On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations

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Abstract

A brief discussion is presented regarding the operating temperature of one-sun commercial grade silicon-based solar cells/modules and its effect upon the electrical performance of photovoltaic installations. Suitable tabulations are given for most of the known algebraic forms which express the temperature dependence of solar electrical efficiency and, equivalently, solar power. Finally, the thermal aspects of the major power/energy rating methods are briefly discussed.

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Keywords: Solar cell; Photovoltaic module; PV module efficiency; PV power rating methods; Temperature dependence

1. Introduction

The pronounced effect that the operating temperature of a photovoltaic (PV) cell/module has upon its electrical efficiency is well documented. There are many correlations expressing $T_c$, the PV cell temperature, as a function of weather variables such as the ambient temperature, $T_a$, and the local wind speed, $V_w$, as well as the solar radiation flux/irradiance, $G_T$, with material and system-dependent properties as parameters, e.g., glazing-cover transmittance, $\tau$, plate absorptance, $\alpha$, etc.

An equally large number of correlations expressing the temperature dependence of the PV module’s electrical efficiency, $\eta_c$, can also be retrieved, although many of them assume the familiar linear form, differing only in the numerical values of the relevant parameters which, as expected, are material and system dependent. Many correlations in this category express instead the module’s maximum electrical power, $P_m$, which is simply related to $\eta_c$ through the latter’s definition ($\eta_c = P_m$ (under standard test conditions)/$AG_T$, with $A$ being the aperture area), and form the basis of various performance rating procedures.

2. PV module efficiency as a function of the operating temperature

The effect of temperature on the electrical efficiency of a PV cell/module can be traced to the former’s influence upon the current, $I$, and the voltage, $V$, as the maximum power is given by

$$P_m = V_m I_m = (FF)V_{oc}I_{sc}$$ (1)

In this fundamental expression, which also serves as a definition of the fill factor, $FF$, subscript $m$ refers to the maximum power point in the module’s $I-V$ curve, while subscripts $oc$ and $sc$ denote open circuit and short circuit

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1 100 mW/cm$^2$(=1000 W/m$^2$) solar flux conforming to the standard reference AM 1.5 G spectrum, and temperature 298.16 K (25 °C). The use of this flux value is very convenient, as the efficiency in percent is numerically equal to the power output in mW/cm$^2$ (Markvart, 2000).
values, respectively. It turns out that both the open circuit voltage and the fill factor decrease substantially with temperature (as the thermally excited electrons begin to dominate the electrical properties of the semiconductor), while the short-circuit current increases, but only slightly (Zondag, 2007). Thus, the net effect leads to a linear relation in the form

$$g = \frac{g_{T_{\text{ref}}}}{C_0} \cdot \frac{1}{b_{\text{ref}}} \cdot \frac{T_c - T_{\text{ref}}}{C_0} + \frac{c \log_{10} G_T}{C_2 C_3}$$

in which $g_{T_{\text{ref}}}$ is the module’s electrical efficiency at the reference temperature, $T_{\text{ref}}$, and at solar radiation flux of 1000 W/m² (Evans, 1981). The temperature coefficient, $b_{\text{ref}}$, and the solar radiation coefficient, $c$, are mainly material properties, having values of about 0.004 K⁻¹ and 0.12, respectively, for crystalline silicon modules (Notton et al., 2005). The latter, however, is usually taken as zero (Evans, 1981), and Eq. (2) reduces to

$$g = \frac{g_{T_{\text{ref}}}}{C_0} \cdot \frac{1}{b_{\text{ref}}} \cdot \frac{T_c - T_{\text{ref}}}{C_0}$$

which represents the traditional linear expression for the PV electrical efficiency (Evans and Florschuetz, 1977).

The quantities $g_{T_{\text{ref}}}$ and $b_{\text{ref}}$ are normally given by the PV manufacturer. However, they can be obtained from flash tests in which the module’s electrical output is measured at two different temperatures for a given solar radiation flux (Hart and Raghuraman, 1982). The actual value of the temperature coefficient, in particular, depends not only on the PV material but on $T_{\text{ref}}$, as well. It is given by the ratio

$$\beta_{\text{ref}} = \frac{1}{T_0 - T_{\text{ref}}}$$

in which $T_0$ is the (high) temperature at which the PV module’s electrical efficiency drops to zero (Garg and Agarwal, 1995). For crystalline silicon solar cells this temperature is 270 °C (Evans and Florschuetz, 1978).

In a number of correlations, the cell/module temperature – which is not readily available – has been replaced by $T_{\text{NOCT}}$, i.e., by the nominal operating cell temperature (see below). One such expression is

$$\eta = n_{\text{ref}} \left( 1 - \beta_{\text{ref}} \left( T_a - T_{\text{ref}} \right) + \left( T_{\text{NOCT}} - T_a \right) \frac{G_T}{G_{\text{NOCT}}} \right)$$

which can be obtained by substitution of a well known expression for $T_c$ (Kou et al., 1998), namely,

$$T_c = T_a + \left( \frac{G_T}{G_{\text{NOCT}}} \right) \left( \frac{U_{L_{\text{NOCT}}}}{U_L} \right) \left( T_{\text{NOCT}} - T_{a,\text{NOCT}} \right) \left[ 1 - \left( \eta / \tau_{\text{w}} \right) \right]$$

into Eq. (3) and using the fact that $(\eta / \tau_{\text{w}}) \ll 1$ (Duffie and Beckman, 2006).
In addition to the “instantaneous” values for the PV electrical efficiency, expressions can be written for the monthly average efficiency, $\bar{\eta}_e$. For example, the monthly electrical energy output of a PV array can be estimated on the basis of the following equation:

$$\bar{\eta}_e = \eta_{ref} \left[ 1 - \beta_{ref} \left( T - T_{ref} \right) - \frac{\beta_{ref} \sqrt{H_T}}{nU_L} \right] \tag{7}$$

in which the over-bar denotes monthly average quantities, $n$ is the number of hours per day, $U_L$ is the overall thermal loss coefficient, $H_T$ is the monthly average daily insolation on the plane of the array, and $T$ is a dimensionless function of such quantities as the sunset angle, the monthly average clearness index, and the ratio of the monthly total radiation on the array to that on a horizontal surface (Siegel et al., 1981).

A number of equations found in the literature for the efficiency of PV cells/modules are shown in Tables 1 and 2. The first table contains values for the parameters of Eq. (3), as reported by a number of authors, and the second presents additional forms for $\gamma_e$, including pertinent comments for each correlation. On the basis of data listed in Table 1 for $T_{ref} = 25^\circ C$, average $\eta_{ref} \approx 0.12$ and average $\beta_{ref} \approx 0.0045 \, ^\circ C^{-1}$. The effect of the temperature coefficient upon the efficiency of various silicon-based PV module types is shown in Fig. 1, where the Evans–Florschuetz ratio $\eta_e/\eta_{ref}$ is plotted against the operating temperature.

The quantities labeled as NOCT are measured under open-circuit conditions (i.e., with no load attached) while operating in the so-called nominal terrestrial environment (NTE), which is defined as follows (Stultz and Wen, 1977):

- Global solar flux: 800 W/m$^2$,
- Air temperature: 293.16 K (20 $^\circ C$),
- Average wind speed: 1 m/s,
- Mounting: open rack, tilted normally to the solar noon sun.

With symbols, $\text{NOCT} = (T_e - T_{e,NTE}) + 20 \, ^\circ C$. This quantity is determined from actual measurements of cell temperature for a range of environmental conditions similar to the NTE and reported by the module’s manufacturer

<table>
<thead>
<tr>
<th>$T_{ref}$ (°C)</th>
<th>$\eta_{ref}$</th>
<th>$\beta_{ref}$ (°C$^{-1}$)</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0.15</td>
<td>0.0041</td>
<td>Mono-Si</td>
<td>Evans and Florschuetz (1977)</td>
</tr>
<tr>
<td>28</td>
<td>0.17 (average)</td>
<td>0.00338 (average) (0.0104-0.124)</td>
<td>Average of Sandia and commercial cells</td>
<td>OTA (1978)</td>
</tr>
<tr>
<td>25</td>
<td>0.11</td>
<td>0.003</td>
<td>Mono-Si</td>
<td>Truncellito and Sattolo (1979)</td>
</tr>
<tr>
<td>25</td>
<td>0.13</td>
<td>0.0041</td>
<td>PV/T system</td>
<td>Mertens (1979)</td>
</tr>
<tr>
<td>20</td>
<td>0.10</td>
<td>0.004</td>
<td>PV/T system</td>
<td>Barra and Coiante (1993)</td>
</tr>
<tr>
<td>25</td>
<td>0.10</td>
<td>0.0041</td>
<td>PV/T system</td>
<td>Prakash (1994)</td>
</tr>
<tr>
<td>20</td>
<td>0.125</td>
<td>0.004</td>
<td>PV/T system</td>
<td>Garg and Agarwal (1995)</td>
</tr>
<tr>
<td>25</td>
<td>0.13</td>
<td>0.004</td>
<td>Mono-Si</td>
<td>Garg and Garg (1994)</td>
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<td>25</td>
<td>0.11</td>
<td>0.004</td>
<td>Mono-Si</td>
<td>Garg et al. (1994)</td>
</tr>
<tr>
<td>25</td>
<td>0.178</td>
<td>0.00375</td>
<td>PV/T system</td>
<td>Hegazy (2000)</td>
</tr>
<tr>
<td>25</td>
<td>0.05</td>
<td>0.0011</td>
<td>a-Si</td>
<td>Yamawaki et al. (2001)</td>
</tr>
<tr>
<td>25</td>
<td>0.11</td>
<td>0.004</td>
<td>Mono-Si</td>
<td>RETScreen (2001)</td>
</tr>
<tr>
<td>25</td>
<td>0.12</td>
<td>0.0045</td>
<td>Mono-Si</td>
<td>Nagano et al. (2003)</td>
</tr>
<tr>
<td>25</td>
<td>0.097</td>
<td>0.0045</td>
<td>PV/T system</td>
<td>Tobias et al. (2003)</td>
</tr>
<tr>
<td>25</td>
<td>0.097</td>
<td>0.0045</td>
<td>PV/T system</td>
<td>Chow (2003)</td>
</tr>
<tr>
<td>25</td>
<td>0.0968</td>
<td>0.0045</td>
<td>PV/T system</td>
<td>Zondag et al. (2003)</td>
</tr>
<tr>
<td>25</td>
<td>0.0968</td>
<td>0.0045</td>
<td>UTC/PV system</td>
<td>Radziemska (2003)</td>
</tr>
<tr>
<td>25</td>
<td>0.09</td>
<td>0.0045</td>
<td>PV/T system</td>
<td>Bakker et al. (2005)</td>
</tr>
<tr>
<td>25</td>
<td>0.12</td>
<td>0.0045</td>
<td>PV/T system</td>
<td>Naveed et al. (2006)</td>
</tr>
<tr>
<td>25</td>
<td>0.12</td>
<td>0.0045</td>
<td>PV/T system</td>
<td>Tiwari and Sodha (2006a)</td>
</tr>
<tr>
<td>25</td>
<td>0.12</td>
<td>0.0045</td>
<td>PV/T system</td>
<td>Tiwari and Sodha (2006b)</td>
</tr>
<tr>
<td>25</td>
<td>0.12</td>
<td>0.0045</td>
<td>PV/T system</td>
<td>Zondag (2007)</td>
</tr>
<tr>
<td>25</td>
<td>0.12</td>
<td>0.0045</td>
<td>PV/T system</td>
<td>Tiwari and Sodha (2007)</td>
</tr>
<tr>
<td>25</td>
<td>0.12</td>
<td>0.0045</td>
<td>PV/T system</td>
<td>Assoa et al. (2007)</td>
</tr>
<tr>
<td>25</td>
<td>0.127</td>
<td>0.0063</td>
<td>PV/T system</td>
<td>Tonui and Tripanagnostopoulos (2007a)</td>
</tr>
<tr>
<td>25</td>
<td>0.127</td>
<td>0.0063</td>
<td>PV/T system</td>
<td>Tonui and Tripanagnostopoulos (2007b)</td>
</tr>
<tr>
<td>25</td>
<td>0.117</td>
<td>0.0054</td>
<td>PV/T system</td>
<td>Othman et al. (2007)</td>
</tr>
</tbody>
</table>

Notes:
- At $T_{ref} = 25^\circ C$, average $\eta_{ref} \approx 0.12$ and average $\beta_{ref} \approx 0.0045 \, ^\circ C^{-1}$.
- The same correlation has been adopted in Hart and Raghuraman (1982), Cox and Raghuraman (1985), Sharan and Kandpal (1987), and Sharan et al. (1987), although no numerical values are given for the parameters.
Table 2
PV array efficiency as a function of temperature.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Comments</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_T = \eta_{ref}[1 - \beta_T(T - T_{ref})]$</td>
<td>$T_{ref} = 25 \degree C$, $\eta_{ref} = 0.15$, $\beta_T = 0.0041 \degree C^{-1}$, c-Si, $T$ in $\degree C$</td>
<td>Evans and Florschuetz (1977)</td>
</tr>
<tr>
<td>$\eta_{PV} = \eta_{ref} - \mu(T_c - T_{ref})$</td>
<td>$\mu = $ overall cell temperature coefficient</td>
<td>Bazilian and Prasad (2002)</td>
</tr>
<tr>
<td>$\eta = n_a - c(T - T_a)$</td>
<td>$T = $ mean solar cell temp, $n_a = $ efficiency at $T_a$, $c = $ temperature coefficient</td>
<td>Bergene and Løvvik (1995)</td>
</tr>
<tr>
<td>$\eta(G_T, T_c) = \eta(G, 25 \degree C)[1 + c_3(T - 25)]$</td>
<td>$b = b(G_T)$, $T$ in $\degree C$, $c_3 = -0.5$ (%) loss per $\degree C$ for c-Si, $-0.02, \ldots, -0.41$ for thin film cells</td>
<td>Durisch et al. (1996)</td>
</tr>
<tr>
<td>$\eta_T = \eta_0 - K(T^{1/4} - T_0^{1/4})$</td>
<td>$T_0 = 273 K$, $K = 22.4$</td>
<td>Mohring et al. (2004)</td>
</tr>
<tr>
<td>$\eta = n_a \times k_1 \times k_2 \times k_3 \times k_4$ with $k_i = 1 - \gamma(T_i - 25)/100$</td>
<td>$k_1 = $ power temperature coefficient, $k_2, j = 0, \alpha, \lambda$, optical absorption, spectrum correction factors</td>
<td>Ravindra and Srivastava (1979/80)</td>
</tr>
<tr>
<td>$T_{ambient} = G_T/1000$</td>
<td>$\eta = $ monthly average efficiency, $V = $ dimensionless, $15%$ low predictions, $\beta_{T_{average}} = 0.004 \degree C^{-1}$</td>
<td>Siegel et al. (1981)</td>
</tr>
<tr>
<td>$\eta = \eta_{ref} - \alpha_1(T - T_{ref}) + \alpha_2 \ln(G_T/1000)$</td>
<td>$\eta = $ monthly average efficiency, $\beta_{T_{average}} = 0.004 \degree C^{-1}, \gamma \sim 0.12$</td>
<td>Siegel et al. (1981)</td>
</tr>
</tbody>
</table>

Notes:
- In Oshiro et al. (1997): KPT cell temperature factor.
- In Jardim et al. (2008): NOCT-corrected efficiency.
- With MPTC = $-0.5\%$ loss per $\degree C$, the efficiency is $\eta = 11.523 - 0.0512 T_c$.

(Kirpich et al., 1980). When a module operates at NOCT, the term “standard operating conditions” (SOC) is sometimes used.

The open rack mounting condition, i.e., fixing the modules on a free-standing open to the ambient frame, seemed at first to prohibit the use of NOCT-based correlations in the recently popular BIPV modeling/design. As the possible error in the $T_c$ value could be as high as $20 \degree K$ (Davis et al., 2001). The ever-increasing interest in BIPV applications, however, brought forward the need for a proper estimation of NOCT which would take into account the integration-dependent deviation from NTE conditions. That is, the proper NOCT to use should accommodate the BIPV encountered angles of incidence of say 90°, and not just 0°, as well as the observed higher module-back tempera-
Fig. 1. The ratio $\eta_f/\eta_{ref}$ as predicted by the Evans–Florschuetz efficiency correlation for typical silicon-based PV module types.

3. PV power output dependence on module operating temperature

The prediction of PV module performance in terms of electrical power output in the field, that is, the deviation from the standard test conditions reported by the manufacturer of the module, is modeled in a manner analogous to the above. For example, a recently proposed correlation of the module, is modeled in a manner analogous to the standard test conditions reported by the manufacturer, like the BIPV test facility at the US National Institute of Standards and Technology (Fanney and Dougherty, 2001) or the European Commission’s Test Reference Environment (TRE) rig that was recently set up at the JRC Ispra, specially for BIPV testing (Bloem, 2008).

Fig. 2. BIPV mounting induced temperature difference from NOCT as a function of irradiance (Bloem, 2008).

$P_{mp} = d_1 G_T + d_2 T_c + d_3 [\ln(G_T)]^m + d_4 T_c [\ln(G_T)]^m$ (9)

resulting from an analysis which addresses the fact that the cells within a module are not identical. (Here, $d_i, j = 1-4$ and $m$ are model parameters.) Another unusual nonlinear correlation (Furusshima et al., 2006) gives a correction coefficient for the output power – as defined by Eq. (1) – of a water cooled PV system, namely,

$P = V_c I_c \left[1 - \frac{G_T - 500}{2 \times 10^4} + \frac{C_{T_c}}{4 \times 10^4} (50 - T_c)^2 \right]$ (10)

in which $V_c$ and $I_c$ are the output voltage and current, respectively, while the parameter $C_{T_c}$ takes values 1 or 3, for values of $T_c$ below or above 50 °C, respectively.

Aside from correlations like those listed in Table 3, there are a few expressions which are trying to predict the power output of PV modules without direct reference to temperature, either the operating temperature or the ambient one. (Two such equations are given in the “notes” at the end of Table 3.) It is expected that correlations of this kind over-predict the performance of the modules.

With regard to the wind’s indirectly beneficial effect of lowering the operating temperature by forced convection and, thus, increasing the power output of the modules, it is considered in only two correlations among those in the listing of Table 3 – which by no means is exhaustive. The relevant expression, that of the photovoltaics for utility scale application (PVUSA) model (Farmer, 1992), is of the form

$P = G_T (b_1 + b_2 G_T + b_3 T_a + b_4 V_f)$ (11)

In this nonlinear equation, $V_f$ is the free-stream local wind speed, i.e., it is measured at a height of 10 m above ground, and the regression coefficients $b_j, j = 1-4$ are determined using solar radiation flux values above 500 W/m² (Meyer and van Dyk, 2000). In contrast, the wind speed is taken into account in many correlations for the efficiency (cf. Table 2), either directly or indirectly, i.e., through the forced convection coefficient component of $U_L$.
<p>Table 3</p>Table 3: PV array power as a function of temperature P = η<sub>A</sub>Gr<sub>T</sub>.

<table>
<thead>
<tr>
<th>Correlation</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ P = \eta_A Gr(T) (1 + \delta(T)\ln(\frac{T}{T_0})) ]</td>
<td>( \delta(T) ) is an offset ( \delta(T) ) is an offset</td>
<td>E. Skoplaki, J.A. Palyvos / Solar Energy 83 (2009) 614–624</td>
</tr>
<tr>
<td>[ P = \eta_A Gr(T) (1 - \beta(T - T_0) ) ]</td>
<td>( \beta(T - T_0) ) is a slope</td>
<td>E. Skoplaki, J.A. Palyvos / Solar Energy 83 (2009) 614–624</td>
</tr>
</tbody>
</table>

Notes:
- Ref. Bürcher et al. (1998) reports PV power temperature coefficients for various module types in the range [-0.0022/K to 0.0071/K], values around -0.002 referring to a-Si.
- Ref. Fatih and Salem (2007) reports a dimensional expression for “power” – actually specific energy!
- Energy production correlation \( E_{out} \) (W hr) = \( (q_{a} + q_{T}) \) \( E \) (W hr/m<sup>2</sup>), with 36.41 \( \leq q_{a} \leq 44.14 \) and -0.20 \( \leq q_{T} \leq -0.16 \) is given in del Cueto (2001).
- Daily energy production (W h/day) is given by \( E = A_{r} H + A_{s} H_{max} \) for \( T_{n} = 25 ^{\circ}C \) the maximum ambient temperature (C), \( H_{max} = \) the daily total insolation (W h/m<sup>2</sup>/day) and \( A_{r} \) efficiency parameters.
- Ref. Zhou et al. (2007) presents an expression for \( P_{max} \) based on BIPV data, which, for two states 0 and 1, is proportional to \( (T_{0}/T_{1})^{\gamma} \) with \( \gamma = \frac{1}{0.01516} \).
- There are few equations with no explicit temperature dependence. Among them, the single regression yearly average form \( P_{p} = 0.1103 G_{r} T_{s} \) (Liu et al., 2004) and the nonlinear expression \( P = c_{1} G_{r} + c_{2} G_{r}^{2} + c_{3} G_{r} \ln G_{r} \), with \( c_{j} \) regression coefficients, known as the ENRA model (Giancoli Rossi and Krebs, 1988), which over-predicts the PV performance.
- The \( V_{o} \) and \( I_{o} \) expressions have been combined as in Eq. (1).
- The regression equation shown combines the original equation for \( P \) and the analogous expression for \( T_{o} \).
- For pc-Si, \( D_{1} = 0.000554, D_{2} = -7.275 \times 10^{-2}, D_{3} = 2.242 \times 10^{-2}, D_{4} = -4.763 \times 10^{-4}, m = 7.0306 \). Analogous sets are given for c-Si, a-Si, and thin film modules.
An interesting question, at this point, is whether the electrical efficiency or power which is “lost” at higher than $T_{ref}$ operating temperatures can be compensated by the rejected thermal energy. It can be shown that if a low enthalpy thermal load exists, it is better to accept the efficiency losses and directly utilize the rejected heat rather than to improve the electrical efficiency of the module in order to use a PV-powered heat pump to meet this thermal load (OTA, 1978). In hybrid systems such as PV/thermal (PV/T) modules, on the other hand, the temperature effect can be as small as 2% on an annual basis or even purely beneficial, as is the case with unglazed PV/T systems (Zondag, 2007).

4. Temperature involvement in module performance characterization methods

From the PV-system designer’s point of view, the ultimate interest is the proper sizing of the installation for a given service and, thus, the actual energy yield of the relevant array. In order to estimate the latter, the designer starts with the PV module manufacturer’s reported performance of his modules at standard test conditions (STC). But such energy/power figures are only useful for comparing the peak performance of different module makes and types. That is, the STC rating is not capable of predicting exactly how much energy a module will produce in the field, i.e., when operating under real conditions.

To this end, there are several proposals for a PV module’s energy rating procedure which would attempt to account for the varying operating conditions encountered in the field. In most cases, actual field measurements lead to a regression equation for power (or energy) that is based on a particular model and, having calculated the regression coefficients, a straightforward application to standard conditions gives the true power rating for the module (Taylor, 1986). Thus, the main differences between the proposed methods lie in the set of parameters used in the respective power/energy model, some of which are not always available, in the type of measurements employed to determine the pertinent values, and in the implicit compromise between accuracy and practicality.

One such popular method, as a result of the PVUSA activity mentioned in the previous section, involves a model which relates grid-connected photovoltaic system performance to the prevailing environmental conditions, i.e., it uses as parameters the total plane-of-array solar radiation flux, the ambient temperature, and the free-stream wind speed (cf. Eq. (11)). The regression analysis covers 28-day periods of measurements, using solar flux values above 500 W/m$^2$ and, therefore, it leads to the average power output of midday clear-sky in the particular location (Jennings, 1987). The power rating itself is calculated from Eq. (11) using $G_T = 1000$ W/m$^2$, $T_a = 20$ °C, and $V_f = 1$ m/s, and if the result is multiplied by the number of sun-hours (a total of 1000 Wh/m$^2$ equals 1 sun-hour) during a given time period, i.e., the reference yield, an energy rating is obtained for that period (Meyer and van Dyk, 2000). The use of $T_a$ incorporates in the rating the various thermal characteristics of module, array, and system, and the rating is closer to real life (Emery, 2003). On the negative side, the method is time consuming, as it requires continuous data recording over extended time periods, it is unsuitable for low solar flux values, and it ignores solar spectral and angle-of-incidence variations (King et al., 1998).

The spectral characteristics of the incident solar radiation, among other things, are taken into account in the more complicated module energy rating (MER) procedure, which was developed at the US National Renewable Energy Laboratory (NREL) for five reference days (“hot-sunny”, “cold-sunny”, “hot-cloudy”, “cold-cloudy”, and “nice day”) that represent different climatic conditions (Kroposki et al., 1996). The method employs laboratory tests in order to establish the electrical performance of a module and to determine correction factors for performance deviation from linearity, when module temperature and solar radiation flux vary. Using meteorological data for the reference days, module temperature and incident solar flux are calculated for each hour of the MER reference days, taking into account spectral and thermal response characteristics. The resulting PV module hourly $I-V$ curves for each one of the reference days are translated to actual $G_T$ and $T_c$ conditions, as required by the MER procedure, using the equations

$$I_{sc} = \frac{G_T}{G_{ref}}I_{sc0}\left[1 + \alpha(T_c - T_0)\right]$$

and

$$V_{oc} = V_{oc0}\left[1 + \beta(G_T/G_{ref})(T_c - T_0)\right]\left[1 + \delta(T_c)\ln\left(G_T/G_{ref}\right)\right]$$

in which $\alpha$ and $\beta$ are current and voltage correction coefficients for temperature, $\delta$ is a correction coefficient for solar radiation, and the subscript zero refers to SRC. Finally, a summation of the appropriate values – using Eqs. (1), (12), and (13) – from the hourly $I-V$ curves, will determine the MER reference energy rating for the particular module (Marion et al., 1999).

In contrast to the above methodologies, the US Sandia National Laboratories (SNL) method relies on outdoor periods of measurements, using solar flux values above 500 W/m$^2$ and, therefore, it leads to the average power output of midday clear-sky in the particular location (Jennings, 1987). The power rating itself is calculated from Eq. (11) using $G_T = 1000$ W/m$^2$, $T_a = 20$ °C, and $V_f = 1$ m/s, and if the result is multiplied by the number of sun-hours (a total of 1000 Wh/m$^2$ equals 1 sun-hour) during a given time period, i.e., the reference yield, an energy rating is obtained for that period (Meyer and van Dyk, 2000). The use of $T_a$ incorporates in the rating the various thermal characteristics of module, array, and system, and the rating is closer to real life (Emery, 2003). On the negative side, the method is time consuming, as it requires continuous data recording over extended time periods, it is unsuitable for low solar flux values, and it ignores solar spectral and angle-of-incidence variations (King et al., 1998).

The spectral characteristics of the incident solar radiation, among other things, are taken into account in the more complicated module energy rating (MER) procedure, which was developed at the US National Renewable Energy Laboratory (NREL) for five reference days (“hot-sunny”, “cold-sunny”, “hot-cloudy”, “cold-cloudy”, and “nice day”) that represent different climatic conditions (Kroposki et al., 1996). The method employs laboratory tests in order to establish the electrical performance of a module and to determine correction factors for performance deviation from linearity, when module temperature and solar radiation flux vary. Using meteorological data for the reference days, module temperature and incident solar flux are calculated for each hour of the MER reference days, taking into account spectral and thermal response characteristics. The resulting PV module hourly $I-V$ curves for each one of the reference days are translated to actual $G_T$ and $T_c$ conditions, as required by the MER procedure, using the equations

$$I_{sc} = \frac{G_T}{G_{ref}}I_{sc0}\left[1 + \alpha(T_c - T_0)\right]$$

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5 Instead of the terms standard “testing” or “reference” conditions, certain authors prefer the term standard reporting conditions (SRC), because measurements can be made at conditions other than the standard ones (cf. footnote 1) and then carefully “translated” to STC (Emery, 2003).

6 The temperature is calculated using $T_a f_1(G_T, T_a, V_f) \times NOCT + f_2(G_T, T_a, V_f)$, with $NOCT = NOCT - 3$ °C and $f_1, f_2$ the slope and the $y$-intercept in the $T_a$ versus $NOCT$ plot.
testing\(^7\) to determine the module/array performance parameters, it applies to all PV technologies, and, hopefully, is accurate enough for the needs of PV system designers (King et al., 1998). The method involves day-long \(I–V\) measurements with the module mounted on a two-axis tracker, a shade/un-shade procedure meant to determine temperature coefficients for the module’s electrical quantities, and a programmed sequence of moving the tracker at various off-set angles. In this way, the thermal, spectral, and angle-of-incidence influences are separately quantified and, thus, most of the five-equation model elements can be linearized. At the same time, the model equations remain consistent with solar cell physics (Kroposki et al., 2000), and this explains the versatility and accuracy of the overall method. As for the newer, empirical thermal model within the rating framework, it is simpler and more adaptable than the original rigorous one, providing, however, the same ±5 °C accuracy in the prediction of the PV module’s operating temperature. Finally, a noteworthy characteristic is that it relates in a simple way the PV cell’s temperature with the module’s back-side temperature (King et al., 2004).

A recent simpler approach incorporates existing standard measurements to determine the energy output as a function of only global in-plane irradiance and ambient temperature. The procedure involves use of standard measurement methods (indoor tests) in creating a “performance surface” for the module, as a function of \(G_T\) and \(T_a\). The prediction of energy production at a given location from the performance surface, requires a distribution surface of environmental conditions, which will indicate the probability of occurrence of any given combination of \(G_T\) and \(T_a\) for the location. If the daily variations of these two parameters are not available for the site, they can be modeled from daily or monthly-mean location data. The precise prediction of the annual energy production, then, involves calculations over one full year using the two surfaces (Anderson et al., 2000). The method has been successful in testing c-Si modules at the European Solar Testing Installation, and a proposal has been made for a simple energy rating labeling of the PV modules (Kenny et al., 2006).

Among the purely energy-based performance rating methods, which involve power integrated over time and comparison of this total energy produced with the corresponding incident solar energy, is the so-called “AM/PM” method, that was proposed by ARCO Solar (now Siemens Solar Industries). According to this method, the rating is based on the energy delivery during a standard solar day, with a given reference temperature and total solar radiation flux distribution. The aim at the time (Gay et al., 1982) was the development of a new rating system that would predict the energy-conversion performance in the field better than the peak-power ratings. However, the AM/PM method’s basic appeal lies in the fact that it is independent of site (Emery, 2003).

In view of the fact that most PV rating models require daily solar radiation flux, temperature, and wind speed profiles, i.e., data which are not always readily available to designers, an energy rating at maximum ambient temperature (EMAT) model has been developed (Meyer and van Dyk, 2000). The EMAT model, which uses only the total daily solar radiation, \(H\) (W/h/m\(^2\)/day), and the maximum ambient temperature, \(T_{\text{max}}\) (°C), as parameters, is defined by the following regression equation

\[
E = a_1H + a_2HT_{\text{max}}^{-2} + a_3T_{\text{max}}
\]

(14)

in which \(E\) is the total daily electrical energy produced by the module (W/day), and \(a_j, j = 1–3\) are the regression coefficients.

Finally, there are performance rating procedures based on site-dependent conditions rather than on standard days. Instead of predicting the energy output at standard reporting/operating conditions (SRC/SOC), it was proposed that “realistic reporting conditions” (RRC) be used for the energy/efficiency rating of PV modules (Bücher et al., 1991). The RRC efficiency gives site-specific characteristics to the PV modules, stemming from the variability of specific microclimate conditions at the location in question. That is, the deviation of RRC from SRC/SOC efficiency has a strong site and PV cell material dependence. The influence of the local spectral distribution of the solar radiation flux and the site-dependent thermal effects can lead to RRC efficiencies that, on an annual basis, are more than 10% lower than the SRC counterparts (Raicu et al., 1992).

5. Conclusions

The operating temperature plays a central role in the photovoltaic conversion process. Both the electrical efficiency and – hence – the power output of a PV module depend linearly on the operating temperature, decreasing with \(T_c\). The various correlations that have been proposed in the literature, represent simplified working equations which apply to PV modules or PV arrays mounted on free-standing frames, to PV/Thermal collectors, and to BIPV arrays, respectively. They involve basic environmental variables, while the numerical parameters are not only material dependent but also system dependent. Thus, care should be exercised in applying a particular expression for the electrical efficiency or the power output of a PV module or array, as each equation has been developed for a specific mounting frame geometry or level of building integration. The same holds for choosing a PV module rating method, the details and limitations of which should be very clear to the prospective user. The reader, therefore, should consult the original sources and try to make intelligent decisions when

\(^7\) Outdoor testing is also used in the power rating method draft of the Florida Solar Energy Center (FSEC, 2005).
seeking a correlation or a rating procedure to suit his/her needs.

References


