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Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review

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Abstract

Solar cell performance decreases with increasing temperature, fundamentally owing to increased internal carrier recombination rates, caused by increased carrier concentrations. The operating temperature plays a key role in the photovoltaic conversion process. Both the electrical efficiency and the power output of a photovoltaic (PV) module depend linearly on the operating temperature. The various correlations proposed in the literature represent simplified working equations which can be apply to PV modules or PV arrays mounted on free-standing frames, PV-Thermal collectors, and building integrated photovoltaic arrays, respectively. The electrical performance is primarily influenced by the material of PV used. Numerous correlations for cell temperature which have appeared in the literature involve basic environmental variables and numerical parameters which are material or system dependent. In this paper, 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. Generally, the performance ratio decreases with latitude because of temperature. However, regions with high altitude have higher performance ratios due to low temperature, like, southern Andes, Himalaya region, and Antarctica. PV modules with less sensitivity to temperature are preferable for the high temperature regions and more responsive to temperature will be more effective in the low temperature regions. The geographical distribution of photovoltaic energy potential considering the effect of irradiation and ambient temperature on PV system performance is considered.

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Keywords: Solar energy; photovoltaic; temperature coefficient; efficiency

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1. Introduction

The important role of the operating temperature in relation to the electrical efficiency of a photovoltaic (PV) device, be it a simple module, a PV/thermal collector or a building-integrated photovoltaic (BIPV) array, is well established and documented, as can be seen from the attention it has received by the scientific community. There are many correlations expressing T_c, the PV cell temperature, as a function of weather variables such as ambient temperature, T_a, local wind speed, V_w, and solar radiation flux/irradiance, I(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. With regard to the relevant weather variables, and qualitatively speaking, it was found that the PV cell temperature rise over the ambient is extremely sensitive to wind speed, less to wind direction, and practically insensitive to the atmospheric temperature [1]. On the other hand, it obviously depends strongly on the impinging irradiation, i.e. the solar radiation flux on the cell or module. From the mathematical point of view, the correlations for the PV operating temperature are either explicit in form, thus giving T_c directly, or they are implicit, i.e. they involve variables which themselves depend on T_c. In this last case, an iteration procedure is necessary for the relevant calculation. Most of the correlations usually include a reference state and the corresponding values of the pertinent variables.

The electrical performance is primarily influenced by the type of PV used. A typical PV module converts 6-20% of the incident solar radiation into electricity, depending upon the type of solar cells and climatic conditions. The rest of the incident solar radiation is converted into heat, which significantly increases the temperature of the PV module and reduces the PV efficiency of the module. This heat can be extracted by flowing water/air beneath the PV module using thermal collector, called, photovoltaic thermal (PVT) collectors. In practice, only a-Si and crystalline Si have been found in the literature on PVT. The higher efficiency of crystalline Si will result in a higher electrical efficiency and a higher electrical-to-thermal ratio of the PVT than in the case of a-Si. Tripanagnostopoulos *et al.* [2] presents experimental measurements on PVT-liquid and PVT-air collectors for both a-Si and c-Si. He finds that at zero reduced temperature, for his PVT liquid collector, the efficiency of his c-Si prototype is 55% and his a-Si prototype 60%, while for his PVT air collector the c-Si prototype is 38% and the a-Si prototype 45%. However, the electrical performance for the c-Si modules is 12% and for the a-Si it is 6%. A higher thermal yield was also found for a-Si by Ji *et al.* [3]. However, in other experiments a lower thermal efficiency was found for a-Si than for c-Si, Affolter et al. [4, 5] and Platz *et al.* [6]. Zondag *et al.* [7] compared a conventional PV module, an unglazed PVT module and a glazed PVT module. The average annual electrical efficiency was found to be 7.2%, 7.6% and 6.6%, respectively. Chow [8] calculated the electrical performance of a thermosyphon PVT collector with the PV at the high end and at the low end of the absorber. For the colder low end, he found a 3% higher electrical efficiency. Naveed *et al.* [9] examined a PVT air system in which PV was connected to an unglazed transpired collector. It was found that a temperature reduction of 3-9^{o}C resulted in an improved electrical performance, allowing a reduction in PV area from 25 to 23 m^2. Krauter and Ochs [10] and Krauter [11, 12] have developed an unglazed integrated solar home system, in which a PV laminate is connected to a triangular water tank. The tank serves to cool the PV by means of an 'extended heat capacity'. Typically, at high irradiance a PV temperature reduction of about 20^{o}C is reported relative to a conventional solar home system, which leads to a 9-12% increase in electrical yield, depending on the stratification.

2. Temperature dependent electrical efficiency of PV module

The correlations expressing the PV cell temperature (T_c) as a function of weather variables such as the ambient temperature (T_a), local wind speed (V_w), solar radiation (I(t)), material and system dependent properties such as, glazing-cover transmittance (τ), plate absorptance (α), etc. [13]. The effect of temperature on the electrical efficiency of a PV cell/module can be obtained by using fundamental equation,

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

In this equation FF is fill factor, I_{sc} is short circuit current, V_{oc} is open circuit voltage and subscript m refers to the maximum power point in the modules I-V curve. 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 short-circuit current increases, but only slightly, Zondag [14]. Thus, the net effect leads to a linear relation in the form

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

in which η_{Tref} is the module's electrical efficiency at the reference temperature, T_{ref} and at solar radiation of 1000 W/m^2. 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.[15]. The latter, however, is usually taken as zero, Evans [16], and Eq. (2) reduces to

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

which represents the traditional linear expression for the PV electrical efficiency, Evans and Florschuetz [17]. The quantities η_{Tref} 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 [18]. 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

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

in which T_o is the (high) temperature at which the PV module's electrical efficiency drops to zero, Garg and Agarwal [19]. For crystalline silicon solar cells this temperature is 270°C, Evans and Florschuetz [20]. 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. One such expression is

$$\eta = \eta_{ref}\left[1 - \beta\left[T_a - T_{ref} + \left(T_{NOCT} - T_a\right)\frac{I(t)}{I(t)_{NOCT}}\right]\right] \tag{5}$$

The quantities labelled 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 [21]:

Global solar flux: 800 W/m^2,

Air temperature: 293.16 K (20^{o}C),

Average wind speed: 1 m/s,

Mounting: open rack, tilted normally to the solar noon sun.

Table 1. Evans–Florschuetz PV efficiency correlation coefficients, $\eta_c = \eta_{Tref}\left[1-\beta_{ref}(T_c - T_{ref})\right]$

T_{ref} (^{o}C)	η_{Tref}	β_{ref}	Comments	References
25	0.15	0.0041	Mono-Si	[17]
28	0.117	0.0038	Average of Sandia and commercial cells	[22]
25	0.11	0.003	Mono-Si	[23]
25	0.13	0.0041	PVT system	[24]
		0.005	PVT system	[25]
20	0.10	0.004	PVT system	[26]
25	0.10	0.0041	PVT system	[19]
20	0.125	0.004	PVT system	[27]
25		0.0026	a-Si	[28]
25	0.13	0.004	Mono-Si	[29]
	0.11	0.004	Poly-Si	
	0.05	0.0011	a-Si	
25	0.178	0.00375	PVT system	[30]
25	0.12	0.0045	Mono-Si	[8]
25	0.097	0.0045	PVT system	[7]
25	0.09	0.0045	PVT system	[31]
25	0.12	0.0045	PVT system	[32]
25	0.12	0.0045	PVT system	[33]
25	0.127	0.0063	PVT system	[34]
25	0.127 unglazed	0.006	PVT system	[35]
25	0.117 glazed	0.0054	PVT system	[36]

In addition to the 'instantaneous' values for the PV electrical efficiency, expressions for the monthly average efficiency can be written. The monthly electrical energy output of a PV array can be estimated on the basis of the following equation:

$$\overline{\eta} = \eta_{Tref}\left[1-\beta_{ref}(\overline{T}_a - T_{ref}) - \frac{\beta_{ref}\left(\overline{\tau\alpha}\right)\overline{VH_T}}{nU_L}\right] \quad (6)$$

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 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.* [37]. Temperature coefficient and equations found in the literature for the efficiency of PV cells/modules are shown in Tables 1 and 2, respectively. The first table contains values for the parameters of Equation (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^{o}C, average $\eta_{ref} \approx 0.12$ and average $\beta_{ref} \approx 0.0045^o C^{-1}$.

Table 2. PV array efficiency as a function of temperature.

Correlation	Comments	References
$\eta(I(t),T_c)=\eta(I(t),25°C)[1+c_3(T_c-25)]$	$c_3=-0.5$ (% loss per °C) for c-Si, -0.02, ..., -0.41 for thin film cells	[38]
$\eta_T=\eta_0-K(T^{1/4}-T_0^{1/4})$	$T_0=273\,K, K=22.4$	[39]
$\eta_a=\eta_n\times k_\gamma\times k_\theta\times k_\alpha\times k_\lambda$, 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	[40]
$\eta=\eta_{Tref}\left[1-\beta_{ref}(T_a-T_{ref})-\frac{\beta_{ref}\tau\alpha I(t)}{U_L}\right]$	5% low predictions, $\beta_{ref}\sim 0.004°C^{-1}$, $\eta_{Tref}=0.15, T_{ref}=0°C$	[37]
$\bar{\eta}=\eta_{Tref}\left[1-\beta_{ref}(\bar{T}_a-T_{ref})-\frac{\beta_{ref}\left(\overline{\tau\alpha}\right)\overline{VH_T}}{nU_L}\right]$	$\bar{\eta}$ = monthly average efficiency, V = demensionless, $\beta_{ref}\sim 0.004°C^{-1}$	[37]
$\eta_i=\eta_{Tref}[1-\beta_{ref}(T_{c,i}-T_{ref})+\gamma\log_{10}I_i]$	η_i = hourly efficiency, I_i = incident hourly insol, $\beta_{ref}\sim 0.0045°C^{-1}, \gamma\sim 0.12$	[16, 41]
$\eta=\eta_{Tref}[1-\beta_{ref}(T_c-T_{ref})+\gamma\log_{10}I(t)]$	η = instantaneous efficiency, $\beta_{ref}=0.0044°C^{-1}$, $\eta_{Tref}=0.125, T_{ref}=25°C$	[15]
$\bar{\eta}=\eta_{Tref}\left\{1-\beta_{ref}\left[(T_c-T_a)-(T_a-\bar{T}_a)-(\bar{T}_a-T_{ref})\right]+\gamma\log_{10}\bar{I}\right\}$	$\bar{\eta}$ = monthly average efficiency, $\beta_{ref}\sim 0.0045°C^{-1}$, $\gamma\sim 0.12$	[16]
$\eta=\eta_{ref}\left[1-a_1(T_c-T_{ref})+a_2\ln(I(t)/1000)\right]$	For Si $a_1=0.005, a_2=0.052$, omitting the ln term slightly overestimates η	[42]
$\eta=0.94-0.0043\left[\bar{T}_a+\frac{\overline{I(t)}}{(22.4+8.7\bar{V}_w)}-25\right]\pm 2.6\%$	Overbars denotes daily averages. $\overline{I(t)}$ = Wh/m^2 received/length of day(h), $\bar{V}_w$ in m/s	[43]
$\eta_{MPP}(I(t),T)=\eta_{MPP}(I(t),25°C)(1+\alpha(T-25))$ $eta_{MPP}(I(t),25°C)=a_1+a_2I(t)+a_3\ln(I(t))$	a_1-a_3 device specific parameters, MPP tracking system	[44]

$\eta = \eta_{NOCT}\left[1 - MPTC(T_{NOCT} - T_C)\right]$	$MPCT$ = Maximum power temperature codfficient With $MPCT$ = -0.5% loss per°C, the efficiency is η=11.523-0.0512Tc	[45]
$\eta_T = \eta_{T\,ref}[1 - \beta_{ref}(T - T_{ref})]$	$T_{ref} = 25°C, \eta_{T_{ref}} = 25°C, \eta_{T_{ref}} = 0.15,$ $\beta_{ref} = 0.0041°C^{-1}_{,} c - Si, T\, in°C$	[17]
$\eta_{PV} = \eta_{ref} - \mu(T_c - T_{ref})$	µ = overall cell temperature coefficient	[46]
$\eta(XI(t),T) = \eta(I(t),T_{ref})\left[1 - \beta_{ref}(T - T_0)\right]\left(1 + \frac{k_B T}{q}\frac{\ln X}{V_\infty(I(t),T_0)}\right)$	X = concentration factor, for $X = 1$ it reduces to Eq. $\eta_c = \eta_{T_{ref}}\left[1 - \beta_{ref}(T_c - T_{ref}) + \gamma \log_{10} I(t)\right]$	[47]
$\eta = \eta_{ref}\left[1 - \beta\left[T_a - T_{ref} + (T_{NOCT} - T_a)\frac{I(t)}{I(t)_{NOCT}}\right]\right]$	The T_c expression from Kou et al. [48] introduced into the η expression in Evans and Florschuetz [17]	[48, 17]
$\eta = \eta_{ref}\left\{1 - \beta\left[T_a - T_{ref} + \left(\frac{9.5}{5.7 + 3.8V_w}\right)(T_{NOCT} - T_a)\frac{I(t)}{I(t)_{NOCT}}\right]\right\}$	The T_c expression from Duffie and Beckman [49] introduced into the η expression in Evans and Florschuetz [17]	[49, 17]
$\eta = \eta_{ref}\left[1 - 0.9\beta\frac{I(t)}{I(t)_{,NOCT}}(T_{c,NOCT} - T_{a,NOCT}) - \beta(T_a - T_{ref})\right]$	Assumes $\eta \approx 0.9(\tau\alpha)$	[50]
$\eta_{nom} = -0.05T_{surface} + 13.75$ $\eta_{meas} = -0.053T_{back} + 12.62$	$T_{surface} = 1.06\, T_{back} + 22.6$; Nominal vs measured value	[51]
$\eta = a_0 + a_1\frac{T_c(x.t) - T_\infty}{T_\infty} + a_2\frac{I(t) - I(t)_{ref}}{I(t)_{ref}}$	At k = 0, 1 and 2 are empirical constants, $T\infty$ is the indoor ambient temperature.	[52]
$\eta = \eta_a - c(\overline{T} - T_a)$	$\overline{T}$ = mean solar cell temp, η_a =efficiency at T_a, c =temp coefficient	[53]
$\eta = \eta_{25} + b(T_c - 25)$	$b=b(I(t)), T\,\text{in}\,°\text{C}$	[54]

The increasing interest in BIPV applications brought forward the need for a proper estimation of NOCT which would take into account the integration-dependent deviation from NTE conditions, and the module temperature being higher due to lack of proper cooling from the poorly ventilated back side. Thus, the module's NOCT, which depends on the mounting scheme for a given irradiation level (Fig. 1), must be measured in a properly designed and well controlled outdoor test bed, like the European Commission's test reference environment (TRE) rig that was recently set up at the JRC Ispra for BIPV testing [55].

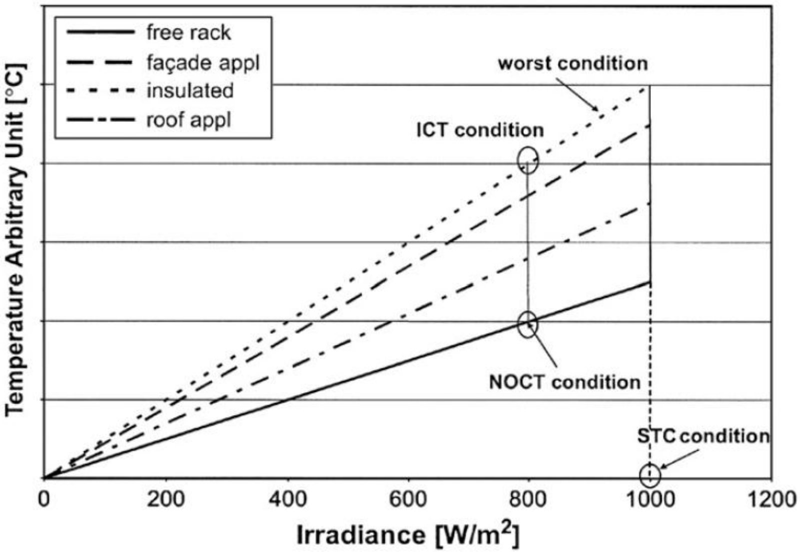

Fig. 1. BIPV mounting induced temperature difference from NOCT as a function of irradiance [55].

3. PV potential in the world

Photovoltaic (PV) electric power generation is a promising technology for generating renewable energy from solar irradiation. However, the output of PV is sensitive to its operating conditions, so estimating PV potential accurately is a complex problem. Furthermore, given the limited availability of data for the entire world, a method that achieves accurate estimates with available data is necessary. Most estimates of PV potential use either the power rating method or the energy rating method. The power rating method integrates the instantaneous PV power generation over time, thereby accounting for the time-dependency of PV output. The main problem of this method is its complexity and data requirements. Complete instantaneous weather data is not available globally, so no work has estimated the global PV potential by the power rating method.

The energy rating method estimates PV potential by multiplying the total solar irradiation during a specific period of time by a performance ratio. The simplicity of the energy rating method and the availability of global weather data have enabled researchers to estimate the PV potential for the world, and numerous countries. These studies use a constant performance ratio. However, the performance ratio actually changes under different operating conditions, especially ambient temperature, which limits the accuracy of these studies. Kawajiri *et al.* [56] have developed a modified energy rating method based on the JIS method (JIS C 8907; Japanese industrial standard) that estimates the effect of ambient temperature on global PV potential. The method was used to generate a global map of c-Si PV potential and annual performance ratio by considering PV systems mounted on a platform above ground and operated under direct connection to the grid without any kind of storage such as batteries.

The global distribution of annual total irradiation (H_y) on equator-pointed tilted surfaces obtained by summing the monthly total solar irradiation values in the NASA database, which are averages of 22 years of data from 1983 to 2005, is shown in Fig. 2 [56]. The global map of annual energy generation potential of c-Si PV systems is shown in Fig. 3. The regions with the largest irradiation values have large PV potentials. In particular, the Himalaya and Southern Andes regions have energy potentials of more than 1800 kWh/kW PV, due to the combination of large irradiation values and low temperatures. The Himalayan region is especially attractive because it is near regions with large future energy demands, such as China and India. Of course, many problems must be addressed when installing PV systems in high altitude regions, such as transporting the PV system and increased need for maintenance due to the severe environmental conditions. Several high-altitude PV plants are currently in operation [57].

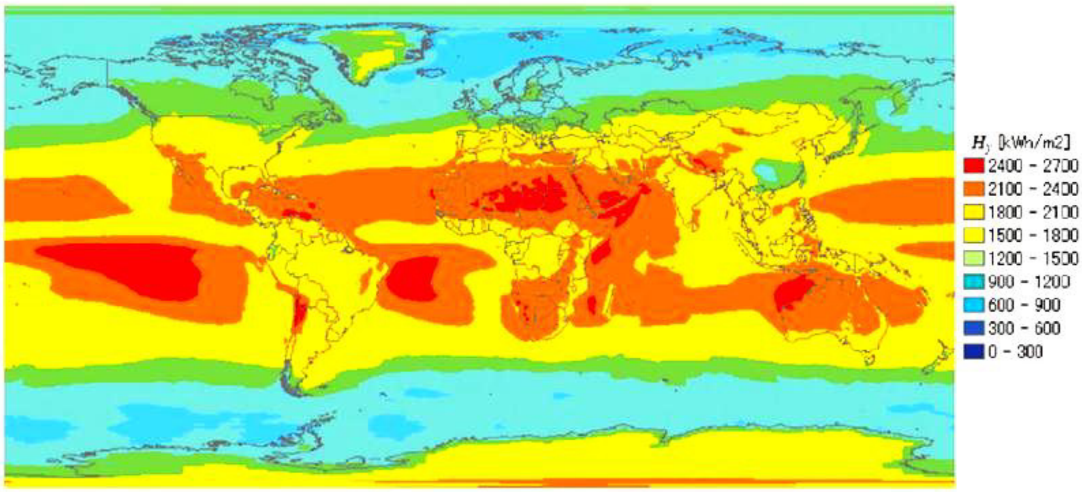

Fig. 2. Global map of annual total irradiation (H_y) on equator-pointed surfaces tilted at the latitude angle [56].

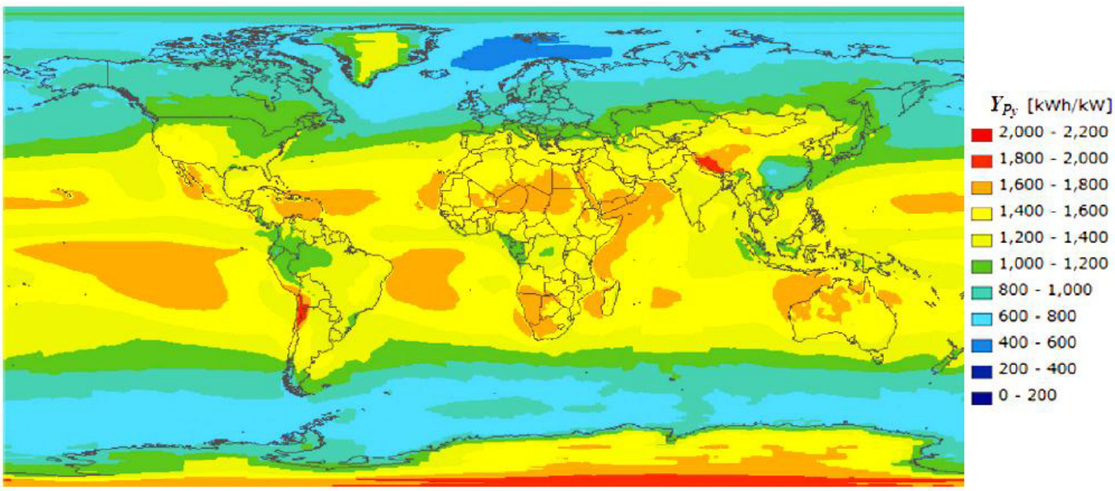

Fig. 3. Global potential map of PV energy generation (Y_{py}) by c-Si PV module [56].

4. Conclusion

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 numerous correlations for T_c which have appeared in the literature apply to freely mounted PV arrays, to PV/thermal collectors, and to BIPV installations, respectively. They involve basic environmental variables, while the numerical parameters are not only material dependent but also system dependent. Thus, one must be careful in applying a particular expression for the operating temperature of a PV module because the available equations have been developed with a specific mounting geometry or building integration level in mind. Therefore, the reader is urged to consult the original sources when seeking a correlation suitable for a particular application.

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