Photovoltaic Panel Temperature and Power Output Analysis Tool

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The extensive use of photovoltaic (PV) systems to produce electricity due to the increase of fossil fuel cost and environmental consideration has become wide spread. The performance of a PV array is affected by temperature, solar insolation, shading, and array configuration. A MATLAB®-based modeling and simulation scheme is presented suitable for studying the current-voltage and power-voltage characteristics of a PV array under outdoor conditions and PV module physical component properties. The validity of the modeling approach was demonstrated by comparing its predicted operating temperature changes and system daily electrical energy produced with the measured data acquired from an experimental rig at the Energy Research and Development Center (ERDC) of Da-Yeh University in Taiwan. The predictions from the model show good agreement with the experimental measurements.

Additional Keywords: Photovoltaic module, thermal performance, outdoor, MATLAB®

Nomenclature

Roman

A	ideal factor
C	specific heat capacity [J/(kg °C]
D	diode
E	electrical energy [W/m²]
G	irradiance [W/m²]
H	heat [W/m²]
h	convective heat transfer coefficient [W/m²K]
I	current [A]
k	Boltzmann's constant [J/K]; conductive heat transfer coefficient [W/(m K)]
q	electron charge [C]
R	resistance [Ω]
T	temperature [°C or K]
t	time [s]
U	overall heat transfer coefficient [W/m²K]
V	voltage [V]
v	velocity [m/s]

Greek Symbols

α	absorptivity
β	parking factor
γ	solar irradiance coefficient [m²/W]
δ	thickness [m]
η	efficiency
λ	temperature coefficient [1/K], coefficient of proportionality between current and irradiance [A m²/W]
μ	temperature coefficient [1/K]
ξ	dimensionless coefficient
ρ	density [kg/m³]
τ	transmissivity

Subscripts

a	ambient
abs	absorbed
b	back
c	solar cell
cond	conducted
conv	convected
D	diode
g	glass; gap
L	light
oc	open circuit

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p	parallel
r	reference
rad	radiated
s	series
sc	short circuit
sh	shunt
trans	transmitted
w	wind

Abbreviations

AM	air mass
ERDC	Energy Research and Development Center
DIY	do-it-yourself
MPPT	maximum power point tracking
PV	photovoltaic
PN	pn junction
rms	root mean square

1. Introduction

The performance of a PV module depends largely on the availability of solar radiation and on the conversion efficiency; these important features are affected by many physical parameters like the site latitude, the typical weather conditions, the panel tilt and azimuth angles, the air temperature, the wind speed, the temperature of the surrounding surfaces, the obstruction and shadow effects, the electrical load, etc. [1].

PV module manufacturers provide performance data for their products only for fixed standard conditions of solar irradiance and operating temperature. Indeed, sometimes, only a few electrical parameters (maximum power, maximum efficiency) are given [1].

In most cases, the PV panel will always operate far from these standard conditions. For this reason, it is very important to have a reliable model of the PV panel that is able to predict the electrical performance, even though the solar irradiance, the electrical load and the operating temperature do not correspond to the standard conditions [1].

Knowledge of the characteristic of a PV panel is a prerequisite for designing and dimensioning a PV power supply. This is the reason for the development of PV panel models useful for electrical measurement applications [2]. This approach allows the development of new high-performances conversion systems, balancing system-components and permitting the evaluation of the behavior of the entire system in various scenarios [2].

Currently, photovoltaic generation systems are actively being promoted in order to mitigate environmental issues such as the green house effect and air pollution [3]. Another advantage is that solar technology is highly modular and can be easily scaled to provide the required power for different loads [4]. Photovoltaic energy is a clean energy, with a long lifespan and a high reliability. So, it can be considered as one of the most sustainable of the renewable energy technologies [5]. These systems can be located in or near where the necessity takes place, avoiding losses of transmission and contributing reductions to the CO_2 emission in urban centers [6].

2. Modelling Of A PV Cell

The solar cell is the basic unit of a photovoltaic module and it is the element transforming the sun rays or photons directly into electric power [6].

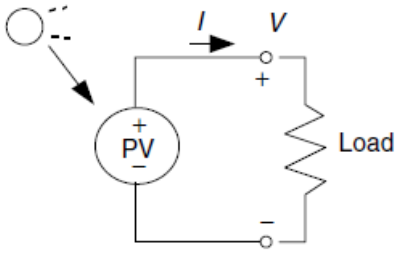

Figure 1: PV cell with a load

Solar cells consist of a p-n junction fabricated in a thin wafer or layer of semiconductor [7]. In the dark, the PV cell's behavior is similar to that of a diode [8]. The PN union electrical characteristics differ very little from a diode, represented by equation 1 of Shockley [6] .

$$I_D = I_o\left(e^{qV_D/kT} - 1\right) \quad (1)$$

Here I_o is the reverse saturated current of the diode. When exposed to light, photons with energy greater than the band gap energy of the semiconductor are absorbed and create an electron-hole pair. These carriers are swept apart under the influence of the internal electric fields of the p-n junction and create a current proportional to the incident radiation [7].

Being the net current of the cell, the difference of the photocurrent I_L, (the current generated by the incident light, directly proportional to the sun irradiation) and I_D (the normal diode current), as shown in equation 2 [6] .

$$I = I_L - I_D \quad (2)$$

Shorting together the terminals of the cell (short circuit), as shown in figure 2a, the photon generated current (I_L) will follow out of the cell as a short-circuit current (I_{sc}).

Thus,

$$I_L = I_{SC} \quad (3)$$

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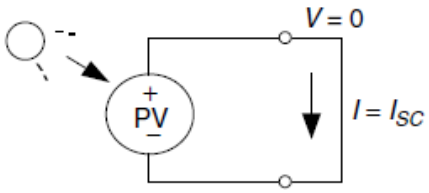
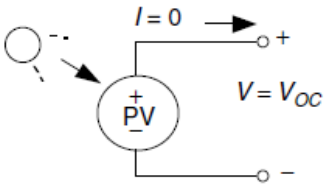
When there is no connection to the PV cell (open-circuit), the photon generated current is shunted internally by the intrinsic p-n junction diode. This gives the open circuit voltage V_{oc} (see figure 2b).



(a): Short circuit current



(b): Open circuit voltage

Figure 2: Diagrams showing short-circuit (a) and open circuit (b) conditions

The PV module or cell manufacturers usually provide the values of these parameters in their data sheets [9].

Equations 1 to 3 give the net current of the solar cell. Equation 4 is the current-voltage relationship of the PV cell.

$$I = I_{SC} - I_O\left(e^{qV/kT} - 1\right) \tag{4}$$

where V is the voltage across the PV cell and I is the output current from the cell. The reverse saturated current I_o is constant under the constant temperature.

The process of modeling this solar cell can be developed based on equations 1, 2 and 4 [6]. Therefore, the ideal solar cell can, theoretically, be modeled as a current source in anti-parallel with a diode [6]. The simplest model of a PV cell is shown as an equivalent circuit shown in figure 3.

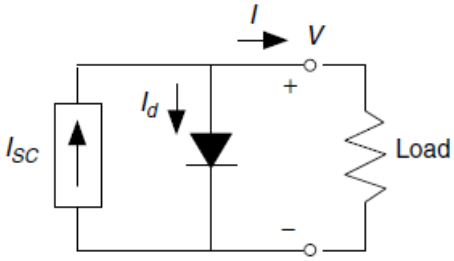


Figure 3: PV cell simple equivalent circuit

Setting the open-circuit condition as shown in figure 3, I = 0 and equation 4 becomes

$$0 = I_{SC} - I_O\left(e^{qV/kT} - 1\right) \tag{5}$$

Solving for $I_{o,}$ we obtain

$$I_O = \frac{I_{SC}}{e^{qV/kT} - 1} \tag{6}$$

To a very good approximation, the photon generated current, which is equal to I_{sc}, is directly proportional to the irradiance G, the intensity of illumination, to PV cell [10]. If λ is the coefficient of proportionality,

$$I_{SC} = \lambda G \tag{7}$$

Thus, if the value, $I_{sc}=I_{scr}$, is known from the data sheet, under the standard test condition, G_o=1000 W/m^2 at the air mass (AM) = 1.5, and the short-circuit current I_{sc} the photon generated current at irradiance G, the quotient of short-circuit currents over respective irradiances is equal to the constant of proportionality λ , thus

$$\lambda = \frac{I_{SCr}}{G_o} = \frac{I_{SC}}{G} \tag{8}$$

There are series resistances, parallel resistances and a recombination in the depletion region of the PV cell that have not been taken into account in the simple model and that will affect the performance of a PV cell in practice.

There is a series of resistances in a current path through the semiconductor material, the metal grid, contacts, and current collecting bus [11]. These resistive losses are lumped together as a series resister (R_s).

There also parallel resistance also called shunt resistance. It is a loss associated with a small leakage of current through a resistive path in parallel with the intrinsic device [11]. This can be represented by a parallel resister (R_p).

Recombination in the depletion region of PV cells provides non-Ohmic current paths in parallel with the intrinsic PV cell [12]. As shown in figure 4, this can be represented by the second diode (D2) in the equivalent circuit.

Adding the impact of R_S,

$$V_D = V - IR_S \tag{9}$$

and summarizing these effects, the current-voltage relationship of the PV cell is written as (equation 10)

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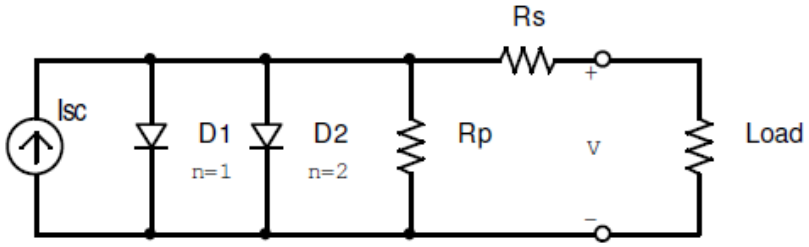

Figure 4: Equivalent circuit for a double exponential model of a PV cell

$$I = I_{SC} - I_{O1}\left[e^{q\left(\frac{V+IR_S}{kT}\right)} - 1\right] - I_{O2}\left[e^{q\left(\frac{V+IR_S}{2kT}\right)} - 1\right] - \frac{V + IR_S}{R_p} \quad (10)$$

The two-diodes equivalent circuit (and the corresponding double-exponential equation) is particularly suited for polycrystalline cells [13]. It is possible to combine the first diode (D1) and the second diode (D2) and rewrite the equation (10) in the following form.

$$I = I_{SC} - I_O\left[e^{q\left(\frac{V+IR_S}{AkT}\right)} - 1\right] - \frac{V + IR_S}{R_p} \quad (11)$$

And is represented by the single exponential model as shown in figure 5.

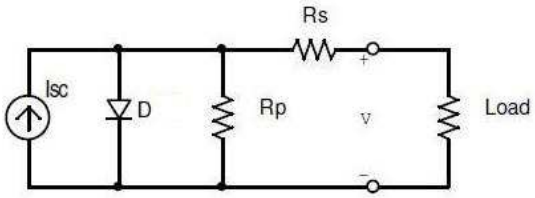

Figure 5: Equivalent circuit for single exponential model of PV cell

In equation 11, A is known as the "ideality factor" ("A" is sometimes also denoted as "n") and takes the value between one and two [12].

However, the more accurate value is estimated by curve fitting. It can be estimated iteratively until an accurate value is achieved [7]. E_g is the band gap energy and some values are 1.12 V for Si; 1.42 for GaAs; 1.5 V for CdTe) and 1.75 V for amorphous Si.

3. Photovoltaic Panel Modeling

A single PV cell produces an output voltage less than 1 V, about 0.6 V for crystalline silicon (Si) cells, thus a number of PV cells are connected in series to archive a desired output voltage. When series-connected cells are placed in a frame, it is called as a module. Also, multiple modules can be wired together in series or parallel to deliver the voltage and current level needed. The group of modules is called an array. Most of commercially available PV modules with crystalline-Si cells have either 36 or 72 series-connected cells. A 36-cell module provides a voltage suitable for charging a 12 V battery, and similarly a 72-cell module is appropriate for a 24 V battery [14].

When the PV cells are wired together in series, the current output is the same as the single cell, but the voltage output is the sum of each cell voltage.

The strategy of modeling a PV module is no different from modeling a PV cell. It uses the same PV cell model. The parameters are the same, but only a voltage parameter (such as the open-circuit voltage) is different and must be divided by the number of cells [14]. Series resistance effects become very conspicuous in a PV module that consists of many series-connected cells, and the value of resistance is multiplied by the number of cells. The parallel resistance effect is much less conspicuous in a PV module compared to the series resistance, and it will only become noticeable when a number of PV modules are connected in parallel for a larger system [14].

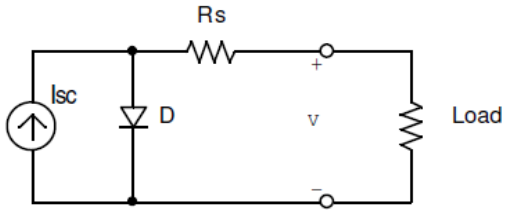

Figure 6: Equivalent circuit in the MATLAB® simulations

The equation describing the current-voltage relationship of the PV cell is given by

$$I = I_{SC} - I_O\left[e^{q\left(\frac{V+IR_S}{AkT}\right)} - 1\right] \quad (12)$$

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where I is the cell current (the same as the module current), V is the cell voltage = (module voltage/number of cells in series), T is the cell temperature in Kelvin (K).

First, calculate the short-circuit current (I_{sc}) at a given cell temperature (T):

$$I_{SC} = I_{SCr}[1 + \alpha(T - T_r)] \quad (13)$$

where I_{scr} at T_r is given in the data sheet (measured under irradiance of 1000 W/m^2), T_r is the reference temperature of the PV cell in Kelvin (K), usually 298 K (25 °C), a is the temperature coefficient of I_{sc} in percent change per degree temperature, which is also given in the data sheet.

The short-circuit current is proportional to the intensity of irradiance, thus I_{sc} at a given irradiance (G) is

$$\mathbf{I_{SC}} = \lambda \mathbf{G} \quad (14)$$

where G is the nominal value of irradiance, which is normally 1000W/m^2 and λ (A/Wm^2) is the coefficient of proportionality.

The reverse saturation current of a diode (I_{or}) at the reference temperature (T_r) is given by equation 6 with the diode ideality factor added

$$I_{Or} = \frac{I_{SCr}}{e^{qV_{OC}/AkT_r} - 1} \quad (15)$$

The reverse saturation current (I_o) is temperature dependant and the I_o at a given temperature (T) is calculated by the following equation [7]

$$I_o = I_{or}\left(\frac{T}{T_r}\right)^{\frac{3}{A}} e^{\frac{-qE_g}{Ak}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \quad (16)$$

The diode ideality factor A is unknown and must be estimated. It takes a value between one and two; the value of n=1 (for the ideal diode) is, however, used until the more accurate value is estimated later by curve fitting [7]. The R_s value has a marked effect on the I-V characteristic near the open circuit condition, while R_{sh} acts on the voltage of the maximum power point (MPP) [2]. A method for obtaining a first good estimation of R_s was proposed by Gow and Manning, and consists in differentiating equation 12, evaluating it at open circuit conditions and rearranging it in terms of R_s [2].

$$dI = 0 - I_o.q\left(\frac{dV + R_S.dI}{AkT}\right).e^{q\left(\frac{V+LR_S}{AkT}\right)} \quad (17)$$

And from equation 17

$$R_S = -\frac{dV}{dI} - \frac{AkT/q}{I_O.e^{q\left(\frac{V+I.R_S}{AkT}\right)}} \quad (18)$$

Then, evaluate the equation 18 at the open circuit voltage that is $V=V_{oc}$ (also let I=0). The obtained equation is

$$R_S = -\frac{dV}{dI} - \frac{1}{X_V} \quad (19)$$

where

$$X_V = I_O\frac{q}{AkT}e^{\frac{qV_{OC}}{AkT}} \quad (20)$$

and dI/dV is the slope of the I-V curve at the V_{oc} (use the I-V curve in the datasheet then divide it by the number of cells in series), V_{oc} is the open-circuit voltage of cell (found by dividing V_{oc} in the datasheet by the number of cells in series).

Finally, it is possible to solve equation 12 for I-V characteristics. It is, however, complex because the solution for the current is recursive as a result of the inclusion of a series resistance in the model. Although it may be possible to find the answer by simple iterations, Newton's method is chosen for accelerated convergence [7].

The Newton's method is described as:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \quad (21)$$

where: f '(x) is the derivative of the function f(x)=0 , x_n is a present value, and x_{n+1} is a next value.

Rewriting equation 21 gives the following function

$$f(I) = I_{SC} - I - I_O\left[e^{q\left(\frac{V+I.R_S}{nkT}\right)} - 1\right] = 0 \quad (22)$$

After substitution into equation 20 the output current I can be computed iteratively.

$$I_{n+1} = I_n - \frac{I_{SC} - I_n - I_O\left[e^{q\left(\frac{V+I_n.R_S}{AkT}\right)} - 1\right]}{-1 - I_O\left(\frac{q.R_S}{AkT}\right)e^{q\left(\frac{V+I_n.R_S}{AkT}\right)}} \quad (23)$$

The open circuit voltage increases logarithmically with the ambient irradiation, while the short circuit current is a linear function of the ambient irradiation [15]. The dominant effect with increasing cell temperature is the linear decrease

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of the open circuit voltage, the cell being thus less efficient. The short circuit current slightly increases with the cell temperature increase [15].

4. PV Module Temperature

In the following a simple energy and exergy analyses of the simultaneous generation of heat and power by PV technology is presented [16] .

The principle of a solar cell can be considered as an ideal simple situation in which the sun irradiates the flat surface of the solar cell on the surface of the earth [16] . The energy exchanged by the solar cell is explained with reference to figure 7 [16] .

The irradiation that reaches the flat surface of a PV module is decomposed in reflected and refracted components. A part of the refracted component is absorbed by the front glazing and the other is transmitted to the solar cells and the back surface.

Only the part transmitted to the solar cells contributes to produce electricity while the part transmitted to the back surface heats the solar cells. Finally a component of energy is lost by conduction and radiation.

To determine temperatures need for simulation of solar module, the energy balance was applied to each component.

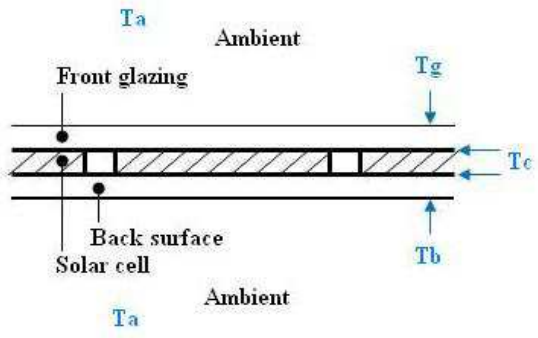

Figure 7: Photovoltaic module component

4.1 Front glazing

Consider the front glazing of the PV module reached by irradiance G as shown in figure 8.

The energy balance yields

$$\rho_g \delta_g C_g \frac{dT_g}{dt} =$$

$$G_{abs,g} + H_{cond,g} - H_{conv,g} - H_{rad,g-a} \quad (24)$$

where ρ_g is the density of front glazing, δ_g is the thickness of the front glazing, C_g is the capacity heat of the front glazing, T_g is the temperature of front glazing, t is the time, $G_{abs,g}$ is the irradiation absorbed by the front glazing, $H_{cond,g}$ is the conduction heat in the front glazing, $H_{conv,g}$ and $H_{rad,g}$ are respectively the convection heat and the radiation from the top of front glass to ambient.

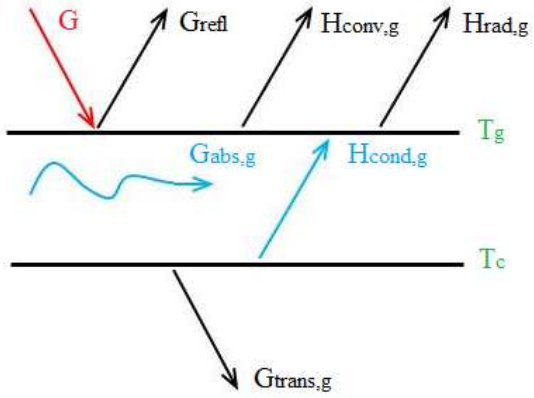

Figure 8: Front glazing energy exchange

4.2 Solar cells

For the solar cells, the irradiance $G_{trans,c}$ transmitted from the front glazing to solar cells is converted into energy $G_{abs,c}$ absorbed by solar cells and heat what is lost at the top and back sides of solar cells. Considering the energy exchange indicated in figure 9 we obtain equation 25

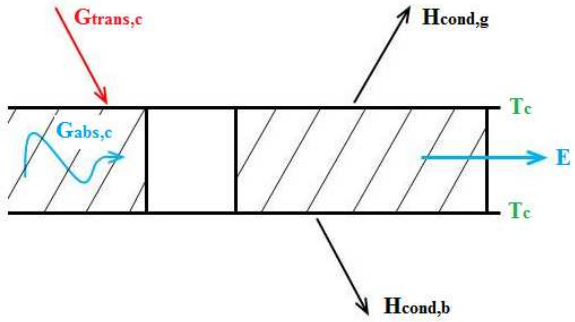

Figure 9: Solar cells input and output energies

$$\rho_c \delta_c C_c \frac{dT_c}{dt} =$$

$$G_{trans,g-c} - H_{cond,g} - H_{cond,b} - E \quad (25)$$

where ρ_c is the density of solar cells, δ_c is the thickness of solar cells, C_c is the heat capacity of the solar cells, $G_{trans,g-c}$ the energy from the front glazing absorbed by solar cells, $H_{cond,b}$ is the conduction heat in the back surface, E is the output electrical energy.

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4.3 Back surface

Figure 10 shows the input and output energies for the back surface of a PV module. Using the same principles as for the previous two cases, we obtain the equation (26)

$$\rho_b \delta_b C_b \frac{dT_b}{dt} = \quad (26)$$

$$G_{trans,g-b} + H_{cond,b} - H_{conv,b} - H_{rad,b-a}$$

where ρ_b is the density of back surface, δ_b is the thickness of back surface, C_b is the heat capacity of back surface, T_b is the temperature of back surface $G_{trans,g-b}$ is the energy transmitted from front glazing to back surface, $H_{conv,b}$ and $H_{rad,b}$ is respectively the convection heat and the radiation from back surface to ambient.

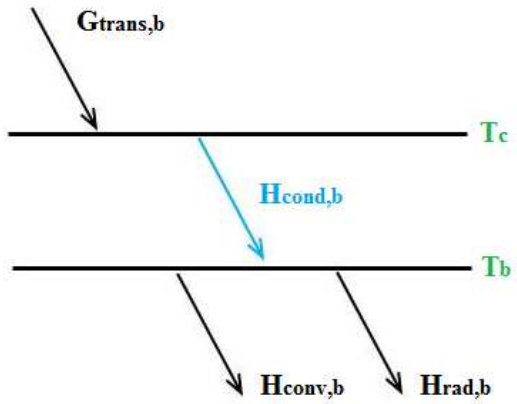

Figure 10: Back surface energy exchange

For steady state; equations 24 to 26 become

$$G_{abs,g} + H_{cond,g} - H_{conv,g} - H_{rad,g-a} = 0 \quad (27)$$

$$G_{trans,g-c} - H_{cond,g} - H_{cond,b} - E = 0 \quad (28)$$

$$G_{trans,g-b} + H_{cond,b} - H_{conv,b} - H_{rad,b-a} = 0 \quad (29)$$

With:

- Solar energy absorbed by front glazing:

$$G_{abs,g} = \alpha_g G \quad (30)$$

- Solar energy transmitted by front glazing to solar cells and back surface:

$$G_{trans,g} = \tau_g G \quad (31)$$

- Heat transfer from solar cells to top of front glazing:

$$H_{cond,g} = U_{c-g}(T_c - T_g) \quad (32)$$

- Heat transfer from top of front glazing to ambient:

$$H_{conv,g} = h_w(T_g - T_a) \quad (33)$$

- Heat transfer front glazing to ambient by radiation:

$$H_{rad,g-a} = h_{rad,g-a}(T_g - T_a) \quad (34)$$

- Solar energy transmitted to solar cells:

$$G_{trans,g-c} = \beta_c \tau_g G \quad (35)$$

- Solar energy absorbed by solar cells:

$$G_{abs,c} = \alpha_c \beta_c \tau_g G \quad (36)$$

- Heat transfer from solar cells to back side of back surface:

$$H_{cond,b} = U_{c-b}(T_c - T_b) \quad (37)$$

- Photovoltaic module output electrical energy:

$$E = \eta_c \beta_c \tau_g G \quad (38)$$

- Solar energy transmitted to the back surface:

$$G_{trans,g-b} = (1 - \beta_c)\tau_g G \quad (39)$$

- Solar energy absorbed by the back surface:

$$G_{abs,b} = \alpha_b(1 - \beta_c)\tau_g G \quad (40)$$

- Heat transfer from top of back surface to ambient:

$$H_{conv,b} = h_w(T_b - T_a) \quad (41)$$

- Heat transfer from back surface to ambient by radiation:

$$H_{rad,b-a} = h_{rad,b-a}(T_b - T_a) \quad (42)$$

The solar energy transmitted by the glass to the solar cells and the back surface thus consists of two components:

$$G_{trans,g} = G_{trans,g-c} + G_{trans,g-b} \quad (43)$$

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From equations (4), (5), (6) and neglecting radiation heat transfer from both surfaces to ambient, we obtain the system of equations below:

$$\begin{bmatrix} h_w + U_{c-g} & -U_{c-g} & 0 \\ U_{c-g} & -(U_{c-g} + U_{c-b}) & U_{c-b} \\ 0 & -U_{c-b} & h_w + U_{c-b} \end{bmatrix} \begin{bmatrix} T_g \\ T_c \\ T_b \end{bmatrix} = \begin{bmatrix} \alpha_g G + h_w T_a \\ \beta_c \tau_g (\eta_c - 1) G \\ \tau_g (1 - \beta_c) G + h_w T_a \end{bmatrix} \quad (44)$$

And solving equation (20), we obtain the solar cell temperature:

$$T_c = \frac{G[\xi_g \alpha_g - \tau_g \beta_c (\eta_c - 1) + \xi_b \tau_g (1 - \beta_c)] + (\xi_g + \xi_b) h_w T_a}{(\xi_g + \xi_b) h_w} \quad (45)$$

Where:

- Front glazing dimensionless coefficient:

$$\xi_g = \frac{U_{c-g}}{h_w + U_{c-g}} \quad (46)$$

- Back surface dimensionless coefficient:

$$\xi_b = \frac{U_{c-b}}{h_w + U_{c-b}} \quad (47)$$

- Heat transfer coefficient from solar cells to top of front glazing:

$$U_{c-g} = \frac{k_g}{\delta_g} \quad (48)$$

- Heat transfer coefficient from solar cells to back side of back surface

$$U_{c-b} = \frac{k_b}{\delta_b} \quad (49)$$

And the convective heat transfer coefficient under wind is given by (Watmuff *et al.*, 1977) [17] .

$$h_w = 2.8 + 3.0 v_w \quad (50)$$

It is well-known that most of the solar radiation absorbed by a photovoltaic (PV) panel is not converted to electricity but contributes to increase the temperature of the module, thus reducing the electrical efficiency. All these effects must be considered in any model for photovoltaic module efficiency [18] .

The most known model is given by the following equation:

$$\eta_c = \eta_{cr}[1 - \lambda_c (T_c - T_r) + \gamma Log G] \quad (51)$$

where η_r is the reference module efficiency at a PV cell temperature Tr of 25 °C and at a solar irradiance G_o on the module equal to 1000 W/m²K. λ_c and γ are, respectively, the temperature and the solar irradiance coefficients for the PV module [18] [are mainly material properties, having average values of about 0.0045 K^{-1} and 0.12, respectively, for silicon modules. The latter, however, is usually taken as zero, so that equation (51) reduces to

$$\eta_c = \eta_{cr} - \mu_c (T_c - T_r) \quad (52)$$

Which represents the traditional simple linear expression for the PV electrical efficiency [19] ,
where

$$\mu_c = \lambda_c \eta_{cr} \quad (53)$$

Evans suggested using λ_c = 0.0048C^{-1} for a silicon module[20] .

From equations (51) and (52) we obtain the cell temperature, front glass and back surface temperature given below.

$$T_c = \frac{G[\xi_g \alpha_g - \tau_g \beta_c (\eta_{cr} + \mu_c T_r - 1) + \xi_b \tau_g (1 - \beta_c)] + (\xi_g + \xi_b) h_w T_a}{(\xi_g + \xi_b) h_w - \mu_c \beta_c \tau_g G} \quad (54)$$

$$T_g = \frac{1 - \xi_g}{h_w} \alpha_g G + T_a + \xi_g (T_c - T_a) \quad (55)$$

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$$T_b = \frac{1-\xi_b}{h_w}(1-\beta_c)\tau_g G + T_a + \xi_b(T_c - T_a) \quad (56)$$

4.4 Other methodologies

In the following we briefly comment on other methodologies previously developed and point to their limitations. The performance of a photovoltaic module is studied versus environmental variables such as solar irradiance, ambient temperature and wind speed. The most common manner to determine the cell temperature T_c consists in using the Normal Operating Cell Temperature (NOCT) developed by Nolay P. in 1987 [21]. The value of NOCT is given by the PV module manufacturer. T_c is then dependent on the ambient temperature T_a and on the solar irradiance G according to equation below:

$$T_c = T_a + (NOCT - 20℃)\frac{G}{800} \quad (57)$$

This simple method yields satisfying results if the PV modules are not roof-integrated [18].

In 2006 Mattei *et al.*[18] established the following model to predicted the PV cell temperature, model:

$$T_c = \frac{U_{PV}T_a + G[(\alpha\tau) - \eta_r - \beta\eta_r T_r]}{U_{PV} - \beta\eta_r G} \quad (58)$$

This simple model used a simple energy balance and neglecting the radiation effects and was developed with the PV module alone, i.e. without the absorber, the glass and the insulation.

In 2008, Skoplaki *et al.*[19] developed a simple semi-empirical explicit correlation for PV cell temperature and the corresponding efficiency form are proposed for modules of arbitrary mounting given below:

$$T_c = \frac{T_a + \left(\frac{G_T}{G_{NOCT}}\right)\frac{h_{w,NOCT}}{h_w}(T_{NOCT} - T_{a,NOCT})\left[1 - \frac{\eta_r}{(\alpha\tau)}(1+\beta_r T_r)\right]}{1 - \frac{\beta_r\eta_r}{(\alpha\tau)}\left(\frac{G_T}{G_{NOCT}}\right)\frac{h_{w,NOCT}}{h_w}(T_{NOCT} - T_{a,NOCT})} \quad (59)$$

They explicitly involve the three basic and readily available environmental variables, namely, solar irradiance, ambient temperature, and wind speed, as well as a dimensionless mounting parameter that is a measure of the integration level of a given installation. The proposed correlation ignores free-convection influences, which are small for all wind speeds, and radiation losses, which are important only at wind speeds of below 1 m/s and, therefore, should be used for wind speeds exceeding this.

The proposed model accounts for free convection for wind speed up to 1 m/s, and physical properties for different components of PV module, particularly the conduction heat transfer coefficients of the front glazing, the PV cells and the back insulation property that allow the PV module to be easily and quickly cooled. Like the three models above, our proposed correlation ignores the PV radiation heat transfer. Our model is simple and user friendly and does not refer to the NOCT.

5. SIMULATION AND VALIDATION

5.1 Model simulation

The mathematic model of PV module temperature is established and this behavior against the temperature change studied by analysis and comparison of different curves and numerical values for temperature and power output[22] at different irradiances and surrounding weather condition change by simulation in MATLAB® .

To simulate the PV module, a MATLAB® code based on a complete model of PV module that provides tables and graphs was written. This model combines both PV electricity model and thermal model and the equations of both electrical characteristics and thermal dynamic are implemented using MATLAB ® codes.

5.2 Experimental validation

To evaluate the cell temperature and output power of the proposed model, experimental data from Da-Yen University was used. The experimentation was done using the commercial Siemens SM46 PV module (see table 1) for different parameters such as sunlight irradiation, ambient temperature, and wind speed in real working conditions. The experiment setup consists of a Siemens SM46 PV module, MPPT controller (SunSaver-10), storage battery, electric fan as a load, and some instrument. The experiment rig was set up in the Energy Research and Development Center (ERDC) of Da-Yeh University in Taiwan[23] .

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5.3 Measurement results and model validation

All observations of sunlight irradiance, temperatures, operating voltage and output currents of the SM46 PV module were recorded at 5-min intervals [23].

Taking a typical cloudy day (2011/07/07), the weather variations are depicted in figure 11.

Characteristics	Specification
Typical peak power (P_{MPP})	46 W
Voltage at peak power (V_{MPP})	14.6 V
Current at peak power (I_{MPP})	3.15 A
Short-circuit current (I_{SC})	3.35 A
Open-circuit voltage (V_{OC})	18.0 V
Temperature coefficient of open-circuit voltage	-77 mV/°C
Temperature coefficient of short-circuit current	1.2 mA/°C
Approximate effect of temperature on power	-0.38 W/°C
Nominal operating cell temperature (NOCT)	45 °C

Table 1: Siemens SM 46 Specifications (1 kW/m², 25 °C)

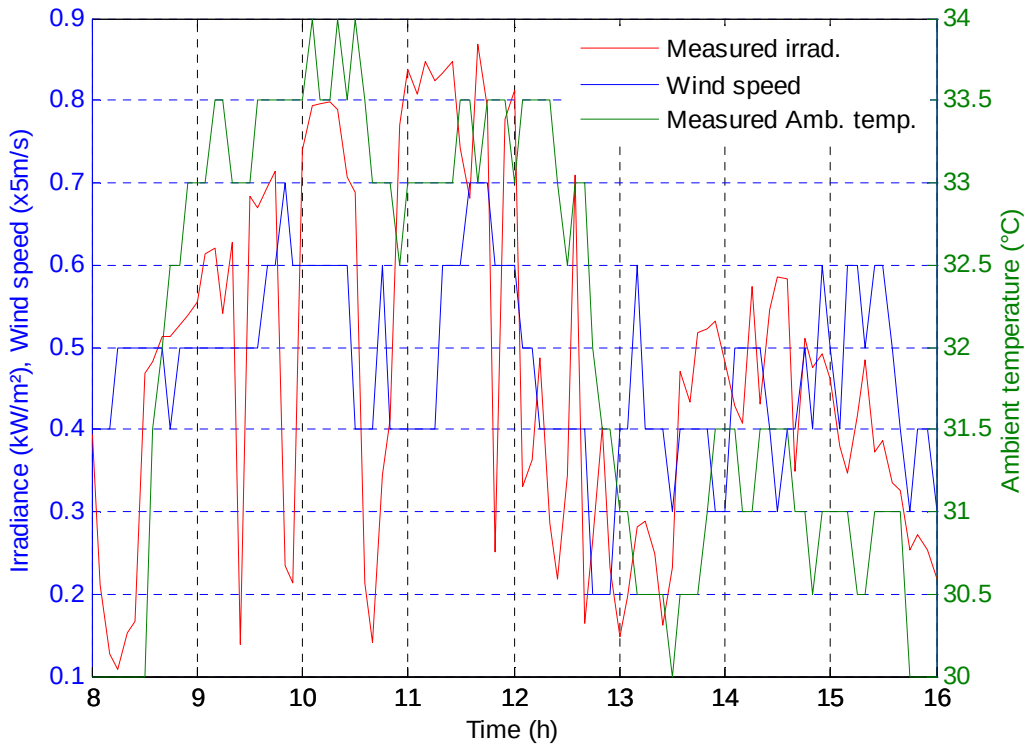

Figure 11: Local weather conditions of typical cloudy day (2011/07/07)

Based on the local weather conditions, the simulated cell temperature of the proposed model and the measured cell temperature are depicted in figure 12a. The results strongly indicate that the simulated cell temperature has a positive bias away from the measured temperature and the simulated cell temperature has a better agreement.

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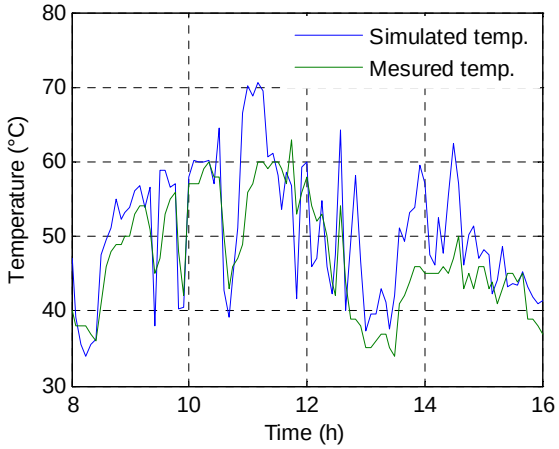
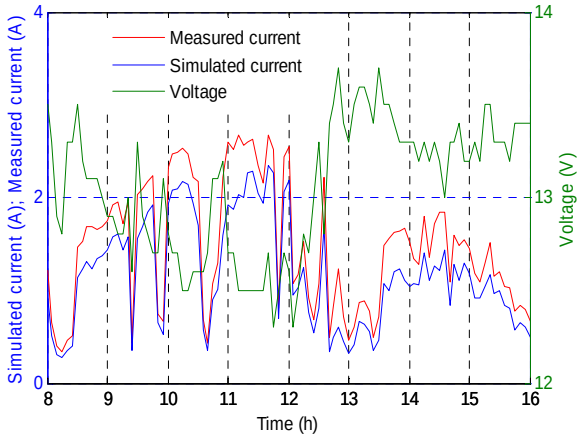
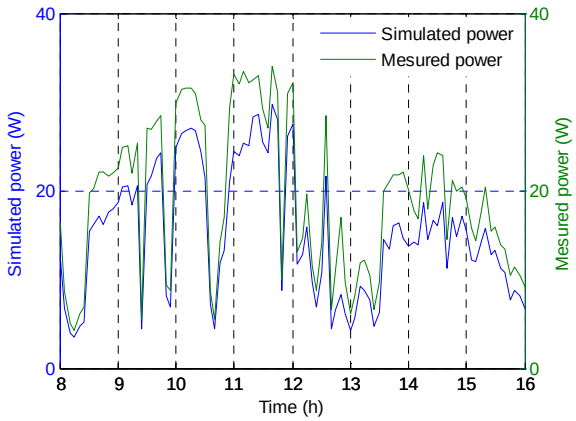


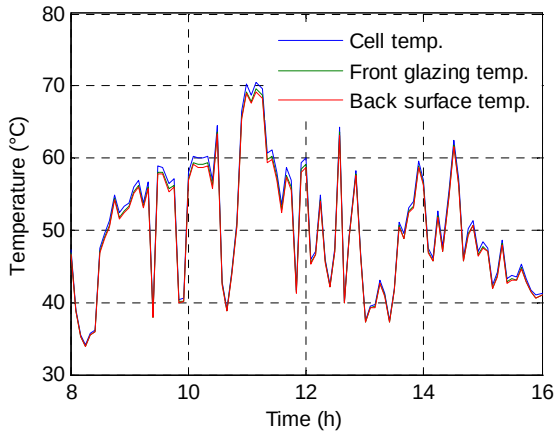
a. Simulated and measured cell temperatures



b. Simulated and measured currents and voltage



c. Simulated and measured power



d. Cell, front glazing and back surface temperatures

Figure 12. Temperature and energy response of SM46 for a typical cloudy day (2011/07/07)

Figure 12b demonstrates the measured operating voltage and output current of the SM46 PV module. The corresponding values of both simulated and measured current at the measured voltage are also depicted in figure 12b.

Figure 12c illustrates the associated output power. It is apparent that both simulated current and power have a better agreement with those measured.

For a typical sunny day (2011/07/08), the weather conditions are shown in figure 13. Both simulated and measured cell temperatures are shown in figure 14a. The agreement between simulated cell temperature and measured temperature is getting worse and a positive bias of temperature difference between the simulated cell temperatures and measured cell temperature is demonstrated.

The root mean square (rms) of the temperature differences are calculated and listed in table 2. In addition, the root mean square operations of the output current and power differences are also calculated and listed in table 2. The simulated results of the integrated thermal dynamics and electricity PV model have a close agreement with the measurement for both cloudy and sunny weather conditions.

6. CONCLUSIONS

The PV module temperature model combined with the electrical model was simulated and results were compared to experimental results for typical cloudy day and typical sunny day.

The simulated output characteristics of the proposed PV model is generally close to operating module with better

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accuracy, which has been validated through short period of experimental measurement under real operating conditions.

The study shows that a model that takes account of irradiance, environmental parameters and physical properties of a PV module can be used as a powerful tool for design, parameter analysis and diagnostic of commercial as well as do-it-yourself (DIY) PV modules under outdoor conditions.

It can also be used for developing and evaluating new maximum power point tracking techniques and to study the effects physical components have on PV panels with different configurations.

The proposed model takes into account not only irradiance and meteorological conditions, but also the physical properties of materials used in the manufacture of a PV module which makes the model much more flexible in the prediction of the production of energy for commercial PV as well as DIY in field conditions.

Based on a verified PV model, this available information can be further used for predicting the PV output characteristics and for further model-based diagnosis applications.

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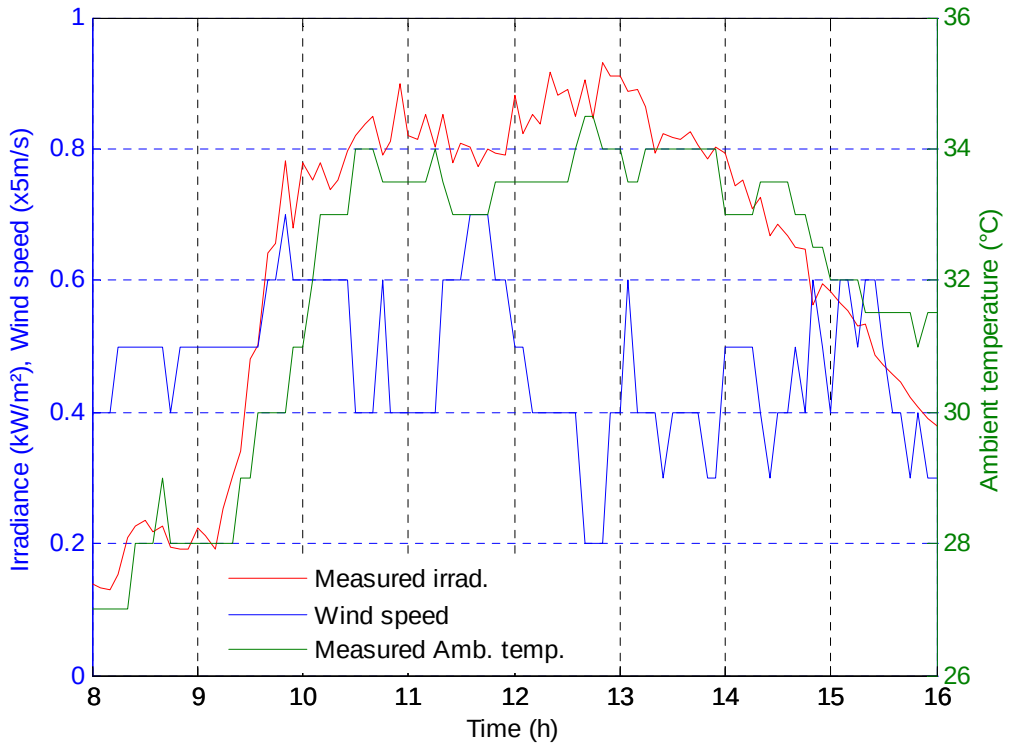

Figure 13: Local weather conditions of typical sunny day (2011/07/08)

rms	Typical cloudy day (2011/07/07)	Typical sunny day (2011/07/08)
Rms (ΔT) (°C)	6.4943	6.1968
rms (ΔI) (A)	0.3356	0.3627
rms (ΔE) (W)	4.3762	4.5895

Table 2: Root mean square analysis (rms) of cell temperature, output current and power for simulated and measured values

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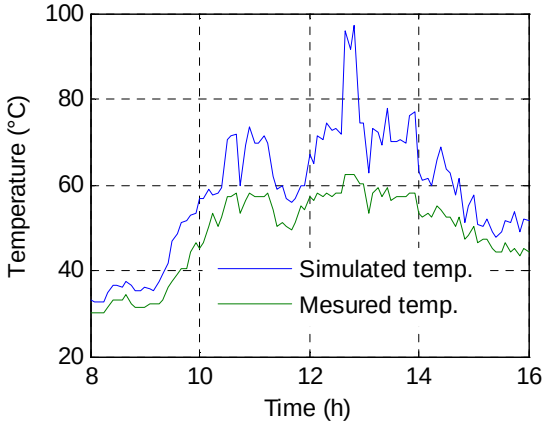
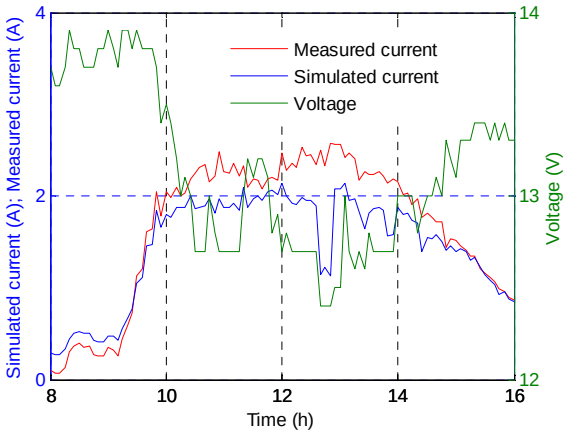
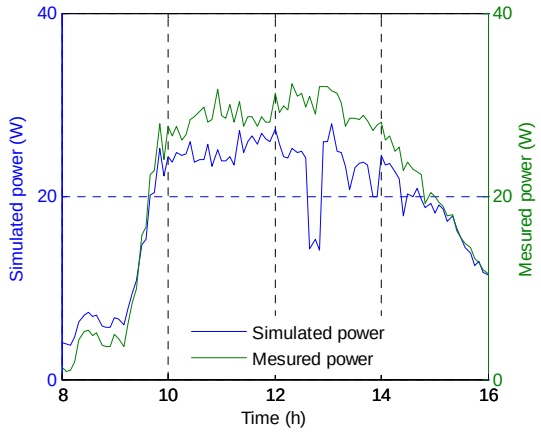


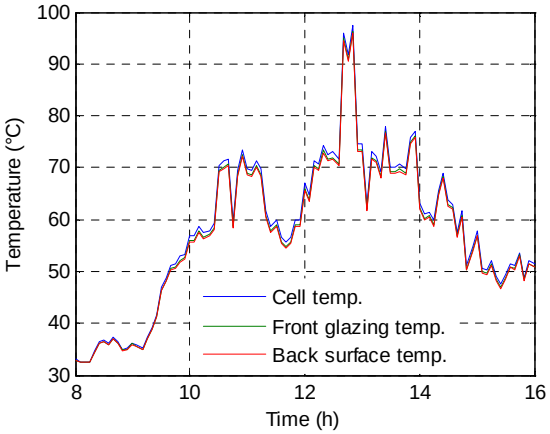
a. Simulated and measured cell temperatures



b. Simulated and measured currents and voltage



c. Simulated and measured powers



d. Cell, front glazing and back surface temperatures

Figure 14: Temperature and energy response of SM46 for a typical cloudy day (2011/07/08)

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