.

The BIPV configuration is 110W$_p$ consisting of 2 c-Si SIEMENS SM55 modules integrated in the roof of an experimental test cell shown in Fig.2(c-e) alongside with a building integrated solar collector on the roof and the façade of the test cell. The BIPV test cell with dimensions (W, L, H) 2.8m x 2.8m x 1.75-2.5m has inclination 15° and orientation 10°SW. The dimensions of each module are: 1.293m x 0.329m. The parameters monitored in the BIPV include $T_{pv}$ measured at the back of the modules using Cu-Const thermocouples, the irradiance at horizontal and the diffuse irradiance measured with Kipp & Zonen CM11 pyranometers and were used to convert to the irradiance on the inclined PV plane. Meteorological parameters $T_a$ and $v_w$ were measured with the meteo-station and the $v_w$ converted to 3m height with the aforementioned formula. The two data-loggers of the systems were synchronised and data were recorded in 1 min intervals. The BIPV data captured for the duration of 32 days across the months April, May, June include varying conditions during clear sky, partly clouded and cloudy days. The range of the conditions recorded in the 1 min intervals are: $T_a$ from 6.6 to 37°C, $I_T$ from 0 to 1132 W/m$^2$, $v_w$ from 0 to 8.2m/s. The BIPV unit has 14 years of operation in the field and 13% degradation is experimentally determined. Their STC efficiency at present status is $\eta_{pv} = 0.113$ compared to their nominal value 0.129.
Fig. 2. (a) fixed-angle and sun-tracking PV array, (b) back side of sun-tracking PV array, (c) BIPV with the PV modules integrated in the roof, (d) the back side of the PV modules in the BIPV test cell with wooden case removed to reveal the back of the modules (e) the end of the wooden case forms an air orifice profile for the heated air to be exhausted through the solar chimney or self-circulated in the room.

The design of this BIPV test cell is based on a concept similar to a naturally ventilated BIPV/T [57]. $T_{pv}$ profiles have been studied in similar designs [47-55, 58-61], with the modules directly mounted on the roof tiles or at a small distance above them, off-roof. Heat from the PV front side may be extracted by free, mixed or forced air convection in contrast to the wind protected BIPV back side as outlined in [43, 45, 62-63]. Wooden planks are placed 18cm below the PV backside (these have been removed in Fig.2(d) to show the back of the PV modules) and form the ceiling of the BIPV, which operates as a PV/T with the heat extracted by natural convection of the warm air self-pumped due to temperature difference with the indoor temperature through an orifice pattern (Fig.2(e)). In warm days, the air is self-pumped out of the BIPV through a solar chimney. Similar designs have been studied with regard to $T_{pv}$ profiles and thermal performance of building in [64-67]. Both sides of the modules experience radiated heat exchange with sky, ground and indoor walls estimated using the view factors, $F_{ij}$ and the $h_{r, f}$ and $h_{r,b}$ coefficients.

The estimation of the $h_{c}$ and $h_{r}$ done in [17, 65, 68-73] is not required in this model. Their effect is integrated into a $f$ function which incorporates deviations of actual field conditions from the average environmental conditions: $I_f=800 \text{ W/m}^2$, $T_s=20^\circ\text{C}$, $v_w<1\text{ m/s}$ (SOC) and for $\beta=\phi=38^\circ$. Corrections to the
for T<sub>pv</sub> prediction are introduced using the rates of change of the above coefficients with respect to the deviations of I<sub>f</sub>, T<sub>pv</sub>, η<sub>pv</sub>, T<sub>in</sub>, v<sub>w</sub> from their SOC values and of β from β<sub>ref</sub>=38°. The rates of change of h<sub>c,f</sub>, h<sub>c,b</sub>, h<sub>f</sub>, h<sub>b</sub> vs T<sub>pv</sub> and β, are discussed in Section 3 and integrated in the model in Section 4. These rates of change contribute essentially to the accurate prediction of the T<sub>pv</sub> profiles.

3. The heat convection and radiated heat coefficients and their rate of change with respect to PV temperature and inclination

3.1 The natural heat convection coefficients h<sub>c,f</sub> and h<sub>c,b</sub> for the front and back PV sides

Nu expressions valid for the entire range of the Ra number, Ra=Gr·Pr are critically discussed in [17] for the estimation of h<sub>c,f</sub> and h<sub>c,b</sub> for any heat transfer mode. The transition to turbulent is determined by the critical Grashof number, Gr<sub>c</sub>. This phenomenon depends on β or θ which is the angle between the vertical and the module. β+θ=90°.

The transition for facing down heated planes occurs at Gr<sub>c</sub>=3x10<sup>11</sup> for θ=75°, 2·10<sup>10</sup> for 60°, 10<sup>9</sup> for 45°, 7·10<sup>7</sup> for 30° and 4·10<sup>6</sup> for 15° [74]. The Gr<sub>c</sub> for the facing upward heated plate is lower: 5·10<sup>9</sup> for θ=15°, 2·10<sup>8</sup> for 30°, 10<sup>8</sup> for 60° and 10<sup>6</sup> for 75° [70].

3.2 The transition from laminar free convection to turbulent in the PV front and back sides

The transition to turbulent at various β needs to be examined especially for BIPV and BAPV. Let T<sub>pv</sub>=60°, T<sub>b</sub>=20°C, and the SM55 module length, L=1.33m. Also, Gr = g·cos(θ)·β·(ΔT)·x<sup>2</sup>/(ν<sup>2</sup>). For θ=75° or β=15°, and boundary layer temperature, T<sub>b</sub>=(60°+20°C)/2=40°C, β'=1/(273+40) and for ΔT =T<sub>pv</sub>−T<sub>b</sub>=60°-20°C, the value of g·cos(θ)·β·ΔT/ν<sup>2</sup> is calculated equal to 11,150·10<sup>4</sup>. The Gr<sub>c</sub> criterion for the back side gives transition to turbulent at x=6.3m > L. Hence, the air flow in the BIPV back side is laminar. In the free standing PV at low wind, for θ=60° and 45°, i.e. β=30° and 45° respectively, and according to the Gr<sub>c</sub> criterion the transition to turbulent is calculated at x=2.07m and x=0.68m, respectively. The latter is smaller than L and that implies transition to turbulent at β=45°. Therefore, h<sub>c,b</sub> takes higher values than in the smaller β. Similar analysis must be followed for the front side using the proper Gr<sub>c</sub>. This is the source of the high dispersion of T<sub>pv</sub> measured values in low v<sub>w</sub> as shown in [17].

3.3 The h<sub>c,f</sub> and h<sub>c,b</sub> rate of change vs inclination, β, and temperature, T

3.3a The rate of change of h<sub>c,b</sub> vs β, ∂h<sub>c,b</sub>/∂β

At natural convection, ∂h<sub>c,b</sub>/∂β was estimated using eq.(10) [73]:
\[ Nu = 0.48 \left( \frac{(1+\cos\theta)}{2} \right) Gr^{1/4} \]

or equivalently

\[ h_{c,b} = 0.48 \left( \frac{k}{L} \right) \left( \frac{1+\cos\theta}{2} \right) Gr^{1/4} \]

(10)

For \( \theta = 75^\circ \) or \( \beta = 15^\circ \), \( L = 1.33 \text{m} \), and air conductivity at boundary layer temperature \( 40^\circ \), \( k = 28 \text{mW/mK} \), eq.(10) gives \( \partial h_{c,b}/\partial \theta = -0.94 \text{W/m}^2\text{K/rad} \). For a change \( \delta \theta = 10^\circ \), that is, 0.1744 rad, \( \delta h_{c,b} \) is calculated equal to -0.16 W/m²K which is just the value obtained in [69]. This rate increases slowly with Gr. As calculated, \( \partial c/b/\partial \theta \) changes linearly from \((-3/\pi)\text{W/m}^2\text{K/rad} \), at \( \Delta T = T_{wv} - T_o = 10^\circ \text{C} \), to \(-4/\pi \) at \( \Delta T = 30^\circ \text{C} \), and \(-5/\pi \), at \( \Delta T = 50^\circ \text{C} \). The negative sign signifies that \( h_{c,b} \) decreases as \( \theta \) increases, i.e. \( \beta \) decreases.

The corresponding values for \( \partial h_{c,b}/\partial \theta \) are: 0, for \( 60^\circ < \theta < 90^\circ \); that is, \( h_{c,b} \) is constant in that range. For \( 30^\circ < \theta < 60^\circ \), or \( 30^\circ < \beta < 60^\circ \), \( \partial h_{c,b}/\partial \theta = +0.2 \text{W/m}^2\text{K/rad} \), while for \( 0^\circ < \theta < 30^\circ \) or \( 60^\circ < \beta < 90^\circ \), \( \partial h_{c,b}/\partial \theta = +0.5 \text{W/m}^2\text{K/rad} \) for \( \Delta T = 10^\circ \text{C} \). In average, its value is +0.8 W/m²K/rad for \( \Delta T = 30^\circ \text{C} \), and +1.0 W/m²K/rad for \( \Delta T = 50^\circ \text{C} \). The positive sign signifies that \( h_{c,b} \) increases as \( \theta \) increases.

3.3b The \( h_{c,b} \) and \( h_{c,f} \) rate of change vs \( T \)

\( \partial h_{c,b}/\partial T \), is estimated around 0.050 W/m²K per K for all inclinations, while the average values of \( \partial h_{c,f}/\partial T \) are: 0.055, 0.053 and 0.050 W/m²K per K for inclinations \( \beta = 30^\circ, 60^\circ, 90^\circ \), respectively.

3.4 The thermal radiation exchange rates between both PV sides with their environment

To handle the net thermal radiation exchanged between the PV front and back side with sky and ground using a similar expression to the heat convection it is necessary to linearize it. This process introduces the coefficients, \( h_{c,f} \) and \( h_{c,b} \). In the \( h_{c,f} \) and \( h_{c,b} \) expressions the following parameters appear: the sky temperature \( T_{sky} = 0.0552(T_a)^{1.5} \), the Stefan-Boltzmann constant \( \sigma \) equal to 5.67·10⁻⁸ W/m²K and the view factors, \( F_{pv-sky} \) and \( F_{pv-gr} \), which correspond to the fraction of the radiated heat from the PV surface which reaches the sky, the ground surface or the wall(s) according to the PV-ceiling design and geometry and are determined by eqs.(11a,b) provided that the other surface is much larger than \( A_{pv} \). If this is not the case, more elaborated expressions are developed [70].

\[ F_{pv-sky,f} = \frac{(1+\cos(\beta))}{2}, \quad F_{pv-sky,b} = \frac{(1+\cos(\pi-\beta))}{2} \]

(11a)

\[ F_{pv-gr,f} = \frac{(1-\cos(\beta))}{2}, \quad F_{pv-gr,b} = \frac{(1-\cos(\pi-\beta))}{2} \]

(11b)

The \( h_{r,f(pv-sky)} \) and \( h_{r,f(pv-gr)} \) are given in [70,73]. For \( A_{pv}/A_{sky} \) practically zero and for low \( \beta \), \( F_{pv-sky} \gg F_{pv-gr} \) and then, a simplified formula is provided

\[ h_{r,f(pv-sky)} = F_{pv-sky,f} \varepsilon_{pv} \sigma (T_f^2 + T_{sky}^2) (T_f + T_{sky}) \]

(12a)

Similarly, for \( A_{pv}/A_{gr} \) practically zero, and high inclination, \( \beta \), \( F_{pv-gr} \gg F_{pv-sky} \) and then

\[ h_{r,f(pv-gr)} = F_{pv-gr,f} \varepsilon_{pv} \sigma (T_f^2 + T_{gr}^2) (T_f + T_{gr}) \]

(12b)
For $A_{pv}$ equal to the surface close and opposite to it, as it is the case of the BIPV, $F_{pv,plank}=1$ and the coefficient $h_{r,b}$ for the radiated heat exchanged between PV back side and its back cover is given by,

$$h_{r,b(pv-int)} = \frac{\sigma (T_b^2 + T_{pl}^2)(T_b + T_{pl})}{\left( \frac{1}{\varepsilon_{pv}} + \frac{1}{\varepsilon_{pl}} - 1 \right)}$$

(13)

$\varepsilon_{pl}$ is the emissivity coefficient of the plank opposite the PV back side inside the BIPV and $T_{pl}$ its temperature, in K. The radiative heat exchange rates differ due to the different sky and ground temperatures, $T_{sky}$ and $T_{gr}$, the view factors of the front and back PV sides which depend on the module inclination $\beta$, eqs.(11a),(11b), the geometry of the BIPV configuration and the emissivity coefficients for Tedlar and glass cover. Those were measured $e_{b}=0.91$ and $e_{g}=0.85$ respectively, by using the Surface Optics Corp. ET10 emissometer. The sky, ground and indoor walls/plaster emissivity coefficients were taken equal to $e_{sky}=0.91$, $e_{gr}=0.94$, $e_{pl}=0.92$ [5,18,75,76].

Based on the analysis so far, $h_{r,b}$ in the BIPV was estimated around $2-3$W/m$^2$K compared to $4-6$W/m$^2$K for the $h_{r,f}$ at low $v_w$ for the open air BIPV, PV fixed and sun-tracking configurations. $h_{r,f}$ and $h_{r,b}$ using the above equations were estimated $5\pm0.5$W/m$^2$K for the above PV configurations. The rates of change of $h_{r,f}$ and $h_{r,b}$ vs $\beta$ and $T$ are given below.

### 3.5 $h_{r,f}$ and $h_{r,b}$ dependence on $\beta$ and $T$

$h_{r,f}$ increases vs $\beta$ or decreases vs $\theta$. At horizontal, the view factor $F_{pv,sky}$ is 1 and the net thermal radiation exchanged is higher as $T_{sky}$ is much lower than $T_{gr}=T_{a}$. For $\beta>45^o$ the thermal radiation exchanged has a strong component between PV front side and ground, while for $\beta<45^o$ the thermal radiation exchanged between PV and ground is lower than 15% due to the low $F_{pv,gr}$ where $F_{pv,gr}=(1-\cos(\beta))/2$, while the $F_{pv,sky}=(1+\cos(\beta))/2$. $h_{r,b}$ is considered the same way.

### 3.6 The $h_{r,f}$ and $h_{r,b}$ rates of change vs $T$

The estimated average rate is equal to $\partial h_{r,f}/\partial T= \partial h_{r,b}/\partial T=0.02$W/m$^2$K per K for deviation of the $T_{pv}$ from a reference temperature, $\delta T_{pv}=T_{pv,T_{pv,ref}}$. Note $T_{pv,ref}$ is defined as the $T_{pv}$ at SOC.

### 3.7 The rate of change $\partial h_{r,f}/\partial \beta$

It is negligible for $60^o<\beta<90^o$ or $0^o<\beta<30^o$. For $30^o<\beta<60^o$, $\partial h_{r,f}/\partial \beta$ was estimated around $+0.12$W/m$^2$K per rad. For $60^o<\beta<90^o$ its value is $+0.22$W/m$^2$K per rad. The sign changes when $\partial h_{r,f}/\partial \theta$ is used.

### 3.8 The rate of change $\partial h_{r,b}/\partial \beta$

In the PV fixed and the sun-tracking system the rate of change is negligible for $0^o<\beta<30^o$ while, for $30^o<\beta<60^o$ it was estimated equal to $-0.12$W/m$^2$K/rad and for $60^o<\beta<90^o$ it was estimated equal to $-0.20$W/m$^2$K/rad. Its sign is opposite to the one of $\partial h_{r,f}/\partial \beta$. 


3.9 The inclination effect at natural and air forced flow.

The $h_{c,f}$ and $h_{c,b}$ depend on $\beta$ and $T$ and strongly on $v_w$. Their values increase faster compared to $h_{c,t}$ and $h_{c,b}$ which are loosely $\beta$ and $T$ dependent. For moderate to high wind speed $h_{c,t}$ gets higher than $h_{c,f}$ and hence its $\beta$ dependence gets much weaker [77]. The issues highlighted in this section explain the pattern of scattered values in the $f$ profile for low $v_w$ shown in [17]. Using the above mentioned rates of change and the theoretical analysis in [55-66,68-69], the sum of $h_{c,f}$, $h_{c,b}$, $h_{c,t}$ and $h_{c,b}$ which equals $U_{pv}$ is calculated.

4. Theoretical elaboration of the proposed model to predict $T_{pv}, f$ and $P_m$.

The model proposed is based on 3 key issues:

1. The determination of an implicit function $f$ shown below:

$$
T_{pv} = T_a + f(v_w, \eta_{pv}(T_a, T_{pv}, I_T, v_w), U_{pv}(T_{pv}, I_T, v_w, \beta)) I_T
$$

(14)

2. The development of an empirical expression $f(v_w)$ to reflect the contribution of $v_w$ on $f$. That was done through a regression analysis of the PV sun tracking monitored data $I_T, T_a, T_{pv}$ and $v_w$.

3. The development of a set of mathematical expressions for the accurate determination of $f$ taking into consideration the PV module age, the PV module efficiency, the field conditions $v_w$, $T_a$, $I_T$, the (BI)PV configuration and the deviations of $\eta_{pv}(T_a, T_{pv}, I_T, v_w)$ and $U_{pv}(T_{pv}, I_T, v_w, \beta)$ from their corresponding values at SOC.

The combination of the EBE for a PV module at steady state [7] with eq.(14) gives,

$$
f = \frac{1-\eta_{pv}}{U_f+U_b} - \frac{U_f}{(U_f+U_b)I_T} \Delta T_{f-b}
$$

(15)

The first term in eq.(15) is considered as a zero approach to $f, f_0$, where:

$$
f_0 = \frac{1-\eta_{pv}}{U_f+U_b}
$$

(16)

$$
f = f_0 - \frac{U_f}{(U_f+U_b)I_T} \Delta T_{f-b}
$$

(17)

$\Delta T_{f-b}$ was experimentally measured between 0 and -3°C. The value depends on the PV mounting mode, the cell material, construction and the $v_w$ strength and direction. $U_f$ and $U_b$ may be estimated through iterations [21]. However, this would not lead to a compact $T_{pv}$ prediction tool as sought for here. At low $v_w$ or in wind protected areas such as the BIPV back side with the modules integrated within the roof, $U_f$ and $U_b$ according to Section 3 take values within $[10-13]$W/m²K and $[7-10]$W/m²K.
respectively. Hence, $U_f + U_b = [17-23] \text{W/m}^2\text{K}$. Using these values for this BIPV mode, eq.(17) gives $f$ in the range of $[0.035, 0.050] \text{m}^2\text{K/W}$. Similarly, the same range of $f$ values holds for the PV fixed and sun-tracking at low $v_w$, whereas as $v_w$ increases, $>3 \text{m/s}$, $U_f$ and $U_b$ increase to about $20 \pm 2 \text{W/m}^2\text{K}$ each, and thus $f$ reduces to within $[0.020 - 0.025] \text{m}^2\text{K/W}$, as shown in Fig.3. The $v_w$ effect on $f$ is strong, while the effect of the correction term in eqs.(17,18) due to $T_{pv}$ may reach up to $[7.5\% - 10\%]$. 

Fig.3. The profiles of (a) $f$ and (b) $v_w$ during a day in July for the sun-tracking and fixed PV systems. 

The effect of $v_w$ on $f$ is obvious and ranges from $0.038 \text{m}^2\text{K/W}$ when $v_w$ is low to $0.022 - 0.025 \text{m}^2\text{K/W}$ for higher $v_w$. 

To build the new model, $f$ may be expressed instead by eq.(18) as a product of a function of $v_w$ the dominant part and a weaker function of $\eta_{pv}$ and $(U_f + U_b) = U_{pv}$, both dependent on $T_{pv}$, $I_T$, $v_w$ and $\beta$: 

$$f = f(v_w) f\left(\eta_{pv}(T_a, T_{pv}, I_T, v_w), U_{pv}(T_{pv}, I_T, v_w, \beta)\right)$$ (18) 

A Taylor series expansion of the $f$ function at $v=v_{ws}$, and estimation of its partial derivatives for $\eta_{pv}$ and $U_{pv}$ around the SOC values provide a general expression for $f$ in the form of eq.(19): 

$$f = f(v_w) \left(1 - \frac{\delta \eta_{pv}}{1-\eta_{pv, SOC}}\right)\left(1 - \frac{\delta U_{pv}}{U_{pv, SOC}}\right)$$ (19) 

Therefore, the compact formula to predict $f$ for natural flow or $v_w<1.5\text{m/s}$ is: 

$$f = f(v_w) \left(1 - \frac{\left(\frac{\delta \eta_{pv}}{\delta T_{pv}}\right)\delta T_{pv} + \left(\frac{\delta \eta_{pv}}{\delta I_T}\right)\delta I_T}{1-\eta_{pv, SOC}}\right)\left(1 - \frac{\left(\frac{\delta U_f}{\delta T_{pv}}\right)\delta T_{pv} + \left(\frac{\delta U_f}{\delta I_T}\right)\delta I_T + \left(\frac{\delta U_b}{\delta \beta}\right)\delta \beta}{U_{pv, SOC}}\right)$$ (20) 

Regression analysis was applied on the 1st year recorded $T_b$, $v_w$, $I_T$, $T_a$ data from the sun-tracking PV. 

A rational function, eq.(21), was fitted because it complies with the weak $v_w$ dependence of $\eta_{pv}$ in the
nominator in eq.(19) and the strong dependence of $U_{pv}$ on $v_w$ in the denominator. The parameters in eq.(21) correspond to the SOC values of $T_a$, $I_T$, used as a reference for the $f$ corrections due to environmental fluctuations. In this analysis, it holds: $\delta T_a = T_a - 20°C$, $\delta I_T = I_T - 800W/m^2$, and $\delta \beta = \beta - 38°$.

$$f(v_w) = \frac{a+bv_w}{1+crv_w+dv_w^2} \quad (21)$$

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

The analysis outlined in the Appendix is used to determine the quantities and parameters in eq.(20). For this, eq.(21) and the expressions (A.1)-(A.6) in the Appendix are used to consider the effect of $\delta \eta_{pv}(T_{pv},I_T)$ and $\delta U_{pv}(T_{pv},\beta)$. When heat transfer from the module to the environment is due to air forced flow the factor $\delta U_{pv}/U_{pv,SOC}$ gets negligible because of the weak dependence of $U_{pv}$ on $T_{pv}$ and $\beta$ compared to natural heat flow. Then, eq.(20) is reduced to eq.(22) which is the compact formula to predict $f$ for forced convection or $v_w \geq 1.5 m/s$:

$$f = f(v_w) \left( 1 - \frac{(\delta \eta_{pv}/\delta T_{pv})\delta T_{pv} + (\delta \eta_{pv}/\delta I_T)\delta I_T}{1-\eta_{pv,SOC}} \right) \quad (22)$$

Accurate $f$ values are estimated from eqs.(20,22) for natural or forced flow, respectively, by setting initially $(\delta \eta_{pv}/\delta I_T)\delta I_T=0$ and neglecting the effect of $\delta U_{pv}$ in eq.(20). This approximate $f$ value is then substituted into eq.(A.5) to estimate $(\delta \eta_{pv}/\delta I_T)\delta I_T$. Then $f$ is re-estimated from eq.(20) or eq.(22). Eqs.(A.1)-(A.6) provide the expressions to estimate the parameters required in eq.(20). Under air forced flow where the terms $\delta U_{f}/\delta T_{pv}$, $\delta U_{f}/\delta I_T$, $\delta U_{f}/\delta \beta$, $\delta U_{f}/\delta \beta$ are negligible.

For natural air flow $f$ is obtained by eq.(20). In this case, the $U_{pv}$ at SOC is denoted as $U_{pv,SOC}$. $\eta_{pv,SOC}$ is determined from eq.(A.1) while eq.(21) for $v_w=0 m/s$ gives $f(v_w=0)=0.0347$. $U_{pv,SOC}$ is then estimated from eq.(23).

$$U_{pv,SOC} = \frac{(1-\eta_{pv,SOC})}{f(v_w=0)} \quad (23)$$

The average rates of change for $U_{pv}$ with respect to $T_{pv}$ and $\beta$ in eq.(20) are provided by eqs.(A.6a)-(A.6d). Note, for a PV module with $\delta \beta = 10°$ and $\delta T_{pv} = T_{pv} - T_{pv,SOC} = 10°C$, with reference to $(\beta = \phi$, and $T_{pv,SOC} = 20°C + f(v_w=0) - 800W/m^2)$, and for a $U_{pv,SOC}$ value at the average environmental conditions, $U_{pv,SOC} = 23.9Wm^2K$, determined from eq.(23), the contribution of $\delta U_{pv}$ due to $\delta \beta$ and $\delta T_{pv}$ variations is estimated +5-6%, while, the corresponding of $\delta \eta_{pv}$ is -12%.

Additional correction terms are introduced in the $f$ and $T_{pv}$ prediction, to cater for the PV cell type, and the age of the module under testing. The $f(v_w)$, eq.(21), was derived for a pc-Si with nominal $\eta_{pv}=0.121$. Its efficiency at STC after 8 years of operation was estimated equal to $\eta_{pv,STC}=0.11$ taking into account 9% degradation overall. Eq. (A.1) is used to estimate the efficiency at SOC, $\eta_{pv,SOC}$. To generalize the
formula for any PV module tested of a given efficiency at SOC denoted as $\eta_{pv,n}$ an additional correction factor is introduced in eqs.(20,22) which has the form, $(1-\delta \eta_{soc}(1-\eta_{pv,SOC})). \delta \eta_{soc} = \eta_{pv,n} - \eta_{pv,SOC}$, where $\eta_{pv,SOC}=0.095$ and $\eta_{pv,n}$ is the efficiency of the new type of module at SOC. A third correction term is introduced for the natural degradation of the module and provides the decrease $\delta \eta_{ag}$ due to aging with reference to the age, 8 years, of the pc-Si module used to develop the model.

$$\delta \eta_{ag} = -\eta_{pv,SOC} \cdot (0.8\% \cdot N - 9\%)$$  \hspace{1cm} (24)

where $N$ are the years in operation of the PV module to be studied.

The holistic $f$ prediction formula which considers field conditions, cell type, and age takes the form

$$f = f(v_w)\left(1 - \frac{\delta \eta_{pv}}{1-\eta_{pv,SOC}}\right)\left(1 - \frac{\delta U_{pv}}{U_{pv,SOC}}\right)\left(1 - \frac{\delta \eta_{ag}}{1-\eta_{pv,SOC}}\right)\left(1 - \frac{\delta \eta_{soc}}{1-\eta_{pv,SOC}}\right)$$  \hspace{1cm} (25)

The $f(v_w)$ expression is the same for any PV cell technology as it echoes the effect of $v_w$ on $U_f$ and $U_b$ whose values for any planar PV cell technology are practically the same.

**Scaling factor SF for BIPV configurations**

The proposed expressions for $f$ and $T_{pv}$ prediction hold for both free-standing PV and BIPV configurations, however for the latter case, a scale factor, SF, is required to adapt this model for the BIPV where $v_w$ has a negligible effect on its PV back side. Note that this factor is not required for BAPV configurations. For the BIPV case $f$ in eqs.(20,22) is multiplied with SF, which takes into account the $U_b$ decrease in the BIPV compared to the open air PV. $U_f$ for the free environment and $U_b$ for both free and indoor conditions were estimated in the beginning of Section 4. SF is derived by substituting into eq.(17) the $U_f$ and $U_b$ values once for indoor conditions and then for free. Their ratio gave $SF=1.35$ for forced flow with $v_w \geq 1.5$ m/s and $SF=1.18$ for natural flow or $v_w < 1.5$ m/s.

$P_m$ may then be predicted at any hour h from the predicted $T_{pv}$ and the $I_f$ through eq.(26a):

$$P_m = P_{m,STC} \cdot [1 + \gamma(T_{pv} - 25)°C] + \delta \cdot \ln(I_f/1000)] \cdot (I_f/1000)$$  \hspace{1cm} (26a)

$$P_{m,STC} = P_{m,STC}(1 - r_{ageing})$$  \hspace{1cm} (26b)

$$P_{m,sys} = P_m(1 - \epsilon_{losses})$$  \hspace{1cm} (26c)

where $\gamma$ is the temperature coefficient for $P_m$ with value in the region [-0.4, -0.5] °C and $\delta$ the solar irradiance coefficient with value 0.085 for sc-Si and 0.11 for pc-Si modules [79]. $P'_{m,STC}$ the PV peak power at STC at the current state of the system considering PV degradation due to ageing. The overall percentage due to ageing is denoted here as $r_{ageing}$. $P_m$ represents the array output at operating conditions and $P_{m,sys}$ the final power output of the system with $\epsilon_{losses}$ the percentage of additional power conditioning losses at system level.
5. Results and Analysis

The theoretical analysis in Section 4 shows that the factors $\beta$, $v_w$, $T_{pv}$ and $I_T$ affect explicitly and/or implicitly $f$, $T_{pv}$ and $P_m$. The proposed model succeeded to integrate the overall effect of those factors into one formula, eqs.(14,20,22,25) and to addresses the impact of those parameters through correction terms. The predicted by this model $T_{pv}$ for free-standing PV and BIPV modes is compared with the measured values and also, with those predicted by other known models as shown in the following sections.

5.1 $T_{pv}$ prediction results for the PV sun-tracking configuration and model validation

For the model validation, $f$ and $T_{pv}$ for the sun-tracking PV system, operating at a wide range of $I_T$, $v_w$, $T_a$ and $\beta$, were predicted using eqs.(20-25). The predicted $T_{pv}$ values were compared with measured ones, using the 2nd year monitoring data from the sun-tracking system and are presented in Fig.4. The proposed model exhibits an excellent prediction capacity with slope equal to 1.004 with $R^2=0.9183$. Extensive comparison was carried out comparing measured $T_{pv}$ with predicted values by 3 other models proposed in [11,31,36]. For the model in [36] the predicted vs measured $T_{pv}$ has slope 0.8658 with $R^2=0.8992$, see Fig.5. For the model in [11], the slope is 0.871 with $R^2=0.8851$, Fig.6, and for the model in [31] the slope is 0.8396 with $R^2=0.8572$, see Fig.7. The linear fit in Figs.5-7 discloses that the 3 models underestimate $T_{pv}$ at high values, which occur at high $I_T$ and low $v_w$. On the other hand, the proposed model shows an excellent behavior with the linear fit nearly matching the diagonal across the entire spectrum of $I_T$ and $v_w$.  

![Validation of the proposed model. Predicted $T_{pv}$ vs measured values using the 2nd year monitored data from the sun-tracking PV system.](image)
Fig. 5. Predicted $T_{pv}$ applying Mani’s model [36] vs measured values using the 2nd year monitored data from the sun-tracking PV system.

Fig. 6. Predicted $T_{pv}$ applying King’s model [11] vs measured values using the 2nd year monitored data from the sun-tracking PV system.
Fig. 7. Predicted $T_{pv}$ applying Faiman’s model [31] vs measured values using the 2nd year monitored data from the sun-tracking PV system.

$P_m$ was predicted by eqs.(26a-26c) using the $T_{pv}$ predicted by this model, and compared with the experimentally determined $P_m$ values from the sun-tracking PV system using the monitoring data of the 2nd year. For the $P_m$ prediction the PV module power degradation was determined 10% for the 9th year of operation, while 5% power conditioning losses were considered for the PV system final power output. The predicted vs measured $P_m$ is displayed in Fig. 8, showing excellent results with slope 1.005 and $R^2=0.8579$. This performance is superior to the predictions by the other 3 models and similar to the predictions by the dynamic electro-thermal PV temperature simulation model, as shown in [21].
Fig. 8. $P_m$ predicted by this model vs experimentally determined values using the 2nd year monitored data from the PV sun-tracking PV system.

5.2. $T_{pv}$ prediction results for the BIPV configuration and model validation

$T_{pv}$ for the BIPV of Fig.2(c) was predicted with this model using eqs.(20) for $v_w<1.5\text{m/s}$ and eq.(22) for $v_w \geq 1.5\text{m/s}$ multiplying the predicted $f$ values with $\text{SF}=1.18$ and 1.35 respectively, according to the analysis outlined in Section 4. Fig.9 shows the predicted $T_{pv}$ profiles by the proposed model and by the 3 other models vs the measured $T_{pv}$ profiles at the PV back surface of the BIPV system during 5 clear-sky consecutive days in June, with 1 min time interval. The $v_w$ and $I_T$ profiles are plotted in the bottom subplots, with wind speed ranging from 0 to 7.9m/s. Fig.10 shows the same comparison for 3 days in April with partly cloudy sky and wind speed ranging from 0 to 8.2m/s. The $T_{pv}$ predicted by this model lies very close to the measured $T_{pv}$ profile data, and exhibits superior performance for both clear sky and partly cloudy days and across the large range of wind speeds 0-8.2m/s, when compared to the other well-known models [11,31,36] which exhibit large deviations from the measured values. The effect of $v_w$ on the predicted and measured profiles is obvious and conforms with the analysis in Section 4.
Fig. 9. Predicted $T_{pv}$ profiles by this model and by the 3 other models in [11,31,36] vs measured ones at the BIPV back surface during 5 consecutive days in June with 1 min time interval. $I_T$ and $v_w$ are plotted in the bottom subplots.

Fig. 10. Same as in Fig. 9 for 3 consecutive days in April.
The predictive capacity of this model for the BIPV case is shown in Fig.11, where the predicted vs measured $T_{pv}$ for the period April-May-June is displayed. The linear fit has slope 1.027 with $R^2=0.9184$, very close to the diagonal, exhibiting excellent model performance. For comparison the predicted $T_{pv}$ by the models in [36,11,31] vs the measured BIPV data for the same period are shown in Figs.12-14 respectively. The slope of the fitted line show that the models [31,36] underestimate $T_{pv}$ while the model [11] overestimates it. This comparison highlights the high predictive capacity of the proposed model which is attributed to this novel approach integrating most of the environmental parameters which affect $T_{pv}$ and $\eta_{pv}$, and the latter’s deviation from the SOC values, the rates of change of $U_{pv}$ vs $T_{pv}$ and $\beta$, the PV mounting through SF, the module technology through the $\eta_{pv}$ and the operational condition of the module through the number of years of operation and degradation rate.

Fig.11. Predicted $T_{pv}$ by this model vs measured values from the BIPV system monitored across the period April-May-June, with 1 min interval.
Fig. 12. Predicted $T_{pv}$ applying Mani’s model [36] vs measured values from the BIPV system monitored across the period April-May-June, with 1 min interval.

Fig. 13. Predicted $T_{pv}$ applying King’s model [11] vs measured values from the BIPV system monitored across the period April-May-June, with 1 min interval.
Fig. 14. Predicted $T_{pv}$ applying Faiman’s model [31] vs measured values from the BIPV system monitored across the period April-May-June, with 1 min interval.

5.3 Proposed model applied to other BIPV configurations

The model’s predictive performance is further evaluated against experimental data reported in other studies for different BIPV types, mounting configurations and conditions as shown in Table 2. The BIPV in NREL [59] includes two mounting configurations, one with the PV modules directly mounted on the roof and the other with counter-battens mount, which allows air flow at the back of the modules.

The model of eq.(25) is evaluated with the experimental data of the above study for both mounting configurations. The scaling factor SF=1.35 (forced flow) is applied for the BIPV with direct-mount while no scaling factor (SF=1) is applied for the counter-battens mount because it allows air to flow free at the back of the module. The predicted values are within ±1°C from the measured values for both mounting configurations and both set of conditions as shown in Table 2. Since the conditions reported in [59] were for $v_w>2\text{m/s}$, then according to the analysis in Section 4, the 3rd term $(1 - \delta U_{pv}/U_{pv,SOC})$ in eq.(25) is dropped as this term accounts only for natural flow ($v_w<1.5\text{m/s}$). The performance of the model for natural convection which now includes this term is shown in comparison to the measured data for BIPV in the façade and roof of [46,54] for the conditions of no wind. The $T_{pv}$ predictions by eq.(25) are within ±1.5°C (Table 2). In this case the scaling factor applied is SF=1.18 corresponding to natural flow and $v_w<1.5\text{m/s}$. In the cases of fully integrated PV with small airgap and direct mount the
SF is applied, whereas for partly integrated PV the SF is not applied according to Section 4. For the conditions of higher wind speed in the aforementioned mounting configurations the $T_{pv}$ predictions by eq. (25) are within $\pm3^\circ$C from the measured values. On the other hand, studies [46,54] include their own predictions using the SNL [11] and NOCT models and refining the Ross coefficient [27], which exhibit deviations from measured values as large as $\pm11^\circ$C. All these illustrate the high accuracy and wide applicability of the model proposed which shows excellent performance compared against the experimental data from BIPVs in different locations, mounting configurations, PV technology and age of operation, similar scale [46,54] to the BIPV of the current study or larger scale [59] and across a variety of weather conditions. The applicability of the SF is illustrated for BIPV/BAPV of different mounting configurations in Table 2.

Table 2: $T_{pv}$ model performance with experimental data of other studies for various BIPV configurations.

<table>
<thead>
<tr>
<th>Reference Study</th>
<th>BIPV type</th>
<th>Prediction Approach</th>
<th>Conditions</th>
<th>Measured $T_{pv}$ in the reference study ($^\circ$C)</th>
<th>Predicted $T_{pv}$ by eq. (25) ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muller et al. [59]</td>
<td>pc-Si modules mounted on the roof, slope 15°, in direct-mount and counter-battens mount</td>
<td>Measured data, average values</td>
<td>$T_a=28.6^\circ$C, $I_T=996.8$ W/m², $v_w=2.49$ m/s</td>
<td>67.4 (direct-mount)</td>
<td>N/A 68.4 (with SF=1.35)</td>
</tr>
<tr>
<td>Toledo et al. [54]</td>
<td>c-Si modules integrated on the South Façade</td>
<td>Refining empirical coefficient of Ross [27] and SNL model [11]</td>
<td>@12:00 $T_a=38.4^\circ$C, $I_T=540$ W/m², $v_w$ not reported ($v_w=0$)</td>
<td>60.5</td>
<td>54.1 (Ross) 58.8 (SNL) 60.7</td>
</tr>
</tbody>
</table>
6. Discussion

The proposed model (eq.(25)) is a function of environmental conditions $T_a$, $I_T$, $v_w$ and interrelated module parameters $\eta_{pv}$, $T_{pv}$, mounting related parameters $\beta$, $U_{pv}$ and the operational condition of the module determined by its natural degradation based on the number of years of operation. It is expressed as a compact formula making it robust in predicting PV temperature both for free-standing PV and BAPV with large air gap behind the PV modules, as well as BIPV designs for roofs or facades, or BIPV/T when multiplied appropriately with SF depending on a natural or forced flow. SF is applied for the BIPV types with insulated back or small airgap behind the module considering full PV integration into the building structure. The SF is not applied for cases of BAPV where the PV modules are adapted or partly integrated into the building forming a large air gap behind the modules allowing the circulation of external air.

In the previous section, the model was shown to have higher predictive capacity than the widely used and universally accepted formulas [11, 31, 36] and NOCT model along with refined Ross coefficient [27,54] and it is shown to have excellent performance with different BIPV types, mounting configurations, PV technologies and at different locations. The model has not incorporated the effect of humidity and water impact which are critical parameters in floating PV systems and therefore is more appropriate for low to medium humidity conditions in in-land PV systems. Exogenous parameters such
as shading from nearby buildings/structures may affect the predictive performance in a similar way to other $T_{PV}$ models. When the solar irradiance is measured locally on the BIPV and the shading impacts on the entire PV array then its effect is reflected directly in the value of solar irradiance which appears reduced and the model predicts $T_{pv}$ and $P_m$ at the new irradiance level. However, localised shading effects, when the module is only partly shaded, would be a challenging issue and is not incorporated within the generalised model – this is outside the scope of the present study.

The effect of PV ageing is taken into account through the term $\left( 1 - \delta \eta_{ag} / (1 - \eta_{PV, SOC}) \right)$ in eq.(25) considering natural degradation of the modules and provides the difference in the efficiency $\delta \eta_{ag} = -\eta_{PV, SOC} \cdot (0.8\% \cdot N - 9\%)$ due to aging of the module under study with reference to the degradation (9%) of the pc-Si modules used to develop the model. In brand new PV installations this term will be used with $N=1$ leading to an increase in $\delta \eta_{ag}$ compared to the reference module used in the study. The higher the degradation the higher the value of the term $\left( 1 - \delta \eta_{ag} / (1 - \eta_{PV, SOC}) \right)$ and the higher the resulting value of $f$ in eq.(25) which illustrates the increase in the predicted $T_{pv}$ due to ageing. Some PV manufacturers nowadays guarantee a smaller degradation rate than 0.8% per year and so the term above could be used with a smaller rate if that is available for the PV installation to be applied. The above term accounts for natural degradation of PV modules and the effect of more severe localized degradation phenomena on $T_{pv}$ is not included here but can be largely accounted for if the term 0.8% N in the above is replaced by the measured degradation of the PV modules to be studied after characterization tests are performed.

An analysis of the predicted ($T_{pv}$) vs measured ($T_m$) values shows that the relative error of the prediction for the free-standing system, based on the results presented in Fig. 4, is: $(T_{pv} - T_m) / T_m = 0.004 + 1.129 / T_m$. This, for PV operating temperatures around the NOCT and specifically $T_m=50^\circ C$ gives a relative error 2.6% and for temperatures in the higher range $T_m=70^\circ C$ the relative error reduces to 2%, while for temperatures in the lower range, $T_m=30^\circ C$ the relative error is 4.2% causing an overestimation of temperature by just 1.3°C. For the BIPV the relative error of the prediction, as obtained from the results of Fig.11, is: $(T_{pv} - T_m) / T_m = 0.027 - 2.418 / T_m$. This, for $T_m=50^\circ C$ gives a relative error -2.1% and for higher temperature $T_m=70^\circ C$ the relative error reduces to just -0.8%. Lower PV temperature $T_m=30^\circ C$ gives a relative error -5.4% which translates to an underestimation of PV temperature by up to 1.6°C. The model can predict $T_{pv}$ with a small relative error throughout the entire temperature range. The relative error of the prediction by the other models is shown for comparison in Table 3, where it is evident that other models exhibit much larger relative error especially in the high end of the temperature range reaching up to -9.5% causing an underestimation of PV temperature by 6.6°C in the free-standing PV system and up to 19.2% causing overestimation by 13.4°C or -18.9% underestimation by 13.2°C in the BIPV system.
Table 3: Relative error in the prediction of $T_{pv}$ for low, mid, high PV temperatures in comparison to other models

<table>
<thead>
<tr>
<th>Relative error %</th>
<th>Free-standing PV system</th>
<th>BIPV system</th>
</tr>
</thead>
<tbody>
<tr>
<td>model</td>
<td>$T_{pv}=30^\circ C$</td>
<td>$T_{pv}=50^\circ C$</td>
</tr>
<tr>
<td>proposed model</td>
<td>4.2</td>
<td>2.6</td>
</tr>
<tr>
<td>King [11]</td>
<td>-5.0</td>
<td>-8.2</td>
</tr>
<tr>
<td>Mani [36]</td>
<td>5.4</td>
<td>-2.1</td>
</tr>
<tr>
<td>Faiman [31]</td>
<td>0.5</td>
<td>-6.1</td>
</tr>
</tbody>
</table>

An analysis of the predicted ($P_{m,\text{pred}}$) vs measured ($P_m$) power output shows that the relative error of the prediction for the free-standing system, based on the results presented in Fig.8, is: 

$$\frac{(P_{m,\text{pred}} - P_m)}{P_m} = 0.005 + 5.599/P_m.$$ 

This, for PV operating with high power output $P_m=400\,\text{W}$ near its nominal value, as it would be during a clear sky day around solar noon, gives a relative error 1.9%, while at low power output $P_m=150\,\text{W}$ during morning/evening hours gives a relative error 4.2%.

The slightly higher relative error at low power output may be partly attributed to the slightly higher relative error of $T_{pv}$ prediction at low PV temperatures, while other factors that may contribute are other environmental parameters such as the solar spectrum, angle of incidence of solar irradiance which may have a stronger effect on $T_{pv}$ and $P_m$ prediction during morning and evening hours. The relative error of the $P_m$ prediction is small across the entire power output range.

### 7. Conclusions

A novel and universally applicable physics based semi-empirical model was developed and validated to predict the PV temperature, $T_{pv}$, and power output $P_m$. It is based on a general purpose implicit expression formulated to predict the coefficient $f$ which relates $T_{pv}$ with $I_T$, $v_w$, $T_a$, $U_{pv}$, and the inclination $\beta$. The model is a product of 5 functions and may be applied to any flat PV module of any type, age, at any environmental conditions. Regression analysis of the 1st year’s monitored data, $T_{pv}$, $T_a$, $I_T$ and $v_w$ from a PV sun-tracker with pc-Si modules gave the function $f(v_w)$ which is the main factor affecting $f$, $T_{pv}$ and $P_m$. The second function accounts for the change $\delta\eta_{pv}$ in the efficiency, and the third for the change $\delta U_{pv}$ in the heat losses due to the effect of the environmental conditions, $(T_a, I_T, v_w)$, and of the inclination $\beta$. The fourth function caters for the PV module natural ageing effect, and the fifth function for the PV module technology to account for the difference in the module efficiency between the module
under study and the reference module used for the model development. This is a unique model expressed in compact form, which has integrated:

1. The effect of the environmental factors on the module parameters, $T_{pv}$ and $P_m$, using an effective approach of perturbation from their SOC values

2. The BIPV, BAPV, BIPV/T mounting design characteristics, using a scaling factor, SF, and

3. The PV module efficiency and operational status as well as the aging effect both compared to the reference PV module used in the model development.

The predicted by this model $T_{pv}$ values were compared for validation purposes with the 2nd year experimental $T_{pv}$ values from a sun-tracking PV system and also with the predictions by 3 well-known models. The relative error in the $T_{pv}$ prediction is small across the entire temperature range. Specifically, for the sun-tracking system the relative error is 2.6% for PV operating temperatures around the NOCT, with a slight increase at lower PV temperatures leading to an overestimation by only 1.3°C. The other models exhibit much larger relative error especially in the high end of the temperature range with an underestimation of PV temperature of up to 6.6°C.

This model is also applicable to BIPV configurations introducing a scaling factor SF, which was estimated for this case. A very good agreement was confirmed between predicted by this model and measured $T_{pv}$ in the BIPV case with a very small relative error across the entire temperature range. The relative error is -2.1% for PV temperatures around the NOCT, which increases slightly at lower PV temperatures leading to an underestimation of PV temperature by up to 1.6°C. Other models exhibit much larger relative error especially in the high end of the temperature range with an overestimation of PV temperature by 13.4°C or underestimation by 13.2°C. Additionally, this model was used to predict $T_{pv}$ for various BIPV and BAPV configurations operating in USA, Spain and Italy. The predicted $T_{pv}$ was very close to the experimental values, with a performance much higher than other widely used formulas showing the universality of the model.

Finally, the PV power output for the sun-tracking PV array was also predicted based on the $T_{pv}$ model and compared to experimentally determined $P_m$ values giving a relative error 1.9% for PV operating with power output near its nominal value as it would be during a clear sky day around solar noon and a relative error 4.2% at low power output of around 1/3 of its nominal value. All these confirm the wide applicability of this model and its high accuracy in the prediction of $f$, $T_{pv}$ and $P_m$ which was shown to be superior than other widely used models.
References


APPENDIX

1. $\eta_{pv,SOC}$ is the efficiency $\eta_{pv}$ at SOC with $T_a=20^\circ C$, $I_T=800W/m^2$, considering $v_w<1$ m/s. According to [78]:

$$\eta_{pv,SOC} = \eta_{pv,STC} \left(1 + \gamma (T_{pv,SOC} - 25^\circ C) + \delta \cdot \ln \left(\frac{800}{103}\right)\right) \quad (A.1)$$

Parameters $\gamma = \phi_{\eta_{pv}}/\phi_{T_{pv}}$ and $\delta$ depend on the PV cell technology. The values for c-Si are -0.005K$^{-1}$ and 0.11, respectively. $\eta_{pv,STC}$ is the efficiency at STC in the present status of the module.

2. $T_{pv,SOC}$ in (A.1) is estimated by:

$$T_{pv,SOC} = 20^\circ C + f(v_w = 0)800W/m^2, \text{ the higher order terms in eq.}(20) \text{ are dropped} \quad (A.2)$$

3. $\delta T_{pv} = T_{pv} - T_{pv,SOC} = T_a + f(v_w)I_T - T_{pv,SOC} \quad (A.3)$

4. The infinitesimal change $\delta \eta_{pv}$ may be estimated by:

$$\delta \eta_{pv} = \left(\frac{\partial \eta_{pv}}{\partial T_{pv}}\right) \delta T_{pv} + \left(\frac{\partial \eta_{pv}}{\partial I_T}\right) \delta I_T \quad (A.4)$$

the first term was given above and the second one is estimated as below.

5. ($\partial \eta_{pv}/\partial I_T$) $\delta I_T$ is determined by the following expression using eq.(A.1) and eq.(14)

$$\left(\frac{\partial \eta_{pv}}{\partial I_T}\right) \delta I_T = \eta_{pv,SOC} \left(\frac{1}{I_T} \delta + \gamma f + \gamma \frac{dT_a}{dl}\right) (I_T - I_{T,SOC}) \quad (A.5)$$

dT/df depends on the local climate and season and may be taken equal to 1-2$^\circ$C/100W/m$^2$. Eq.(A.5) implies positive and negative contribution during the day and depends on the $I_T$, $f$ and dT/df. The contribution of $\partial \eta_{pv}/\partial I_T$ to the $f$ prediction is negligible for $I_T$ around $I_{T,SOC}= 800W/m^2$. 
4. The following expressions provide the average values of the rates of change for $U_{pv}$ with respect to $T_{pv}$ and $\beta$ for natural air flow when the dependence of $f$ on $T_{pv}$ and $\beta$ is essential, eq.(20). At forced flow conditions the terms below take negligible values and the $f$ is predicted by eq.(22).

\[
\frac{\partial U_f}{\partial T} \delta T_{pv} = \frac{\partial (h_{cf} + h_{rf})}{\partial T} \delta T_{pv} = 0.065 \cdot \delta T_{pv} \tag{A.6a}
\]

\[
\frac{\partial U_b}{\partial T} \delta T_{pv} = \frac{\partial (h_{cb} + h_{rb})}{\partial T} \delta T_{pv} = 0.062 \cdot \delta T_{pv} \tag{A.6b}
\]

\[
\frac{\partial U_f}{\partial \beta} \delta \beta = \frac{\partial (h_{cf} + h_{rf})}{\partial \beta} \delta \beta = -0.0074 \cdot \delta \beta \tag{A.6c}
\]

\[
\frac{\partial U_b}{\partial \beta} \delta \beta = \frac{\partial (h_{cb} + h_{rb})}{\partial \beta} \delta \beta = 0.0195 \cdot \delta \beta \tag{A.6d}
\]

where $\delta \beta = \beta - \varphi$

\[\]
**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: