Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 83 (2009) 614–624
SOLAR ENERGY
www.elsevier.com/locate/solener

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

E. Skoplaki, J.A. Palyvos *

Solar Engineering Unit, School of Chemical Engineering, National Technical University of Athens, 9 Heroon Polytechneiou, Zografos Campus, 15780 Athens, Attica, Greece

Received 16 January 2008; received in revised form 22 June 2008; accepted 14 October 2008
Available online 4 November 2008

Communicated by: Associate Editor Elias K. Stefanakos

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.

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, τ, plate absorptance, α, etc.

An equally large number of correlations expressing the temperature dependence of the PV module's electrical efficiency, η_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 η_c through the latter's definition ($\eta_c = P_m$ (under standard test conditions[1])$/AG_T$, 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

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

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

---

* Corresponding author. Tel.: +30210 772 3297; fax: +30210 772 3298.
E-mail address: jpalyvos@chemeng.ntua.gr (J.A. Palyvos).

[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).

0038-092X/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.solener.2008.10.008

Nomenclature

A	aperture surface area of PV module (m^2)
BIPV	building integrated photovoltaic
E	total daily electrical energy (W/day)
FF	fill factor of PV module (cf. Eq. (1))
G_T	solar radiation flux (irradiance) on module plane (W/m^2)
H	total daily solar radiation (J/m^2/day)
H_T	total daily solar radiation on module plane (J/m^2/day)
I	electric current (A)
INOCT	installed normal operating cell temperature (°C)
NOCT	normal operating cell temperature (°C)
NTE	normal temperature environment
P	electrical power (W)
RRC	realistic reporting conditions
SOC	standard operating conditions
SRC	standard reporting conditions
STC	standard test conditions
T	temperature (K)
T_c	cell/module operating temperature (K)
T_a	ambient temperature (K)
U_L	overall thermal loss coefficient (W/m^2 K)
V	voltage (V)
V_f	free stream wind speed (m/s)
V_w	wind speed at monitored surface (m/s)

Greek letters

α	solar absorptance of PV layer
β	temperature coefficient (K^{-1})
γ	solar radiation coefficient
δ	solar radiation coefficient
η	cell/module electrical efficiency
τ	solar transmittance of glazing

Subscripts

0	at SRC
a	ambient
b	back side
c	cell (module)
f	free stream
L	loss
m	maximum, at maximum power point
$NOCT$	at NOCT conditions
oc	open circuit
pv	PV layers
ref	reference value, at reference conditions
sc	short circuit
T	on module's tilted plane
w	wind induced

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 semi-conductor), while the short-circuit current increases, but only slightly (Zondag, 2007). Thus, the net effect leads to a linear relation in the form

$$\eta_c = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right) + \gamma \log_{10} G_T\right] \tag{2}$$

in which $\eta_{T_{ref}}$ is the module's electrical efficiency at the reference temperature, T_{ref}, and at solar radiation flux of 1000 W/m^2 (Evans, 1981). The temperature coefficient, β_{ref}, and the solar radiation coefficient, γ, 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

$$\eta_c = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(T_c - T_{ref}\right)\right] \tag{3}$$

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

The quantities $\eta_{T_{ref}}$ and β_{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_{ref}, as well. It is given by the ratio

$$\beta_{ref} = \frac{1}{T_0 - T_{ref}} \tag{4}$$

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_{NOCT}, i.e., by the nominal operating cell temperature (see below). One such expression is

$$\eta = \eta_{ref}\left\{1 - \beta_{ref}\left[T_a - T_{ref} + (T_{NOCT} - T_a)\frac{G_T}{G_{NOCT}}\right]\right\} \tag{5}$$

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

$$T_c = T_a + \left(\frac{G_T}{G_{NOCT}}\right)\left(\frac{U_{L,NOCT}}{U_L}\right)(T_{NOCT} - T_{a,NOCT})\left[1 - \left(\frac{\eta_c}{\tau\alpha}\right)\right] \tag{6}$$

into Eq. (3) and using the fact that $(\eta_c/\tau\alpha) \ll 1$ (Duffie and Beckman, 2006).

In addition to the “instantaneous” values for the PV electrical efficiency, expressions can be written for the monthly average efficiency, $\bar{\eta}_c$. For example, the monthly electrical energy output of a PV array can be estimated on the basis of the following equation:

$$\bar{\eta}_c = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(\overline{T}_a - T_{ref}\right) - \frac{\beta_{ref}\,(\overline{\tau\alpha})\overline{V}\overline{H}_T}{nU_L}\right] \tag{7}$$

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, $\overline{H}_T$ is the monthly average daily insolation on the plane of the array, and $\overline{V}$ 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 η_c, including pertinent comments for each correlation. On the basis of data listed in Table 1 for $T_{ref} = 25$ °C, average $\eta_{ref} \approx 0.12$ and average $\beta_{ref} \approx 0.0045$ °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–Floschuetz ratio $\eta_T/\eta_{T_{ref}}$ 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 °C),
Average wind speed: 1 m/s,
Mounting: open rack, tilted normally to the solar noon sun.

With symbols, $NOCT = (T_c - T_a)_{NTE} + 20\,^{\circ}\mathrm{C}$. 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 1
Evans–Florschuetz PV efficiency correlation coefficients $\eta_T = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(T - T_{ref}\right)\right]$.

T_{ref} (°C)	$\eta_{T_{ref}}$	β_{ref} (°C^{-1})	Comments	References
25	0.15	0.0041	Mono-Si	Evans and Florschuetz (1977)
28	0.117 (average) (0.104–0.124)	0.0038 (average) (0.0032–0.0046)	Average of Sandia and commercial cells	OTA (1978)
25	0.11	0.003	Mono-Si	Truncellito and Sattolo (1979)
25	0.13	0.0041	PV/T system	Mertens (1979)
		0.005		Barra and Coiante (1993)
20	0.10	0.004	PV/T system	Prakash (1994)
25	0.10	0.0041	PV/T system	Garg and Agarwal (1995) Agarwal and Garg (1994) Garg et al. (1994)
20	0.125	0.004	PV/T system	Hegazy (2000)
25		0.0026	a-Si	Yamawaki et al. (2001)
25	0.13	0.004	Mono-Si	RETScreen (2001)
	0.11	0.004	Poly-Si	
	0.05	0.0011	a-Si	
25	0.178	0.00375	PV/T system	Nagano et al. (2003)
25		0.005	Mono-Si	Tobias et al. (2003)
25	0.12	0.0045	Mono-Si	Chow (2003)
25	0.097	0.0045	PV/T system	Zondag et al. (2003)
25		0.0045	PV/T system	Radziemska (2003)
25	0.0968	0.0045		Bakker et al. (2005)
		0.005	UTC/PV system	Naveed et al. (2006)
25	0.09	0.0045	PV/T system	Tiwari and Sodha (2006a)
25	0.12	0.0045	PV/T system	Tiwari and Sodha (2006b)
25		0.0045 c-Si 0.0020 a-Si	PV/T system	Zondag (2007)
25	0.12	0.0045	PV/T system	Tiwari and Sodha (2007)
25	0.12	0.0045	PV/T system	Assoa et al. (2007)
25	0.127	0.0063	PV/T system	Tonui and Tripanagnostopoulos (2007a)
25	0.127 unglazed 0.117 glazed	0.006	PV/T system	Tonui and Tripanagnostopoulos (2007b)
25		0.0054	PV/T system	Othman et al. (2007)

Notes:

- At $T_{ref} = 25$ °C, average $\eta_{ref} \approx 0.12$ and average $\beta_{ref} \approx 0.0045$ °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.

Correlation	Comments	Ref.
$\eta_T = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(T - T_{ref}\right)\right]$	$T_{ref} = 25$ °C, $\eta_{T_{ref}} = 0.15$, $\beta_{ref} = 0.0041$ °C^{-1}, c-Si, T in °C	Evans and Florschuetz (1977)
$\eta_{PV} = \eta_{ref} - \mu(T_c - T_{ref})$	μ = overall cell temperature coefficient	Bazilian and Prasad (2002)
$\eta = \eta_a - c(\overline{T} - T_a)$	$\overline{T}$ = mean solar cell temp, η_a = efficiency at T_a, c = temperature coefficient	Bergene and Løvvik (1995)
$\eta = \eta_{25} + b(T_c - 25)$	$b = b(G_T)$, T in °C	Durisch et al. (1996)
$\eta(G_T, T_c) = \eta(G_T, 25\,°\mathrm{C})[1 + c_3(T_c - 25)]$	$c_3 = -0.5$ (% loss per °C) for c-Si, $-0.02, \ldots, -0.41$ for thin film cells	Mohring et al. (2004)
$\eta_T = \eta_0 - K(T^{1/4} - T_0^{1/4})$	$T_0 = 273$ K, $K = 22.4$	Ravindra and Srivastava (1979/80)
$\eta_a = \eta_n \times k_\gamma \times k_\theta \times k_\alpha \times k_\lambda$ with $k_\gamma = 1 - \gamma(T_c - 25)/100$	k_γ = power temperature coefficient, k_j, $j = \theta, \alpha, \lambda$ optical, absorption, spectrum correction factors	Aste et al. (2008)
$\eta = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(T_a - T_{ref}\right) - \frac{\beta_{ref}\tau\alpha G_T}{U_L}\right]$	5% low predictions, $\beta_{ref} \sim 0.004$ °C^{-1}, $\eta_{T_{ref}} = 0.15$, $T_{ref} = 0$ °C	Siegel et al. (1981)
$\bar{\eta} = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(\overline{T}_a - T_{ref}\right) - \frac{\beta_{ref}\overline{(\tau\alpha)}V\overline{H}_T}{nU_L}\right]$	$\bar{\eta}$ = monthly average efficiency, V = dimensionless, $\beta_{ref} \sim 0.004$ °C^{-1}	Siegel et al. (1981)
$\eta_i = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(T_{c,i} - T_{ref}\right) + \gamma \log_{10} I_i\right]$	η_i = hourly efficiency, I_i = incident hourly insol, $\beta_{ref} \sim 0.0045$ °C^{-1}, $\gamma \sim 0.12$	Evans (1981) and Cristofari et al. (2006)
$\eta = \eta_{T_{ref}}\left[1 - \beta_{ref}(T_c - T_{ref}) + \gamma \log_{10} G_T\right]$	η = instantaneous efficiency, $\beta_{ref} = 0.0044$ °C$^{-1}\eta_{T ref} = 0.125$, $T_{ref} = 25$ °C	Notton et al. (2005)
$\bar{\eta} = \eta_{T_{ref}}\left\{1 - \beta_{ref}\left[(T_c - T_a) - (T_a - \overline{T}_a) - (\overline{T}_a - T_{ref})\right] + \gamma \log_{10} I\right\}$	$\bar{\eta}$ = monthly average efficiency, $\beta_{ref} \sim 0.0045$ °C^{-1}, $\gamma \sim 0.12$	Evans (1981)
$\eta = \eta_{ref}\left[1 - a_1(T_c - T_{ref}) + a_2 \ln(G_T/1000)\right]$	For Si $a_1 = 0.005$, $a_2 = 0.052$, omitting the ln term slightly overestimates η	Anis et al. (1983)
$\eta(XG_T, T) = \eta\left(G_T, T_{ref}\right)\left[1 - \beta_{ref}(T - T_0)\right]\left(1 + \frac{k_B T}{q}\frac{\ln X}{V_{oc}(G_T, T_0)}\right)$	X = concentration factor, for $X = 1$ it reduces to Eq. (2)	Lasnier and Ang (1990)
$\eta = \eta_{ref}\left\{1 - \beta\left[T_a - T_{ref} + (T_{NOCT} - T_a)\frac{G_T}{G_{NOCT}}\right]\right\}$	The T_c expression from Kou et al. (1998) is introduced into the η expression in Evans and Florschuetz (1977)	–
$\eta = \eta_{ref}\left\{1 - \beta\left[T_a - T_{ref} + \left(\frac{9.5}{5.7+3.8V_w}\right)(T_{NOCT} - T_a)\frac{G_T}{G_{NOCT}}\right]\right\}$	The T_c expression from Duffie and Beckman (2006) is introduced into the η expression in Evans and Florschuetz (1977)	–
$\eta = \eta_{ref}\left[1 - 0.9\beta\frac{G_T}{G_{T,NOCT}}\left(T_{c,NOCT} - T_{a,NOCT}\right) - \beta\left(T_a - T_{ref}\right)\right]$	Assumes $\eta \approx 0.9(\tau\alpha)$	Hove (2000)
$\eta_{nom} = -0.05T_{surface} + 13.75$	$T_{surface} = 1.06T_{back} + 22.6$	Yamaguchi et al. (2003)
$\eta_{meas} = -0.053T_{back} + 12.62$	Nominal vs measured values	
$\eta = a_0 + a_1\frac{T_c(x,t) - T_\infty}{T_\infty} + a_2\frac{G_T - G_{ref}}{G_{ref}}$	A_k, $k = 0$, 1 and 2 are empirical constants, T_∞ is the indoor ambient temperature	Zhu et al. (2004)
$\eta_{MPP}(G_T, T) = \eta_{MPP}(G_T, 25\,°\mathrm{C})(1 + \alpha(T - 25))eta_{MPP}(G_T, 25\,°\mathrm{C})$ $= a_1 + a_2G_T + a_3\ln(G_T)$	a_1–a_3 device specific parameters, MPP tracking system	Beyer et al. (2004)
$\eta = \eta_{NOCT}[1 - MPTC(T_{NOCT} - T_c)]$	$MPTC$ = maximum power temperature coefficient[a]	Perlman et al. (2005)
$\eta = a + b\frac{T_{in} - T_a}{G_T}$	PV/T collector. PV cover: 100% → $a = 0.123$, $b = -0.464$ 50% → $a = 0.121$, $b = -0.450$	Chow et al. (2006)
$\eta = 0.94 - 0.0043\left[\overline{T}_a + \frac{\overline{G}_T}{(22.4 + 8.7\overline{V}_w)} - 25\right] \pm 2.6\%$	Overbars denote daily averages. $\overline{G}_T$ = Wh/m^2 received/length of day (h) $\overline{V}_w$ in m/s	CLEFS CEA (2004)

Notes:

- In Bücher (1997): PRT factor temperature effect on PV performance.
- In Oshiro et al. (1997): KPT cell temperature factor.
- In Jardim et al. (2008): NOCT-corrected efficiency.

[a] With MPTC = −0.5% loss per °C, the efficiency is $\eta = 11.523 - 0.0512T_c$.

(Kirpich et al., 1980). When a module operates at NOCT, the term "standard operating conditions" (SOC[2]) 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 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-

---

[2] In an alternate definition the number 45 ± 2 °C is used in place of NOCT FSEC, 2005.

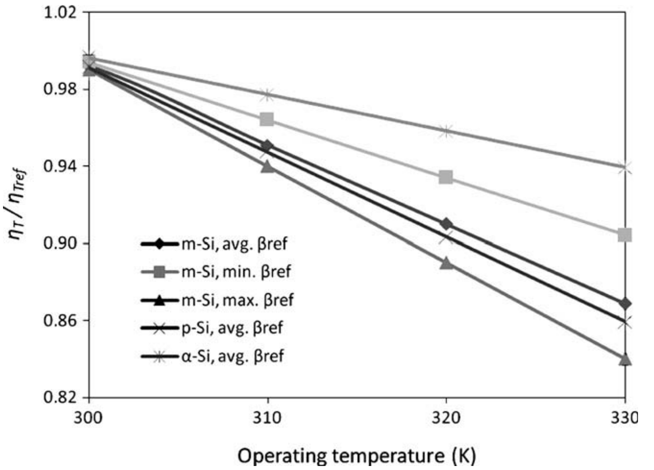

Fig. 1. The ratio $\eta_T/\eta_{T_{ref}}$ as predicted by the Evans–Florschuetz efficiency correlation for typical silicon-based PV module types.

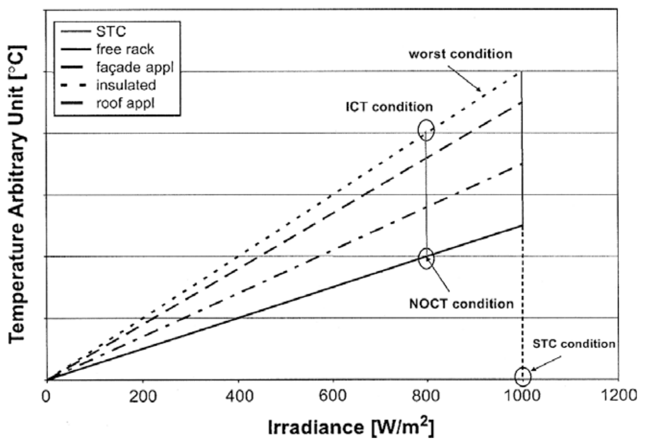

Fig. 2. BIPV mounting induced temperature difference from NOCT as a function of irradiance (Bloem, 2008).

tures, due to lack of proper cooling from the poorly ventilated back side.[3] Thus, the module's correct NOCT, which obviously depends on the mounting scheme for a given solar radiation flux level (cf. Fig. 2), must be measured in a properly designed and well controlled outdoor test bed, 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[4] (Bloem, 2008).

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 for PV power, similar in form to Eq. (3), is

$$P = G_T \tau_{pv} \eta_{T_{ref}} A[1 - 0.0045(T_c - 25)] \tag{8}$$

in which τ_{pv} is the transmittance of the PV cells' outside layers (Jie et al., 2007).

Table 3 lists a number of correlations found in the literature for PV electrical power as a function of cell/module operating temperature and basic environmental variables. Many of them are linear and similar to Eqs. (3) or (8), while others are more complex, such as the following nonlinear multivariable regression equation (Rosell and Ibáñez, 2006),

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

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

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

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 overpredict 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

$$P = G_T(b_1 + b_2 G_T + b_3 T_a + b_4 V_f) \tag{11}$$

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/m^2 (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.

---

[3] Thermal inertia is another problem in the NOCT calculation, as $T_c - T_a$ is higher in the afternoon for the same G_T values. This can cause a ±3 °C error in NOCT but, still, only a ±1.5% error in annual performance estimations (Alonso Garcia and Balenzategui, 2004).

[4] In the context of the relevant energy rating procedure, a site and mounting specific temperature has been postulated at Ispra, i.e., the normal operating specific temperature (NOST) (Kenny et al., 2003).

Table 3
PV array power as a function of temperature $P = \eta_c A G_T$.

Correlation	Comments	References
$P = \eta_{T_{ref}} A G_T (\tau\alpha)\left[1 - \beta_{ref}(T_P - T_{ref})\right]$	T_P = plate temperature, $\eta_{T_{ref}} = 0.118$ at 45 °C – air coll, $\eta_{T_{ref}} = 0.108$ at 28 °C – water coll	Hendrie (1979)
$P_{T_c} = \eta_{ref} A G_T K_f [1 + \alpha(T_c - 25)]$	$T_{ref} = 25$ °C, $\eta_{T_{ref}} = 0.13$, $\alpha = -0.004$ °C^{-1}, K_f factor for rest, frame installation, T_c in °C	Nishioka et al. (2003)
$P = \eta_e A G_T \tau_g p\left[1 - \beta_{ref}(T_c - 25)\right]$	p = packing factor, T_c in °C, τ_g = glazing transmissivity	Chow et al. (2006)
$P = \eta_{T_{ref}} A G_T [1 - 0.0045(T_c - 298.15)]$	$\eta_{T_{ref}} = 0.14$, T_c in K	Jie et al. (2007a)
$P = \eta_{T_{ref}} A G_T \tau_{pv} [1 - 0.0045(T_c - 25)]$	$\eta_{T_{ref}} = 0.14$, T_c in °C, τ_{pv} = pv cell glazing transmittance	Jie et al. (2007b)
$P = \eta_{T_{ref}} A G_T \left[1 - \beta_{ref}\left(T_c - T_{ref}\right) + \gamma \log_{10} G_T\right]$	$\beta_{ref} = 0.0044$ °C^{-1} for pc-Si, γ is usually taken as 0	Cristofari et al. (2006)
$P_T = P_{ref}\left[1 - \beta_{ref}(T - T_{ref})\right]$	$\beta_{ref} = 0.004$–0.006 °C^{-1}, T in °C, T_{ref} = reference temperature	Buresch (1983)
Same as above	$\beta_{ref} = 0.004$	Twidell and Weir (1986)
$P(T) = P(25)[1 - \gamma(T - 25)]$	$\gamma = 0.0053$ °C^{-1} for c-Si range: 0.004–0.006 °C^{-1}	Parretta et al. (1998)
$P_T = P_{25}[1 - 0.0026(T - 25)]$	a-Si, T in °C, power degrades to $0.82 P_{init}$	Yamawaki et al. (2001)
$P_T = P_{25} + \frac{dP}{dT}(T - 25)$	$\frac{dP}{dT} = -0.00407, -0.00535$, Si space cells, T in °C	Osterwald (1986)
$P(T) \approx G_T[\eta_0 - c(T - T_a)]$	η_0 = efficiency at T_a, c = temperature dependence factor	Bergene and Løvvik (1995)
$P_{max} = P_{max,ref}[1 - Df(T_c - 25)]$	Df = "deficiency factor" = 0.005 °C^{-1}	Al-Sabounchi (1998)
$P_{\max} = P_{\max,ref} \frac{G_T}{G_{T,ref}} \left[1 + \gamma\left(T_c - T_{ref}\right)\right]$	γ = temperature factor for power, $\gamma = -0.0035$ (range – 0.005 °C^{-1} to −0.003 °C^{-1}). T_c in °C	Menicucci and Fernandez (1988)
$P_{max} = P_{max,ref} \frac{G_T}{G_{T,ref}} [1 + \gamma(T_c - 25)]$	$\gamma = -0.0035$ (range – 0.005 °C^{-1} to −0.003 °C^{-1}) T_c in °C	Fuentes et al. (2007)
$P_{\max} = P_{\max,ref} \frac{G_T}{1000} \left[1 + \gamma\left(T_c - T_{ref}\right)\right]$	γ = temperature factor for power, $T_{ref} = 25$ °C, used in PVFORM	Marion (2002)
$P_{mp,T_r} = I_{mp,T}[1 - \alpha(T - T_r)]\left[V_{mp,T} - \beta V_{mp}^{STC}(T - T_r)\right]$	STC refers to ASTM standard conditions (1000 W/m^2, AMI = 1.5, $T_r = 25$ °C)	King et al. (1997)
$P_{max} = P_{max,ref} \frac{G_T}{G_{T_{ref}}} \left[1 + \alpha\left(T - T_{ref}\right)\right]\left[1 + \beta_{ref}\left(T - T_{ref}\right)\right] \left[1 + \delta(T) \ln\left(\frac{G_T}{G_{T_{ref}}}\right)\right]$	Adapted from the MER model[a]. Coefficient δ evaluated at actual conditions	Kroposki et al. (2000)
$P = P_0[1 + (\alpha - \beta_{ref})\Delta T]$	α: 0.0005 °C^{-1}, β: 0.005 °C^{-1}	Patel. (1999)
$P = (\alpha T_c + \beta) G_T$	α = temperature coefficient, β = calibration constant	Yang et al. (2000)
$P = -4.0 + 0.053 G_T + 0.13 T_c - 0.00026 G_T T_c$	MPPTracked 100 kWp system	Risser and Fuentes (1983)
$P = -0.4905 + 0.05089 G_T + 0.00753 T_c - 0.000289 G_T T_a$	MPPTracked 100 kWp system	Risser and Fuentes (1983)
$P_T = -8.6415 + 0.076128 G_T + 1.02318 \times G_T^2 + 0.20178 T - 4.9886 \times 10^{-3} T^2$	T is the panel temperature (K), too many significant figures!!!	Jie et al. (2002)
$P = G_T(b_1 + b_2 G_T + b_3 T_a + b_4 V_f)$	EPTC model, b_j regression coefficients, V_w^f wind speed 10 m above ground	Farmer (1992)
$P = c_1 + (c_2 + c_3 T_a) G_T + (c_4 + c_5 V_w) G_T^2$	c_j regression coefficients based on STC module tests[b]	Taylor (1986)
$P_{mp} = D_1 G_T + D_2 T_c + D_3[\ln(G_T)]^m + D_4 T_c [\ln(G_T)]^m$	D_j (j = 1–4), m parameters[c]	Rosell and Ibáñez (2006)
$P = V_c I_c \left[1 - \frac{G_T - 500}{2.0 \times 10^{-4}} + \frac{C_{T_c}}{4 \times 10^4}(50 - T_c)^2\right]$	I_c = output current (A), V_c = output voltage (V), T_c in K, $C_{T_c} = 1$ if $T_c \leqslant 50$ °C or =3 if $T_c \geqslant 50$ °C	Furushima et al. (2006)
$P = A(0.128 G_T - 0.239 \times 10^{-3} T_a)$	p-Si, hybrid PV-fuel cells system G_T in kW/m^2, P in kW, T_a in °C	Zervas et al. (2007)
$P = P_{ref} G_T K_{pt} K_w K_e K_c$ with $K_{pt} = 1 + \alpha(T_c - 25)$	K_w, K_e, K_c loss coefficients due to mounting, dirt etc., AC conversion. Semitransparent PV	Wong et al. (2005)

Notes:

- Ref. Bücher et al. (1998): reports 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.
- Refs. Radziemska (2003) and Radziemska and Klugmann (2006): report power temperature coefficients −0.0065/K for c-Si.
- Ref. Fathi and Salem (2007): reports a dimensional expression for "power" – actually specific energy!
- Energy production correlation E_{out} {W hr} $= (\varepsilon_0 + \varepsilon_1 T_c) E$ {kW hr/m^2}, with $36.41 \leqslant \varepsilon_0 \leqslant 44.14$ and $-0.20 \leqslant \varepsilon_1 \leqslant -0.16$ is given in del Cueto (2001).
- Daily energy production (W h/day) is given by $E = A_1 H + A_2 H (T_{a,max})^{-2} + A_3 T_{a,max}$, with $T_{a,max}$ the maximum ambient temperature (°C), H the daily total insolation (W h/m^2/day) and A_j regression coefficients, according to the EMAT model (Meyer and van Dyk, 2000).
- 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 $\gamma = \frac{\ln(V_{oc_0}/V_{oc_1})}{\ln(T_1/T_0)}$.
- There are few equations with no explicit temperature dependence. Among them, the single regression yearly average form $P_{yr} = 0.1103 G_{T,yr}$ (Liu et al, 2004) and the nonlinear expression $P = c_1 G_T + c_2 G_T^2 + c_3 G_T \ln G_T$, with c_j regression coefficients, known as the ENRA model (Gianolli Rossi and Krebs, 1988), which over-predicts the PV performance.

[a] The V_{oc} and I_{sc} expressions have been combined as in Eq. (1).

[b] The regression equation shown combines the original equation for P and the analogous expression for T_c.

[c] For pc-Si, $D_1 = 0.000554$, $D_2 = -7.275 \times 10^{-5}$, $D_3 = 2.242 \times 10^{-5}$, $D_4 = -4.763 \times 10^{-8}$, $m = 7.0306$. 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).[5] 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 straight forward 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 W h/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[6] 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

$$I_{SC} = \frac{G_T}{G_{T_0}} I_{SC_0}[1 + \alpha(T_c - T_0)] \tag{12}$$

and

$$V_{OC} = V_{OC_0}\left[1 + \beta\left(G_{T_0}\right)(T_c - T_0)\right]\left[1 + \delta(T_c)\ln\left(G_T/G_{T_0}\right)\right] \tag{13}$$

in which α and β are current and voltage correction coefficients for temperature, δ 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

---

[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 $T_c f_1(G_T, T_a, V_w) \times INOCT + f_2(G_T, T_a, V_w)$, with $INOCT = NOCT - 3$ °C and f_1, f_2 the slope and the *y*-intercept in the T_c versus *INOCT* 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_{max} (°C), as parameters, is defined by the following regression equation

$$E = a_1 H + a_2 H T_{max}^{-2} + a_3 T_{max} \tag{14}$$

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

Agarwal, R.K., Garg, H.P., 1994. Study of a photovoltaic-thermal system – thermosyphonic solar water heater combined with solar cells. Energy Conversion and Management 35, 605–620.

Alonso Garcia, M.C., Balenzategui, J.L., 2004. Estimation of photovoltaic module yearly temperature and performance based on nominal operation cell temperature calculations. Renewable Energy 29, 1997–2010.

Al-Sabounchi, A.M., 1998. Effect of ambient temperature on the demanded energy of solar cells at different inclinations. Renewable Energy 14, 149–155.

Anderson, D., Bishop, J., Dunlop, E., 2000. Energy rating of photovoltaic modules. In: Proceedings of 16th EC Photovoltaic Solar Energy Conference, May 1–5, Glasgow, UK, pp. 2087–2091.

Anis, W.R., Mertens, R.P., van Overstraeten, R.J., 1983. Calculation of solar cell operating temperature in a flat plate PV array. In: Proceedings of Fifth EC Photovoltaic Solar Energy Conference, October 12–16, Athens, Greece, pp. 520–524.

Assoa, Y.B., Menezo, C., Fraisse, G., Yezou, R., Brau, J., 2007. Study of a new concept of photovoltaic-thermal hybrid collector. Solar Energy 81, 1132–1143.

Aste, N., Chiesa, G., Verri, F., 2008. Design, development and performance monitoring of a photovoltaic-thermal (PVT) air collector. Renewable Energy 33, 914–927.

Bakker, M., Zondag, H.A., Elswijk, M.J., Strootman, K.J., Jong, M.J.M., 2005. Performance and costs of roof-sized PV/thermal array combined with a ground coupled heat pump. Solar Energy 78, 331–339.

Barra, L., Coiante, D., 1993. Annual energy production and room temperature effect in siting flat plate photovoltaic systems. Solar Energy 51, 383–389.

Bazilian, M., Prasad, D., 2002. Modelling of a photovoltaic heat recovery system and its role in a design decision support tool for building professionals. Renewable Energy 27, 57–68.

Bergene, T., Løvvik, O.M., 1995. Model calculations on a flat-plate solar heat collector with integrated solar cells. Solar Energy 55, 453–462.

Beyer, H.G., Bethke, J., Drews, A., Heinemann, D., Lorenz, E., Heilscher, G., Bofinger, S., 2004. Identification of a general model for the MPP performance of PV-modules for the application in a procedure for the performance check of grid connected systems. In: 19th EC Photovoltaic Solar Energy Conference, June 7–11, Paris, France. <http://www.pvsat.de/paper_beyer.pdf>.

Bloem, J.J., 2008. Evaluation of a PV-integrated building application in a well-controlled outdoor test environment. Building and Environment 43, 205–216.

Bücher, K., 1997. Site dependence of the energy collection of PV modules. Solar Energy Materials and Solar Cells 47, 85–94.

Bücher, K., Heidler, K., Kleiss, G., Raicu, A., 1991. Annual and seasonal energy rating of mono-Si, a-Si and GaAs test cells for the USA by the RRC method. In: Proceedings of 22nd IEEE Photovoltaic Specialists Conference, October 7–11, Las Vegas, NV, pp. 744–749.

Bücher, K., Kleiss, G., Batzner, D., 1998. Photovoltaic modules in buildings: performance and safety. Renewable Energy 15, 545–551.

Buresch, M., 1983. Photovoltaic Energy Systems. McGraw-Hill, New York, p. 76.

Chow, T.T., 2003. Performance analysis of photovoltaic-thermal collector by explicit dynamic model. Solar Energy 75, 143–152.

Chow, T.T., He, W., Ji, J., 2006. Hybrid photovoltaic-thermosyphon water heating system for residential application. Solar Energy 80, 298–306.

CLEFS CEA, 2004. Influence of temperature on photovoltaic module efficiency. CLEFS CEA – No. 50/51 – Winter 2004–2005, p. 119.

Cox, C.H., Raghuraman, P., 1985. Design considerations for flat-plate photovoltaic/thermal collectors. Solar Energy 35, 227–241.

Cristofari, C., Poggi, P., Notton, G., Muselli, M., 2006. Thermal modeling of a photovoltaic module. In: Proceedings of Sixth IASTED International Conference on “Modeling, Simulation, and Optimization”, September 11–13, Gaborone, Botswana, pp. 273–278.

Davis, M.W., Dougherty, B.P., Fanney, A.H., 2001. Prediction of building integrated photovoltaic cell temperatures. Transactions ASME, Journal of Solar Energy Engineering 123, 200–210.

del Cueto, J.A., 2001. Energy production and performance of polycrystalline silicon technology photovoltaic modules in the field. National Renewable Energy Laboratory Report NREL/CP-520-30822.

Duffie, J.A., Beckman, W.A., 2006. Solar Energy Thermal Processes, third ed. Wiley, Hoboken, NJ, §23.3.

Durisch, W., Urban, J., Smestad, G., 1996. Characterisation of solar cells and modules under actual operating conditions. Renewable Energy 8, 359–366.

Emery, K., 2003. Measurement and characterization of solar cells and modules. In: Luque, A., Hegedus, S. (Eds.), Handbook of Photovoltaic Science and Engineering. Wiley, Chichester, pp. 701–752.

Evans, D.L., 1981. Simplified method for predicting photovoltaic array output. Solar Energy 27, 555–560.

Evans, D.L., Florschuetz, L.W., 1977. Cost studies on terrestrial photovoltaic power systems with sunlight concentration. Solar Energy 19, 255–262.

Evans, D.L., Florschuetz, L.W., 1978. Terrestrial concentrating photovoltaic power system studies. Solar Energy 20, 37–43.

Fanney, A.H., Dougherty, B.P., 2001. Building integrated photovoltaic test facility. Transactions ASME Journal of Solar Energy Engineering 123, 194–199.

Farmer, B.K., 1992. PVUSA Model Technical Specification for a Turnkey Photovoltaic Power System. Appendix C, p. c2.

Fathi, N.Y., Salem, A.A., 2007. The reliability of the photovoltaic utilization in southern cities of Libya. Desalination 209, 86–90.

Florida Solar Energy Center, 2005. Test method for photovoltaic module power rating. FSEC Standard 202-05. www.fsec.ucf.edu.

Fuentes, M., Nofuentes, G., Aguilera, J., Talavera, D.L., Castro, M., 2007. Application and validation of algebraic methods to predict the behaviour of crystalline silicon PV modules in mediterranean climates. Solar Energy 81, 1396–1408.

Furushima, K., Nawata, Y., Sadatomi, M., 2006. Prediction of photovoltaic power output considering weather effects. In: ASES Conference SOLAR 2006 – Renewable Energy Key to Climate Recovery. July 7–13, Denver, Colorado.

Garg, H.P., Agarwal, R.K., Joshi, J.C., 1994. Experimental study on a hybrid photovoltaic-thermal solar water heater and its performance predictions. Energy Conversion and Management 35, 621–633.

Garg, H.P., Agarwal, R.K., 1995. Some aspects of a PV/T collector/forced circulation flat plate solar water heater with solar cells. Energy Conversion and Management 36, 87–99.

Gay, C., Rumburg, J., Wilson, J., 1982. ‘AM/PM’ – all-day module performance measurements. In: Proceedings of 16th IEEE Photovoltaic Specialists Conference, September 27–30, San Diego, CA, pp. 1041–1046.

Gianolli Rossi, E., Krebs, K., 1988. Energy rating of PV modules by outdoor response analysis. In: Eighth EC Photovoltaic Solar Energy Conference, Florence, Italy.

Hart, G.W., Raghuraman, P., 1982. Simulation of thermal aspects of residential photovoltaic systems. MIT Report DOE/ET/20279-202.

Hegazy, A.A., 2000. Comparative study of the performances of four photovoltaic/thermal solar air collectors. Energy Conversion and Management 41, 861–881.

Hendrie, S.D., 1979. Evaluation of combined photovoltaic/thermal collectors. In: Proceedings of ISES Solar World Congress, May 28–June 1, Atlanta, GA, pp. 1865–1869.

Hove, T., 2000. A method for predicting long-term average performance of photovoltaic systems. Renewable Energy 21, 207–229.

Jardim, C.S., Rüther, R., Salamoni, I.T., Viana, T.S., Rebechi, S.H., Knob, P.J., 2008. The strategic siting and the roofing area requirements of building-integrated photovoltaic solar energy generators in urban areas in Brazil. Energy and Buildings 40, 365–370.

Jennings, C., 1987. Outdoor versus rated photovoltaic module performance. In: Proceedings of 19th IEEE Photovoltaic Specialists Conference, May 4–8, New Orleans, LA, pp. 1257–1260.

Jie, J., Hua, Y., Gang, P., Bin, J., Wei, H., 2007a. Study of PV-Trombe wall assisted with DC fan. Building and Environment 42, 3529–3539.

Jie, J., Hua, Y., Wei, H., Gang, P., Jianping, L., Bin, J., 2007b. Modelling of a novel Trombe wall with PV cells. Building and Environment 42, 1544–1552.

Jie, J., Wei, H., Lam, H.N., 2002. The annual analysis of the power output and heat gain of a PV-wall with different integration mode in Hong Kong. Solar Energy Materials and Solar Cells 71, 435–448.

Kenny, R.P., Friesen, G., Chianese, D., Bernasconi, A., Dunlop, E.D., 2003. Energy rating of PV modules: comparison of methods and approach. In: Proceedings of Third World Conference on Photovoltaic Energy Conversion, Osaka, Japan, May 11–18, pp. 2015–2018.

Kenny, R.P., Dunlop, E.D., Ossenbrink, H.A., Müllejans, H., 2006. A practical method for the energy rating of c-Si photovoltaic modules based on standard tests. Progress in Photovoltaics: Research and Applications 14, 155–166.

King, D.L., Boyson, W.E., Kratochvil, J.A., 2004. Photovoltaic array performance model. Report SAND2004-3535. <http://www.sandia.gov/pv/docs/PDF/King%20SAND.pdf>.

King, D.L., Kratochvil, J.A., Boyson, W.E., 1997. Temperature coefficients for PV modules and arrays: measurement methods, difficulties, and results. In: Proceedings of 26th IEEE Photovoltaic Specialists Conference, September 29–October 3, Anaheim, CA.

King, D.L., Kratochvil, J.A., Boyson, W.E., Bower, W.I., 1998. Field experience with a new performance characterization procedure for photovoltaic arrays. In: Proceedings of Second World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna, Austria, pp. 1947–1952.

Kirpich, A., O'Brien, G., Shepard, N., 1980. Electric power generation: photovoltaics. In: Dickinson, W.C., Cheremisinoff, P.N. (Eds.), Solar Energy Technology Handbook, Part B. Marcel Dekker, New York, p. 329.

Kou, Q., Klein, S.A., Beckman, W.A., 1998. A method for estimating the long-term performance of direct-coupled PV pumping systems. Solar Energy 64, 33–40.

Kroposki, B., Marion, W., King, D.L., Boyson, W.E., Kratochvil, J.A., 2000. Comparison of module performance characterization methods. In: Proceedings of 28th IEEE Photovoltaic Specialists Conference, September 16–22, Anchorage, AK, pp. 1407–1411.

Kroposki, B., Myers, D., Emery, K., Mrig, L., Whitaker, C., Newmiller, J., 1996. Photovoltaic module energy rating methodology development. In: Proceedings of 25th IEEE Photovoltaic Specialists Conference, May 13–17, Washington DC, pp.1311–1314.

Lasnier, F., Ang, T.G., 1990. Photovoltaic Engineering Handbook. Adam Hilger, New York, NY, p. 80.

Liu, Q., Ryu, Y., Gao, W., Ruan, Y., 2004. Field study and sensitive analysis of PV system by multiple regression method. Journal of Asian Architecture and Building Engineering 3, 247–252.

Marion, B., 2002. A method for modelling the current–voltage curve of a PV module for outdoor conditions. Progress in Photovoltaics: Research and Applications 10, 205–214.

Marion, B., Kroposki, B., Emery, K., del Cueto, J., Myers, D., Osterwald, C., 1999. Validation of a photovoltaic module energy ratings procedure. National Renewable Energy Laboratory Report NREL/TP-520-26909.

Markvart, T., 2000. Solar Electricity, second ed. Wiley, Chichester, p. 37.

Menicucci, D., Fernandez, J.P., 1988. User's manual for PVFORM: a photovoltaic system simulation program for stand-alone and grid-interactive applications. SAND85-0376, Sandia National Laboratories, Albuquerque, NM.

Mertens, R., 1979. Hybrid thermal-photovoltaic systems. In: Proceedings of UK-ISES Conference on C21 Photovoltaic Solar Energy Conversion, September, 1979, p. 65.

Meyer, E.L., van Dyk, E.E., 2000. Development of energy model based on total daily irradiation and maximum ambient temperature. Renewable Energy 21, 37–47.

Mohring, H.D., Stellbogen, D., Schäffler, R., Oelting, S., Gegenwart, R., Konttinen, P., Carlsson, T., Cendagorta, M., Hermann, W., 2004. Outdoor performance of polycrystalline thin film PV modules in different European climates. In: Proceedings of 19th EC Photovoltaic Solar Energy Conference, June 7–11, Paris, France, presentation 5CO.3.1.

Nagano, K., Mochida, T., Shimakura, K., Murashita, K., Takeda, S., 2003. Development of thermal-photovoltaic hybrid exterior wallboards incorporating PV cells in and their winter performances. Solar Energy Materials and Solar Cells 77, 265–282.

Naveed, A.T., Kang, E.C., Lee, E.J., 2006. Effect of unglazed transpired collector on the performance of a polycrystalline silicon photovoltaic module. Transactions ASME, Journal of Solar Energy Engineering 128, 349–353.

Nishioka, K., Hatayama, T., Uraoka, Y., Fuyuki, T., Hagihara, R., Watanabe, M., 2003. Field-test analysis of PV system output characteristics focusing on module temperature. Solar Energy Materials and Solar Cells 75, 665–671.

Notton, G., Cristofari, C., Mattei, M., Poggi, P., 2005. Modelling of a double-glass photovoltaic module using finite differences. Applied Thermal Engineering 25, 2854–2877.

Oshiro, T., Nakamura, H., Imataki, M., Sakuta, K., Kurokawa, K., 1997. Practical values of various parameters for PV system design. Solar Energy Materials and Solar Cells 47, 177–187.

Osterwald, C.R., 1986. Translation of device performance measurements to reference conditions. Solar Cells 18, 269–279.

OTA – Office of Technology Assessment, 1978. Application of Solar Technology to Today's Energy Needs, Energy Conversion with Photovoltaics. Princeton, p. 406 (Chapter X).

Othman, M.Y., Yatim, B., Sopian, K., Abu Bakar, M.N., 2007. Performance studies on a finned double-pass photovoltaic-thermal (PV/T) solar collector. Desalination 209, 43–49.

Parretta, A., Sarno, A., Vicari, L.R.M., 1998. Effects of solar irradiation conditions on the outdoor performance of photovoltaic modules. Optics Communications 153, 153–163.

Patel, M.R., 1999. Wind and Solar Power Systems. CRC Press, Boca Raton, FL, §8.6.4.

Perlman, J., McNamara, A., Strobino, D., 2005. Analysis of PV system performance versus modelled expectations across a set of identical PV systems. In: Proceedings of ISES Solar World Congress "Bringing Water to the World", August 6–12, Orlando, FL.

Prakash, J., 1994. Transient analysis of a photovoltaic-thermal solar collector for co-generation of electricity and hot air/water. Energy Conversions Management 35, 967–972.

Radziemska, E., 2003a. The effect of temperature on the power drop in crystalline silicon solar cells. Renewable Energy 28, 1–12.

Radziemska, E., 2003b. Thermal performance of Si and GaAs based solar cells and modules: a review. Progress in Energy Combustion Science 29, 407–424.

Radziemska, E., Klugmann, E., 2006. Photovoltaic maximum power point varying with illumination and temperature. Transactions ASME, Journal of Solar Energy Engineering 128, 34–39.

Raicu, A., Heidler, K., Kleiss, G., Bücher, K., 1992. Realistic reporting conditions – RRC – for site-dependent energy rating of PV devices. In: Proceedings of 11th EC Photovoltaic Solar Energy Conference, October 12–16, Montreaux, Switzerland, pp. 1323–1326.

Ravindra, N.M., Srivastava, V.K., 1979/80. Temperature dependence of the maximum theoretical efficiency in solar cells. Solar Cells 1, 107–109.

RETScreen International, Photovoltaic Project Analysis, 2001. PV.22.

Risser, V.V., Fuentes, M.K., 1983. Linear regression analysis of flat-plate photovoltaic system performance data. In: Proceedings of Fifth EC Photovoltaic Solar Energy Conference, October 12–16, Athens, Greece, pp. 623–627.

Rosell, J.I., Ibáñez, M., 2006. Modelling power output in photovoltaic modules for outdoor operating conditions. Energy Conversion and Management 47, 2424–2430.

Sharan, S.N., Kandpal, T.C., 1987. Optimum concentration ratio for a combined photovoltaic-thermal concentrator–receiver system. Energy Conversions Management 27, 355–359.

Sharan, S.N., Mathur, S.S., Kandpal, T.C., 1987. Analytical performance evaluation of combined photovoltaic-thermal concentrator–receiver systems with linear absorbers. Energy Conversions Management 27, 361–365.

Siegel, M.D., Klein, S.A., Beckman, W.A., 1981. A simplified method for estimating the monthly-average performance of photovoltaic systems. Solar Energy 26, 413–418.

Stultz, J.W., Wen, L.C., 1977. Thermal performance testing and analysis of photovoltaic modules in natural sunlight. LSA Task Report 5101-31.

Taylor, R.W., 1986. System and module rating: advertised versus actual capability. Solar Cells 18, 335–344.

Tiwari, A., Sodha, M.S., 2006a. Performance evaluation of a solar PV/T system: an experimental validation. Solar Energy 80, 751–759.

Tiwari, A., Sodha, M.S., 2006b. Performance evaluation of a solar PV/T system: a parametric study. Renewable Energy 31, 2460–2474.

Tiwari, A., Sodha, M.S., 2007. Parametric study of various configurations of hybrid PV/thermal air collector: experimental validation of theoretical model. Solar Energy Materials and Solar Cells 91, 17–28.

Tobias, I., del Canizo, C., Alonso, J., 2003. Crystalline silicon solar cells and modules. In: Luque, A., Hegedus, S. (Eds.), Handbook of Photovoltaic Science and Engineering. Wiley, Chichester (Chapter 7).

Tonui, J.K., Tripanagnostopoulos, Y., 2007a. Improved PV/T solar collectors with heat extraction by forced or natural air circulation. Renewable Energy 32, 623–637.

Tonui, J.K., Tripanagnostopoulos, Y., 2007b. Air-cooled PV/T solar collectors with low cost performance improvements. Solar Energy 81, 498–511.

Truncellito, N.T., Sattolo, A.J., 1979. An analytical method to simulate solar energy collection and storage utilizing a flat plate photovoltaic panel. General Electric Advanced Energy Department.

Twidell, J., Weir, T., 1986. Renewable Energy Resources. E&FN Spon, London, UK, p. 160.

Wong, P.W., Shimoda, Y., Nonaka, M., Inoue, M., Mizuno, M., 2005. Field study and modelling of semi-transparent PV in power, thermal and optical aspects. Journal of Asian Architecture and Building Engineering 4, 549–556.

Yamaguchi, T., Okamoto, Y., Taberi, M., 2003. Investigation on abundant photovoltaic power generated by 40 kW PV system in Wakayama National College of Technology. Solar Energy Materials and Solar Cells 75, 597–601.

Yamawaki, T., Mizukami, S., Masui, T., Takahashi, H., 2001. Experimental Investigation on generated power of amorphous PV module for roof azimuth. Solar Energy Materials and Solar Cells 67, 369–377.

Yang, H., Burnett, J., Ji, J., 2000. Simple approach to cooling load component calculation through PV walls. Energy and Buildings 31, 285–290.

Zervas, P.L., Sarimveis, H., Palyvos, J.A., Markatos, N.C.G., 2007. Model-based optimal control of a hybrid power generation system consisting of photovoltaic arrays and fuel cells. Journal of Power Sources. doi:10.1016/j.jpowsour.2007.11.067.

Zhou, W., Yang, H., Fang, Z., 2007. A novel model for photovoltaic array performance prediction. Applied Energy 84, 1187–1198.

Zhu, Z., Yang, H., Jiang, R., Wu, Q., 2004. Investigation of conjugate heat transfer in a photovoltaic wall. Heat Transfer-Asian Research 33, 117–128.

Zondag, H.A., 2007. Flat-plate PV-thermal collectors and systems – a review. Renew. Sustain. Energy Rev. doi:10.1016/j.rser.2005.12.012.

Zondag, H.A., de Vries, D.W., van Helden, W.G.J., van Zolingen, R.J.C., van Steenhoven, A.A., 2003. The yield of different combined PV-thermal collector designs. Solar Energy 74, 253–269.