

# Photovoltaic Cell Operating Temperature Models: A Review of Correlations and Parameters

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**Abstract**—A review of photovoltaic (PV) cell operating temperature ( $T_c$ ) steady-state models developed from the year 2000 onward is shown in the present article. The goal is to help researchers and professionals in the field to choose the most significant parameters and suitable experimental arrangements to compose an accurate steady-state model. Initially, a brief description of  $T_c$  is given and an overview of the models for calculating  $T_c$  is presented. We present a summary of 33 correlations found in the literature for estimating  $T_c$  and the synthesis of those correlations in three general forms. Additionally, we highlight the main parameters in the analyzed correlations along with their most accurate data collection methods. The parameters with the greatest influence on  $T_c$ , appearing in a significant number of formulations, are discussed: solar absorbance, electrical efficiency, and transmittance of the PV cell/module glass cover; irradiance; ambient temperature; wind speed. Strategies of obtaining  $T_c$ —using the module back side temperature or an internal sensor for direct measurement—for model validation purposes are also discussed.

**Index Terms**—Model selection, photovoltaic (PV) cell correlations, PV cell temperature, PV modules thermal models, performance prediction.

## NOMENCLATURE

$C_g$	Geometric concentration ratio of the module.
$FF$	Fill factor.
$G$	Solar irradiance.
$G_{NOCT}$	Reference solar irradiance in NOCT conditions (800 W/m <sup>2</sup> ).
$G_{ref}$	Reference solar irradiance at STC conditions (1000 W/m <sup>2</sup> ).
$I_{sc}$	Short circuit current.
$I_{scr}$	$I_{sc}$ of module at reference conditions.
$k$	Boltzmann's constant.
$n$	Empirically determined cell “diode factor”.
$p$	Packing factor of solar module.
$P_{max}$	Maximum power.
$q$	Elementary charge.

Manuscript received June 24, 2021; revised August 24, 2021; accepted September 6, 2021. Date of publication October 22, 2021; date of current version December 23, 2021. This work was supported in part by CAPES and in part by CNPq. (Corresponding author: Leticia de Oliveira Santos.)

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Color versions of one or more figures in this article are available at <https://doi.org/10.1109/JPHOTOV.2021.3113156>.

Digital Object Identifier 10.1109/JPHOTOV.2021.3113156

$Q_g$	Radiation energy absorbed by the glass cover.
$r$	Ross coefficient.
$T_a$	Ambient temperature.
$T_{a,NOCT}$	Reference ambient temperature at NOCT conditions of 20 °C.
$T_b$	Module back side temperature.
$T_c$	PV cell operating temperature.
$T_{c,NOCT}$	PV cell operating temperature at NOCT conditions.
$T_{ground}$	Ground temperature.
$T_{h,0}$	Heat-sink temperature at shutter initiation.
$T_{sky}$	Sky temperature.
$T_{STC}$	Ambient temperature at STC conditions (25 °C).
$U_L$	Heat loss coefficient.
$U_{L,NOCT}$	Heat loss coefficient at NOCT conditions.
$V_{max}$	Maximum measured Voc for shutter event.
$V_{oc}$	Open circuit voltage.
$V_{ocr}$	$V_{oc}$ of module at reference conditions.
$V_w$	Wind speed.
$V_{w,NOCT}$	Reference average wind speed at NOCT conditions of 1 m/s.

## Abbreviations

BIPV	Building-integrated photovoltaics.
CFD	Computational fluid dynamics.
EVA	Ethylene vinyl acetate.
HCPV	High concentrating photovoltaic.
I-V curve	Current-voltage characteristic curve.
NOCT	Nominal operating cell temperature.
NTE	Nominal terrestrial environment.
OC	Open circuit.
PV	Photovoltaic.
SC	Short circuit.
STC	Standard test conditions.

## Greek Letters

$\eta$	Electrical efficiency.
$\eta_{STC}$	Efficiency coefficient at maximal power under STC conditions.
$\beta$	Module Voc temperature coefficient.
$\beta_{STC}$	$\beta$ at maximal power under STC.
$\tau$	Coefficient of transmissivity.
$\alpha$	Coefficient of absorbance.

## I. INTRODUCTION

**D**ESIGNING a photovoltaic (PV) system involves estimating its electricity production. Thereunto, the PV

performance must be considered, which is influenced by the environmental conditions and the resulting PV cell operating temperature ( $T_c$ ) [1]. Therefore, a thermal model is necessary to estimate the PV operating temperature. However, designing, implementing, and effectively monitoring PV plants performance is a difficult task due to the influence of factors related to the physics of solar cells and the environment. Forecast models performances are affected by many elements of uncertainties, and the influence of the prediction methodology and model parameters on the final error is not clear [2]. A performance model is expected to identify and quantify the influence of all significant factors, including electrical, thermal, spectral, solar, and optical effects [3].

The models for  $T_c$  estimation can be basically classified by two approaches: steady state and dynamic. The main difference between the methodologies is that in the steady-state approach all parameters are assumed to be time-independent, while in the dynamic approach some parameters are time-dependent [4].

Steady-state models are relatively simple, characterized by low computing times; nevertheless, these models are not flexible and can overestimate or underestimate the value of  $T_c$  [5]. The intensity of incoming solar irradiance and other parameters that affect the PV modules performance, in a short period of time, are supposed to be constant. For instance, if the heat transfer variation between the PV module and the surroundings is low, it can be considered as steady-state condition; temperatures in different positions of the PV module are also considered constant for steady-state condition [6].

Dynamic models can express more realistic and precise results considering the fluctuation of the solar irradiance in a short period [6]; this technique is based on  $T_c$  determination using an energy balance [1]. Hence, dynamic models describe  $T_c$  and its thermal process in more details compared to steady-state models. Nevertheless, these models are relatively complex, requiring more computation time, cost, and effort [5].

In recent years, considerable efforts have been devoted by the scientific community to the development and improvement of approaches for  $T_c$  calculation from measurable parameters; in such process, steady state models for  $T_c$  determination have become common. Hence, in the present article, we review PV operating temperature steady-state models from the year 2000 onward, aiming to help researchers and professionals in the field to choose the most appropriate parameters and experimental arrangements to compose an accurate model. Additionally, we summarize 33 equations found in the literature for estimating  $T_c$  in just three general forms. According to our review, no similar approach was proposed previously, highlighting the original contribution.

The rest of this article is organized as follows: In Section II, we discuss the importance of  $T_c$  and present an overview of the calculation methods. In Section III, we analyze correlations found in the literature survey and present the three general forms that can express all the correlations considered in this review. In Section IV, we focus on the main parameters of the considered models, discussing the significant parameters for an accurate model development: PV module electrical efficiency, solar absorption, and glass cover transmittance; solar irradiance

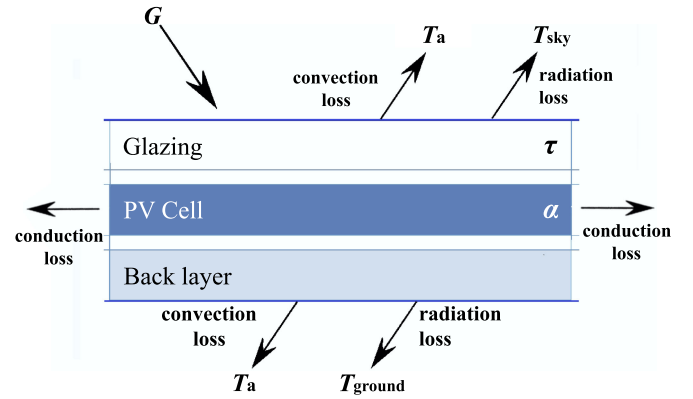


Fig. 1. Thermal processes in a PV module. Adapted from [10].

( $G$ ); ambient temperature ( $T_a$ ); wind speed ( $V_w$ ). In Section V, we comment strategies of obtaining  $T_c$  for model validation purposes and Section VI, concludes this article.

## II. THERMAL MODELS OF PV CELL OPERATING TEMPERATURE

The  $T_c$  is fundamental to characterize the module's behavior, but it is not an easily available parameter [7]. Hence, in the scientific literature, a significant number of contributions demonstrating the adverse effect of an increase in  $T_c$  on the module performance can be found [8]. This adverse effect results from the decrease of PV cell energy interval (bandgap) when the temperature increases, implying a change in the cell electric behavior: open-circuit voltage ( $V_{oc}$ ), efficiency ( $\eta$ ), fill factor ( $FF$ ), and maximum power ( $P_{max}$ ) decrease; a negligible increase of the short circuit current ( $I_{sc}$ ) occurs [9].

The thermal environment that establishes the instantaneous value of  $T_c$  is quite complex. A procedure that leads to the estimation of  $T_c$  is based on the energy balance of the module, which should consider both internal processes that occur during the bombardment of photons on the semiconductor, resulting in production of electricity, and not converted energy release as heat by standard mechanisms of heat transfer such as convection and radiation [10]. In most cases, these mechanisms affect the module front and back side, since in typical installations a distance between the module and the roof/slab is usually left to facilitate the rejected heat removal, allowing the module to operate in an efficient way. In the case of free-standing arrays, also should be considered the heat conduction through the mounting frame structure: heat is transported to the surfaces by conduction, and the surfaces release it to the environment by convection and radiation (see Fig. 1) [11].

In summary,  $T_c$  depends on factors such as: solar absorption properties of the cells; modules constituent materials (semiconductors, cells, layers, encapsulant, among others); thermal dissipation to the environment; installation and environmental conditions (location,  $G$ ,  $T_a$ , and  $V_w$ ) [12], [13].

The  $T_c$  prediction is the last step before reaching the power forecasting possibility [14]. The correlations for  $T_c$  found in the literature usually describe free-standing PV arrays, PV/thermal collectors, and building-integrated photovoltaics (BIPV)

installations [4], [15]. These correlations express  $T_c$  as a function of the relevant meteorological variables and include material and system-dependent properties and parameters depending on the type of assembly arrangements/schemes. Some correlations express the adverse effect of an increasing  $T_c$  on  $\eta$  [16], [17]. Methods based on electrical parameters consider that parameters such as  $V_{oc}$  vary with temperature, allowing estimating  $T_c$  with the help of electrical data measurements, using different procedures [18].

In general, most correlations include a reference state and corresponding values of the significant variables. A method to formulate  $T_c$  involves the use of the nominal operating cell temperature (NOCT) [19], defined as a device temperature in the nominal terrestrial environment (NTE): solar irradiance of  $800 \text{ W/m}^2$  ( $G_{NOCT}$ );  $T_a$  of  $20^\circ \text{C}$  ( $T_{a,NOCT}$ ); average  $V_w$  of  $1 \text{ m/s}$  ( $V_{w,NOCT}$ ); zero electrical charge (open circuit); independent assembly structure oriented “normal to solar noon” [20], [21].

Standard conditions are employed to the PV module performance “classification” or “specification.” The associated performance parameters are usually the manufacturer’s nameplate ratings (specifications) or results of tests from a module testing laboratory. These performance specifications accuracy is fundamental to the design of PV plants, the reference point is provided from which performance in all other operating conditions is supplied [22]. Ideally, NOCT must be exactly the same regardless the testing laboratory, location, month or season [23]. In [24], a modification of the method for obtaining NOCT is proposed to calculate the called “realistic nominal module temperature,” more representative in outdoor since in NOCT conditions, conditions of exposure are “open circuit,” that do not count for the electrical energy withdrawal.

If not available from the data provided by the module manufacturer, the necessary parameters can be measured during outdoor tests under real operating conditions [25]. In BIPV plants, the modules are installed at an optimum distance from the building facade; as a result, the energy balance is not limited to the module layers. In this case, both sides of the modules are under quite different environmental conditions and the simple NOCT model can underestimate  $T_c$  by up to  $20 \text{ K}$  [26]. Consequently, in such applications a system of three equations simultaneously is needed, an energy balance for each of the three layers—PV module, the air layer between the module and the wall, and the wall—resulting in the respective equations, featuring each temperature. Such balances consider heat transfer among layers, ambient, and interior space. The methodology involves a lumped analysis approach, adopting uniform conditions along the gap; in more detailed studies are employed dynamic models and computational fluid dynamics (CFD) methods [27], [28].

From a mathematical viewpoint, the  $T_c$  models can be explicit, providing  $T_c$  directly, or implicit, involving variables that depend on  $T_c$ . In the second case, is required an interactive procedure [29]. Implicit models are based on the module’s thermal properties and heat transfer mechanisms.  $T_c$  is interactively determined from an energy balance applied to the module. The explicit methods calculate  $T_c$  using known parameters [7].  $T_c$  can be associated to the module back side temperature ( $T_b$ ). The

TABLE I  
ROSS PARAMETERS FOR VARIOUS INSTALLATIONS [33]

PV array mounting type	$r \text{ (K m}^2/\text{W)}$
Free standing	0.021
Flat roof	0.026
Sloped roof well-cooled	0.020
Sloped roof not so well-cooled	0.034
Sloped roof highly integrated, poorly ventilated	0.056
Facade integrated transparent PV	0.046
Facade integrated opaque PV	0.054

difference between both temperatures depends on the substrate materials of the module, and the  $G$  levels. A simple implicit empirical thermal model relating  $T_c$  and  $T_b$  has been successfully applied to several module arrangements, providing the expected  $T_c$  value with an accuracy of about  $\pm 5^\circ \text{C}$  [see (1)]. This magnitude of  $T_c$  uncertainties result in an effect of less than 3% on the module power output [3]

$$T_c = T_b + \frac{G}{G_{\text{ref}}} \Delta T. \quad (1)$$

$G$  is the solar irradiance on the PV module ( $\text{W/m}^2$ ),  $G_{\text{ref}}$  = solar irradiance at standard test conditions (STC) ( $1000 \text{ W/m}^2$ ) and  $\Delta T$  = temperature difference between  $T_c$  and  $T_b$  at  $G_{\text{ref}}$ .

The simplest explicit equation links  $T_c$  to the ambient temperature,  $T_a$ , and  $G$  [see (2)] [30]

$$T_c = T_a + rG. \quad (2)$$

This linear expression does not consider wind or electric charge, but a dimensional parameter  $r$ , the so-called Ross coefficient. Reported values for  $r$  vary and can be categorized qualitatively according to the level of integration and the space behind the modules [31], [32]. Some studies associate estimated values of  $r$  with different types of assembly arrangements/schemes [10] (see Table I).

Under NOCT conditions, (3) assumes the same  $T_a$  for both sides of the module, considering that the temperature difference ( $T_c - T_a$ ) is practically independent of  $T_a$ , but linearly proportional to  $G$  [34]. Furthermore, the heat loss coefficient ( $U_L$ ) is considered constant in this equation; this coefficient includes heat losses by convection, radiation, and conduction. Hence, the energy balance for an unitary area of the PV module is

$$T_c = T_a + \left( \frac{G}{G_{NOCT}} \right) \left( \frac{U_{L,NOCT}}{U_L} \right) (T_{NOCT} - T_{a,NOCT}) \left[ 1 - \left( \frac{\eta}{\tau\alpha} \right) \right]. \quad (3)$$

In NOCT conditions, there is no-load operation, i.e.,  $\eta = 0$  [34]. Since  $\eta$  is a function of  $T_c$ , (3) is an implicit equation of  $T_c$ .

Values of cell’s direct measurements include basic performance parameters ( $I_{sc}$  and maximum power point current,  $V_{oc}$  and maximum power point voltage) in the standard condition (reference), as well as other variables [35]. Methods based on the cell’s direct measurements have proved to be more accurate than methods based on meteorological parameters for  $T_c$  estimation. The last presents more uncertainties associated to the sources of data and the model itself [18], but it is a very useful

tool considering the advantage that  $T_c$  can be estimated at any location using meteorological data [36].

The use of a method based on the cell's direct measurements has the benefit of obtaining the parameters from the scientific literature or manufacturer data [37], [38]. However, precise parameter values are required because the given methods are highly sensitive to the chosen values. It is assumed that the spectral influence, module temperature coefficients, and optical losses are available in the results of tests with individual modules. This kind of mathematical model includes internal losses associated with wiring resistance and module incompatibility, values difficult to predict or explicitly determine. Other methods based on direct measurements have the disadvantage that the parameters should be adjusted by outdoor experimental tests—such as requiring a module with a cell temperature sensor for example—or from internal measurements in a sun simulator.

Considering a set of PV modules, the thermal model usually considers the modules as an unity. In general, the effect of incompatibility and resistance losses is small ( $< 5\%$ ) in relation to the expected performance of the nameplate classifications of the individual modules [3]. Optimally, performance measurements are available at the arrangement level, improving the model accuracy. Once developed, the model can be applied for autonomous PV power plants; such plants are more complex than grid connected systems, since they can include batteries for energy storage and generators as auxiliary energy source.

The  $T_c$  correlations found in the literature from the year 2000 onward, are shown in Table II, including pertinent comments for the correlations. These equations have been developed considering a specific assembly geometry or a building integration level; hence, care should be taken when applying any of them. Depending on the specific application, some methods may be more suitable than others. Choose the most suitable method is not easy and depends mainly on the availability of module's data, the necessary precision and technical issues.

### III. GENERAL FORMS OF THE CORRELATIONS

Analyzing the equations of Table II, correlations 1–20 are linear and can be expressed by (4). ISFOC model (Correlation 21 in Table II) is linear if the terms in parentheses are assumed to be constant.

$$T_c = a_0 + a_1 T_a + a_2 G + a_3 V_w + a_4 T_b. \quad (4)$$

The terms  $a_0$ ,  $a_1$ ,  $a_2$ ,  $a_3$ , and  $a_4$  are specific for each of the mentioned linear models and are specified in Table V presented in the Appendix.

Correlations 22–30 of Table II are nonlinear and can be expressed by 5. Sandia's model can fit into this general expression if  $\Delta T = (T_c - T_b)G_{\text{ref}}$  is constant

$$T_c = b_0 + b_1 T_a + C_1(e^{d_1+d_2 V_w} + e_1)G + C_2(e_2 + f_1 T_a)^{g_1}(e_3 + f_2 G)^{g_2}(e_4 + f_3 V_w)^{g_3}. \quad (5)$$

The terms  $b_0$ ,  $b_1$ ,  $C_1$ ,  $d_1$ ,  $d_2$ ,  $e_1$ ,  $C_2$ ,  $e_2$ ,  $f_1$ ,  $g_1$ ,  $e_3$ ,  $f_2$ ,  $g_2$ ,  $e_4$ ,  $f_3$ , and  $g_3$  are specific for each of the mentioned nonlinear models and are specified in Table VI presented in the Appendix. Kurtz *et al.* model is a particular case of the Hornung *et al.* model.

Duffie and Beckman II and Mattei models are nonlinear and can be expressed in the form of (6).

$$T_c = (h_1 T_a + h_2 G)(m_1 + n_1 G)^{-1}. \quad (6)$$

The terms  $h_1$ ,  $h_2$ ,  $m_1$ , and  $n_1$  are specific for Duffie and Beckman II and Mattei models and are specified in Table VII presented in the Appendix. Summarizing, all models of Table II can be grouped in the form of one of the equations defined above according to their terms.

### IV. MAIN MODELS PARAMETERS

The thermal properties of materials and environmental conditions have a great influence on  $T_c$  as part of the solar irradiation is converted into heat [68].  $T_c$  depends heavily on  $G$  and  $T_a$  and is very sensitive to  $V_w$  [69], [70]. In this section, we highlight the parameters that have the greatest influence on  $T_c$ , considering the number of correlations. Considering the 33 correlations analyzed,  $G$ ;  $T_a$ ;  $V_w$ ;  $\eta$ ; solar absorption; glass cover transmittance are the most frequent (see Table III), appearing in: 100%, 93.9%, 54.5%, 33.3%, 30.3%, and 24.2% of the correlations, respectively. These parameters are grouped in meteorological variables and properties dependent on the material and/or system configuration.

#### A. Meteorological Variables

Generally, models for determining  $T_c$  use solar data dependent on the location, meteorological data obtained through recognized databases or meteorological models [71], [72]. Estimates of hourly averaged values are usually applied in thermal models to predict the associated  $T_c$ . If not, methods based on meteorological parameters require an outdoor experimental campaign to obtain  $G$ ,  $T_a$ , and  $V_w$  values and parameters. Data estimate and/or average generates uncertainty related with the tabulated values and the thermal models. When using measurement instruments, models are also not free from uncertainties; there may be external influences or flaws in the measurement and accuracy of the instrument, depending on the experimental arrangement. Some technical difficulties are discussed, such as a system that blocks sunlight [73], the requirement of a solar simulator [74], the need for the entire module  $I$ - $V$  curve [75] and the need for advanced knowledge in some specific issues.

1) *Effective Irradiance*: The output power of the PV cell is directly proportional to  $G$  incident on its surface [8]. Hence, measurements or estimates of  $G$  in a specific location are essential to predict the performance and efficiency of PV systems [76], [77].  $G$  produces heat transfer by radiation, which is the most influential factor on  $T_c$  variations [78]. For an increase of  $100 \text{ W/m}^2$  in  $G$ , increases in  $T_c$  between  $1.8^\circ\text{C}$  and  $4.93^\circ\text{C}$  are found in the literature, these values are not universal and depend on the type of PV module [55]. Some devices are specifically designed to measure  $G$ , as the irradiance meter and the pyranometer [79], [80]. In addition to these, cost-effective tools are found in the literature to estimate  $G$  [81]. Often the most important source of error in determining PV power is related with the procedure and instrument chosen to quantify  $G$  [3]. This is due to the different systematic influences on the test



TABLE II  
EQUATIONS FOR  $T_c$  FROM THE YEAR 2000 ONWARDS INCLUDING PERTINENT COMMENTS

N°	Correlations name	Formulation	Comments	References
1	Fernández <i>et al.</i> <sup>1</sup>	$T_c = \frac{(V_{OC} - c_1 G - c_3)}{c_2}$	$c_1, c_2$ and $c_3$ are linear coefficients	[18], [16]
2	Durisch <i>et al.</i>	$T_c = T_a + kG$	$k = \frac{\Delta T_c}{\Delta G}$ : 0.02 - 0.04°Cm²/W	[39], [40]
3	Nordmann and Clavadetscher	Same as above	0.02 < $k$ < 0.056 for BIPV situations	[10], [32]
4	Krauter	Same as above	$k = 0.03, 0.012, 0.0058$ for conventional, upper or lower module in packaged home system, respectively	[41]
5	Mondol <i>et al.</i> I	$T_c = T_a + 0.031G$	For $V_w$ above 1m/s with a constant heat loss coefficient	[10], [42], [43]
6	Hove	$T_c = T_a + G \left( \frac{\tau\alpha - \eta}{U_L} \right)$	$\frac{\tau\alpha}{U_L}$ determined experimentally	[10], [44]
7	Tiwari	$T_c = T_a + G \left( \frac{\tau\alpha}{U_L} \right) \left[ 1 - \left( \frac{\eta}{\tau\alpha} \right) \right]$	$\frac{\tau\alpha}{U_L}$ taken as constant	[10], [45]
8	Eicker	$T_c = T_a + G \left( \frac{\alpha}{U_L} \right) \left[ 1 - \frac{\eta}{\alpha} \right]$	$U_L = h_{radn} + h_{conv}$ . Where $h_{conv}$ and $h_{radn}$ are coefficients of convection and radiation respectively	[10], [46]
9	Standard	$T_c = T_a + \left( \frac{G}{G_{NOCT}} \right) (T_{c,NOCT} - T_{a,NOCT})$	Steady state model for a flat plate module including crystalline silicon devices and thin-film cells	[7], [8], [4], [29], [47], [48], [49], [50], [51]
10	Davis	$T_c = T_a + \left( \frac{G}{G_{NOCT}} \right) (T_{c,NOCT} - T_{a,NOCT}) \left[ 1 - \left( \frac{\eta}{\tau\alpha} \right) \right]$	Assumes $U_L$ constant	[10], [26]
11	Mondol <i>et al.</i> II	$T_c = T_a + 0.031G - 0.058$	For $V_w$ above 1m/s with a constant heat loss coefficient	[10], [6], [52]
12	Tselepis	$T_c = 30 + 0.0175(G - 150) + 1.14(T_a - 25)$	Estimates $T_c$ for an a-Si module	[6], [53]
13	Tiwari and Sodha I	$T_c = \frac{pG(\tau\alpha - \eta) + (U_t T_a + U_T T_b)}{(U_t + U_T)}$	$U_t, U_T$ : heat transfer coefficients specified in [54]	[55], [54], [56], [57]
14	Tiwari and Sodha II	$T_c = \frac{\tau[\alpha C p + \alpha \gamma (1 - \beta C) G - \eta C G \beta C + U_t T_a + U_T T_b]}{(U_t + U_T)}$	$T_b$ function of the product $\eta T_c$	[10], [54]
15	Almonacid <sup>1</sup>	$T_c = T_a + d_1 G + d_2 V_w$	$d_1, d_2$ : multilinear regression parameters	[18], [58]
16	Markvart	$T_c = 0.943T_a + 4.3 + 0.028G - 1.528V_w$		[6], [48], [59]
17	Muzathik	$T_c = 0.943T_a + 0.3529 + 0.0195G - 1.528V_w$		[6], [60]
18	Akyuz <i>et al.</i>	$T_c = 0.95T_a + 3.1 + 0.025G - 0.3V_w$		[6], [61]
19	NOCT-1p model	$T_c = T_a + \left( \frac{G}{G_{NOCT}} \right) (T_{c,NOCT} - T_{a,NOCT}) + a(V_w - V_{w,NOCT})$	$a$ : parameter determined by data empirical fitting	[7]
20	NOCT-2p model	$T_c = T_a + b \left( \frac{G}{G_{NOCT}} \right) (T_{c,NOCT} - T_{a,NOCT}) + c(V_w - V_{w,NOCT})$	$b$ and $c$ : empirical parameters	[7]
21	ISFOC method <sup>1</sup>	$T_c = T_b + \left( \eta C_g \sum \frac{L_i}{\lambda_i} \right) G$	$i, L_i$ and $\lambda_i$ : layers, thickness and thermal conductivity of material behind the cell, respectively	[62]
22	Faiman	$T_c = T_a + \frac{G}{U_0 + U_1 V_w}$	$U_0, U_1$ : specified in [24] for selected PV cells	[24], [29], [63]
23	Skoplaki and Palyvos	$T_c = T_a + \frac{0.32}{8.91 + 2V_w} G$	Estimates $T_c$ for a p-Si module	[10], [6]
24	Skoplaki <i>et al.</i> I	$T_c = T_a + \frac{0.25}{5.7 + 3.8V_w} G$		[10], [6]
25	Duffie and Beckman I	$T_c = T_a + \frac{G(T_{c,NOCT} - T_{a,NOCT})}{G_{NOCT}} \left( \frac{9.5}{(5.7 + 3.8V_w)} \right) \left[ 1 - \left( \frac{\eta}{\tau\alpha} \right) \right]$	$\tau\alpha \approx 0.9$	[34]
26	Skoplaki <i>et al.</i> II	$T_c = T_a + \frac{G(T_{c,NOCT} - T_{a,ref})}{G_{NOCT}} \left[ \frac{h_{NOCT}}{h} \left\{ 1 - \frac{\eta_{STC}}{\tau\alpha} (1 + \beta_{STC} T_{STC}) \right\} \right]$	$h$ = wind convection coefficient, $h = 5.7 + 3.8V_w$ or $h = 8.91 + 2.0V_w$ specified in [33]	[29], [33], [51]
27	Chenni <i>et al.</i>	$T_c = T_a + 0.0138G(1 + 0.031T_a)(1 - 0.042V_w)$	Estimates $T_c$ for a Polycrystalline module	[10], [53], [59]
28	Kurtz <i>et al.</i>	$T_c = T_a + G e^{-3.473 - 0.0594V_w}$	Estimates $T_c$ for different PV technologies	[6], [51], [64]
29	Hornung <i>et al.</i> <sup>1</sup>	$T_c = T_a + m \left[ e^{\left( \frac{-0.5V_w}{V_{w0}} \right)} + c \right] G$	$m, V_{w0}$ and $c$ : coefficients obtained by multilinear regression specified in [65]	[18], [65]
30	Coskun <i>et al.</i>	$T_c = 1.4T_a + 0.01(G - 500) - V_w^{0.8}$	Estimates $T_c$ for a Polycrystalline module	[6]
31	Sandia's model	$T_c = T_b + \left( \frac{G}{G_{ref}} \right) \Delta T$ and $T_b = G(e^{a+bV_w}) + T_a$	$a$ and $b$ : empirical parameters. $\Delta T = T_c - T_b$ at $G_{ref}$ Adapted for High Concentrating Photovoltaic (HCPV) modules in [18]	[3], [10], [18]
32	Duffie and Beckman II	$T_c = \frac{T_a + \frac{G}{G_{NOCT}} (T_{c,NOCT} - T_{a,ref}) \left\{ 1 - \frac{\eta_{STC}}{\tau\alpha} (1 + \beta_{STC} T_{STC}) \right\}}{1 - \frac{\eta_{STC}}{\tau\alpha} \frac{G}{G_{ref,NTE}} (T_{c,NOCT} - T_{a,ref})}$		[29], [34], [66]
33	Mattei	$T_c = \frac{UT_a + G(\tau\alpha - \eta_{STC} - \beta_{STC} \eta_{STC} T_{STC})}{U - \beta_{STC} \eta_{STC} G}$	$U$ : heat exchange coefficient for the module surface. $U = 26.6 + 2.3v$ or $U = 24.1 + 2.9v$ , specified in [67]. $\tau\alpha = 0.81$	[7], [10], [29], [51], [67]

<sup>1</sup> Applied to HCPV.

TABLE III  
PARAMETERS OF THE ANALYZED EQUATIONS (✓ MEANS A PARAMETER OF THE CORRELATION, × OTHERWISE)

Correlations vs parameters	$G$	$T_a$	$V_w$	$\eta$	$\alpha$	$\tau$	$G_{NOCT}$	$T_{c,NOCT}$	$T_{a,NOCT}$	$\beta$	$U$	Other inputs (appear in five or less of the studied correlations)
Fernández <i>et al.</i>	✓	×	✓	×	×	×	×	×	×	×	×	$V_{oc}, c_1, c_2, c_3$
Durisch <i>et al.</i>	✓	✓	×	×	×	×	×	×	×	×	×	$k$
Nordmann and Clavadetscher	✓	✓	×	×	×	×	×	×	×	×	×	$k$
Krauter	✓	✓	×	×	×	×	×	×	×	×	×	$k$
Mondol <i>et al.</i> I	✓	✓	×	×	×	×	×	×	×	×	×	
Hove	✓	✓	×	✓	✓	✓	×	×	×	×	✓	
Tiwari	✓	✓	×	✓	✓	✓	×	×	×	×	✓	
Eicker	✓	✓	×	✓	✓	×	×	×	×	×	✓	
Standard	✓	✓	×	×	×	×	✓	✓	✓	×	×	
Davis	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	
Mondol <i>et al.</i> II	✓	✓	×	×	×	×	×	×	×	×	×	
Tselepis	✓	✓	×	×	×	×	×	×	×	×	×	
Tiwari and Sodha I	✓	✓	×	✓	✓	✓	×	×	×	×	×	$p, T_b, U_t, U_T$
Tiwari and Sodha II	✓	✓	×	✓	✓	✓	×	×	×	✓	×	$p, T_b, U_t, U_T$
Almonacid	✓	✓	✓	×	×	×	×	×	×	×	×	$d_1, d_2$
Markvart	✓	✓	✓	×	×	×	×	×	×	×	×	
Muzathik	✓	✓	✓	×	×	×	×	×	×	×	×	
Akyuz <i>et al.</i>	✓	✓	✓	×	×	×	×	×	×	×	×	
NOCT-1p model	✓	✓	✓	×	×	×	✓	✓	✓	×	×	$a, V_w, NOCT$
NOCT-2p model	✓	✓	✓	×	×	×	✓	✓	✓	×	×	$b, c, V_w, NOCT$
ISFOC method	✓	×	×	✓	×	×	×	×	×	×	×	$T_b, C_g, L_i, \lambda_i$
Faiman	✓	✓	✓	×	×	×	×	×	×	×	×	$U_0, U_1$
Skoplaki and Palyvos	✓	✓	✓	×	×	×	×	×	×	×	×	
Skoplaki <i>et al.</i> I	✓	✓	✓	×	×	×	×	×	×	×	×	
Duffie and Beckman I	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	
Skoplaki <i>et al.</i> II	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	$h, h_{NOCT}, T_{STC}$
Chenni <i>et al.</i>	✓	✓	✓	×	×	×	×	×	×	×	×	
Sandia's model	✓	✓	✓	×	×	×	×	×	×	×	×	$G_{ref}, e, a, b$
Kurtz <i>et al.</i>	✓	✓	✓	×	×	×	×	×	×	×	×	
Hornung <i>et al.</i>	✓	✓	✓	×	×	×	×	×	×	×	×	$m, V_{w0}, c$
Coskun <i>et al.</i>	✓	✓	✓	×	×	×	×	×	×	×	×	
Duffie and Beckman II	✓	✓	×	✓	✓	×	✓	✓	✓	✓	×	$T_{STC}$
Mattei	✓	✓	✓	✓	✓	✓	×	×	×	✓	✓	$T_{STC}$

TABLE IV  
ISC-VOC METHODS FOR  $T_c$  INCLUDING PERTINENT COMMENTS

Correlations name	Formulation	Comments	References
Muller <sup>1</sup>	$T_c = T_{h,0} + \frac{(V_{max} - V_{oc(t)})}{(N_s \beta)}$	$\beta = -0.0045$ (V/C/cell). $N_s$ : Number of cells in series in a module.	[18], [73]
Voc-IsC method <sup>1</sup>	$T_c = \frac{V_{oc} - V_{ocr} + \beta(C_g)T_r}{\frac{n_k}{q} \ln \frac{I_{sc}}{I_{scr}} + \beta(C_g)}$	$T_{h,0}$ : Heat sink temperature at shutter initiation specified in [73] $T_r = 298.15$ Kelvin Reference temperature	[3], [73], [104]
Improved Voc-IsC method	$T_c = \frac{V_{oc} - V_{ocr} - \frac{n_k T_r}{q} \ln(C_g)}{\frac{n_k}{q} \ln(C_g) + \beta} + T_r$	Similar to the model presented by [3] for $C_g = 1$	[3], [73], [104]
IEC 60904-5 method	$T_c = \frac{\beta T_{c,ref} + V_{oc} - V_{ocr} + \frac{n_k}{q} \ln \left( \frac{G_{ref}}{G} \right)^{273 N_s}}{\beta - \frac{n_k}{q} \ln \left( \frac{G_{ref}}{G} \right) N_s}$	$T_{c,ref}$ is the $T_c$ at the STC conditions	[37]

results: the response of the module and the  $G$  sensor may vary; the orientation and the optical acceptance angle or the module and the  $G$  sensor viewing angle may differ, the response of the module and the  $G$  sensor varies significantly depending on the incidence angle [82]. In addition, in case of shading or dust, the value detected by the measuring instrument and the  $G$  value on the cell can be different [83], [84].

The concept of “effective  $G$ ” provides a method for reduce the difficulty and uncertainty related with PV plants field testing and for dealing with the mentioned systematic influences. The effective  $G$  is the  $G$  on the module plane to which the PV cells really respond, upon the optical losses influences and solar spectral variation due to the angle of solar incidence and the module dirtiness. Depending on the required precision and the available measured data, different approaches can be used to determinate the effective  $G$  as demonstrated in [81], where the authors propose a smartphone-aided accessible setup to estimate the solar irradiance in a certain location. And in [82], where the authors measure irradiance using a mobile multipyranometer array with five pyranometers.

2) *Wind Speed*: The  $V_w$  value becomes a relevant environmental variable, favoring heat loss by convection. The results of the sensitivity analysis for a polycrystalline PV module type 125G-2 are reported in [47]: a  $T_c$  drop of  $3.3^\circ\text{C}$  is quantified when  $V_w$  increases from 1 to 2 m/s; this value is not universal and depend on the type of PV module and type of materials used. Monitoring and/or establishing uniform conditions for relevant wind measurements, especially in field, is not a simple task. Hence, many correlations using heat transfer coefficients related to  $V_w$  can be found in the scientific literature in recent years [85].

The low availability of local data is a barrier to ensure accurate results for assessing the real efficiency of operation in situations, where  $T_c$  plays a fundamental role [86]. Consequently, some of the PV system efficiency simulators that base  $T_c$  on environmental variables usually disregard  $V_w$ . An option to replace field measurements is local data from numerical climate prediction models [51], [87].

The standard meteorological practice for  $V_w$  and wind direction record, locates the measurement device, anemometer, at the height of 10 m in an area with a minimum number of structures or buildings that could obstruct air movement [3]. However, in some studies, after installing the system, the thermal model can be “adjusted” by determining coefficients that compensate for location-dependent influences and installations of anemometers that are different from standard meteorological practice [88].

The empirically determined coefficients also vary for different types of modules and mounting configurations [89]. In some cases, a generic coefficient is presented for typical flat plate PV modules from distinct manufacturers. Nevertheless, the thermal behavior of the concentrator modules can vary significantly, depending on the module design [73], [74]. Therefore, concentrator coefficients must be determined empirically for each module project.

The wind direction can have a small but noticeable influence on  $T_c$ . However, the incorporation of the wind direction effect in the thermal model is unnecessarily complex [51]. Therefore, in most studies, the influence of the wind direction on  $T_c$  is

disregarded or considered as a random influence, adding uncertainty to the thermal model.

3) *Ambient Temperature*: The  $T_a$  value has proved to be an important variable in models, influencing  $\eta$  and  $T_c$  [90]. For a polycrystalline PV module  $T_c$  increases around  $1^\circ\text{C}$  when  $T_a$  gains  $1^\circ\text{C}$ , this increase depends on the type of PV module [47]. Almost all  $T_c$  models require  $T_a$  as input. Monitoring  $T_a$  does not present a major challenge, considering the high precision devices available in the market, with a considerable operating range and resolution at an acceptable cost. Moreover,  $T_a$  accurate monitoring techniques are already known and established [91]. Globally, the scientific literature have shown that the PV performance rate increases with the altitude due to the low temperature. Regions with high altitude such as the southern Andes, the region of Himalayan and Antarctica have demonstrated the largest PV potentials [92].

## B. Properties Dependent on the Material and System Configuration

1) *PV Cell/Module Electrical Efficiency*: The  $\eta$  value decays with increasing  $T_c$  [93]. For crystalline PV modules under an irradiance of  $1000\text{ W/m}^2$ ,  $\eta$  decreases around  $0.03\text{--}0.06\%$  with  $1^\circ\text{C}$  increase in  $T_c$  [55]. Hence,  $\eta$  is a parameter present in a large number of correlations and depends on the PV cell electrical parameters such as  $V_{oc}$ ,  $FF$ , and  $I_{sc}$ , and  $G$  [93]. Usually, the manufacturer provides the values of  $\eta$ ,  $V_{oc}$ ,  $I_{sc}$ , and  $FF$  under standard conditions, since these parameters are directly linked to the production of the cell/module. These variables can be obtained experimentally [94], each of them providing information about the device physics [95].

2) *Solar Absorption and Transmittance of PV Module Glass Cover*: The solar energy incident on a body can be absorbed, reflected, and/or passed through the material. This characteristic can be seen in all semitransparent materials, represented by the well-known coefficients of transmissivity ( $\tau$ ), reflectivity, and absorbance ( $\alpha$ ) [96]. These coefficients are dependent on  $G$  and influence the rate of irradiance converted by the PV cell [9]. Usually, cells are manufactured to maximize the absorption of the wavelengths [97]. The radiation energy absorbed by the glass cover is represented by (7)

$$Q_g = G\alpha = G(1 - \tau_A). \quad (7)$$

$\tau_A$  is the glass transmittance considering loss only through absorption [98].

The  $\alpha$  value appears in correlations of  $T_c$  both independently and through the product  $\tau\alpha$  [99]. Mathematical models relating the sensitivity of the manufacturing parameters to the electrical and thermal efficiency of PV devices have shown that there are gains when considering the product  $\tau\alpha$  [97]. The influence of optical losses (reflectance) for flat plate modules is usually negligible to  $G$  incidence angles under  $55^\circ$ . Such losses for a not oriented perpendicular to the sunlight path module surface are added to the typical “cosine” loss. Hence, the cumulative effect (loss) over the year must be considered in system design. For modules that accurately track the sun, there is no optical loss [3].

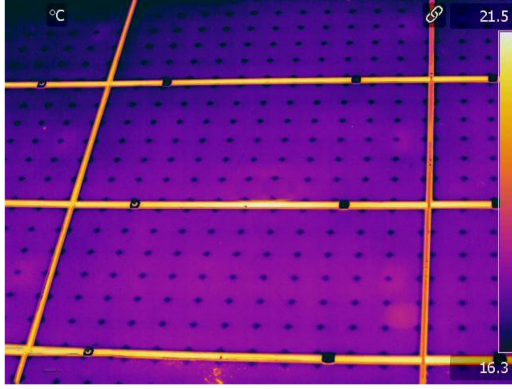


Fig. 2. PV module infrared thermal image. Adapted from [103].



Fig. 3. Representation of the PV cell showing ideal measurement position of  $T_c$ .

3) *Other Factors*: Various coefficients appear in the literature that are related to  $T_c$ , influenced by the module construction, the assembly configuration and the location and height at which  $V_w$  is measured. There are also the so-called factors that “introduce random influences” in  $T_c$ , such as the module thermal capacitance and thermal transients caused by clouds, shading, humidity, and dust [100], [101]. These random effects are averaged daily or annually.

## V. VALIDATION OF MODELS BY $T_c$ DETERMINATION

The cells operate at slightly different temperatures throughout a PV module [63]. To register such behavior, thermography allows reliable monitoring of the PV plant temperature [102], according to Fig. 2. Considering this temperature difference, researchers mention an “average cell temperature,” or just “cell temperature,”  $T_c$  [18]. PV cell is surrounded by encapsulating materials; hence, a direct measurement of  $T_c$  true value is not possible in general. The concept of  $T_c$  is not usually clearly defined, depending on the methodology and technique used.

The measurement of  $T_c$  true value can be implemented inside the PV module structure, between PV cell and the ethylene vinyl acetate (EVA) coating [105] (see Fig. 3).  $T_c$  can be obtained empirically, a nontrivial work, or estimated through a mathematical relationship with  $T_b$ , based on the 1-D thermal conduction through the module materials.  $T_c$  is then calculated using  $T_b$  and a difference between the cell and the back-surface temperature.

In most cases, authors consider the module temperature as the temperature of a representative cell or the mean value of several cells. This temperature can be measured by a sensor attached on the module back-surface, the measured value is the module

temperature. Measuring the temperature by a sensor fixed on the back of the PV module is common practice to estimate  $T_c$  [7]. Generally, the PV module temperature is measured by connecting several temperature sensors (thermocouples) attached to the module back side; however, in the reality, the sensors detect the lower layer temperature.  $T_c$  can be higher than  $T_b$  by a few degrees, this difference depends on the module substrate materials and  $G$ . For flat modules in an open arrangement,  $T_c$  is less sensitive to  $V_w$  than  $T_b$ , as the cell is inside the module structure, while the back-surface is directly exposed to the wind [105]. For flat modules in which the back-surface is thermally insulated, it can be assumed zero temperature difference between  $T_c$  and  $T_b$ .

The influence of  $V_w$ , wind direction, structural support components, junction boxes, and module structures may cause nonuniform temperature distributions across the module surface. Typically, these spatial temperature differences vary by about 5 °C. The module central cells have higher temperatures than those close to the module edges [47]. So, a careful placement of the thermocouples helps to obtain a accurate value for the average module temperature. The spatial temperature variation in the module can be compensated by the average of several temperature measurements, resulting in a reliable average of  $T_b$ .

Methods based on electrical parameters consider that  $V_{oc}$  vary with temperature.  $I_{sc}$ – $V_{oc}$  methods can be used for extracting  $T_c$  from  $I$ – $V$  curve measurements and the results are useful for  $T_c$  validation. These methods are not used to “model”  $T_c$  from weather, they are expressed as a function of the electrical parameters of the PV cell/module, and can be classified as a different class of nonlinear models. It is not possible to compare the functional form of the  $I_{sc}$ – $V_{oc}$  methods with Table II models, as the parameters are different. Some  $I_{sc}$ – $V_{oc}$  methods are represented in Table IV.

The  $T_c$  value can also be estimated based on environmental parameters. However, this estimate has uncertainties that affect the precision of the performance model [3]. Other methods require an outdoor experimental campaign with a module with an internal cell temperature sensor. This type of device is not always available and the procedure takes time to perform measurements. Studies comparing the temperature measured with an internal sensor inserted just below the cell, with the temperature obtained using models based on the heat flow calculation using  $T_b$ , show an accuracy of  $\pm 1$  °C [105]. Hence, the application of models that associate  $T_b$  to  $T_c$  has shown to be attractive since  $T_b$  can be easily obtained, while the temperature measurement using a PV module with an internal sensor, although accurate, is difficult and expensive [18]. However, it should be considered that for a reliable design and a performance estimate of PV plants, accurate and easy to implement models are needed [9].

## VI. CONCLUSION

The  $T_c$  value is a critical parameter to characterize PV modules behavior. In order to help researchers and professionals to choose the significant variables and the most appropriate experimental arrangements to compose an accurate prediction model, we review relevant contributions of PV modules operating temperature models developed from the year 2000 onward. Strategies of obtaining  $T_c$  for model validation are also presented.



According to our study, correlations for  $T_c$  found in the literature apply to free-standing PV arrays, PV/thermal collectors and BIPV installations. These correlations express  $T_c$  as a function of meteorological variables and include material and system dependent properties as parameters. Most of the models for the determination of  $T_c$  can be conveniently represented according to their parameters by one of the three in this article proposed general forms: one linear and two nonlinear. As a possible application, the proposed general forms can help the development of algorithms for continuous and automatic adjustment of models over time, based on machine learning.

The variables with the greatest influence, appearing in a significant number of models, are: solar absorption,  $\eta$ , transmittance,  $G$ ,  $T_a$ , and  $V_w$ . Solar absorption appears in correlations independently or in the product  $\tau\alpha$ . The manufacturer usually provides the  $\eta$  value; if not, the parameter can be obtained empirically using some techniques. Often the most significant source of errors in determining PV power

is associated with the procedure and instrument applied to quantify  $G$ . Therefore, attention should be paid to determining the “effective  $G$ .” Installations of anemometers different from standard meteorological practice, for different types of modules and mounting configurations, require adjustment through modeling. The influence of wind direction on  $T_c$  can be disregarded or considered to be a random influence.

The  $T_c$  value can be measured directly with an internal temperature sensor, obtained through correlation with  $T_b$  or estimated by models based on environmental parameters. The best strategy to obtain  $T_b$  for  $T_c$  estimation is connecting several temperature sensors and averaging the measurements. Hence, special attention should be taken when applying a generic expression to obtain  $T_c$ . Depending on the specific application, some methods may be more suitable than others.

## APPENDIX

See Tables V–VII.

TABLE V  
TERMS OF THE LINEAR CORRELATIONS WHEN EXPRESSED BY (4)

Correlations name	Formulation	$a_0$	$a_1$	$a_2$	$a_3$	$a_4$
Fernández <i>et al.</i>	$T_c = \frac{(V_{oc} - c_1)G - c_3}{c_2}$	$\frac{(V_{oc} - c_3)}{c_2}$	0	$\frac{-c_1}{c_2}$	0	0
Durisch <i>et al.</i>	$T_c = T_a + kG^2$	0	1	$\frac{k}{c_2}$	0	0
Nordmann and Clavadescher	Same as above	0	1	$\frac{k}{c_2}$	0	0
Krauter	Same as above	0	1	$\frac{k}{c_2}$	0	0
Mondol <i>et al.</i> I	$T_c = T_a + 0.031G$	0	1	0.031	0	0
Hove	$T_c = T_a + G \left( \frac{\tau\alpha - \eta}{U_L} \right)$	0	1	$\frac{\tau\alpha - \eta}{U_L}$	0	0
Tiwari	$T_c = T_a + G \left( \frac{\tau\alpha}{U_L} \right) \left[ 1 - \left( \frac{\eta}{\tau\alpha} \right) \right]$	0	1	$\left( \frac{\tau\alpha}{U_L} \right) \left[ 1 - \left( \frac{\eta}{\tau\alpha} \right) \right]$	0	0
Eicker	$T_c = T_a + G \left( \frac{\tau\alpha}{U_L} \right) \left[ 1 - \frac{\eta}{\alpha} \right]$	0	1	$\left( \frac{\tau\alpha}{U_L} \right) \left[ 1 - \frac{\eta}{\alpha} \right]$	0	0
Standard	$T_c = T_a + \left( \frac{G}{G_{NOCT}} \right) (T_{c,NOCT} - T_{a,NOCT})$	0	1	$\frac{(T_{c,NOCT} - T_{a,NOCT})}{G_{NOCT}}$	0	0
Davis	$T_c = T_a + \left( \frac{G}{G_{NOCT}} \right) (T_{c,NOCT} - T_{a,NOCT})$	0	1	$\left( \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{NOCT}} \right) \left[ 1 - \left( \frac{\eta}{\tau\alpha} \right) \right]$	0	0
Mondol <i>et al.</i> II	$T_c = T_a + 0.031G - 0.058$	-0.058	1	0.031	0	0
Tselepis	$T_c = 30 + 0.0175(G - 150) + 1.14(T_a - 25)$	$[30 - 0.0175(150) - 1.14(25)]$	1.14	0.0175	0	0
Tiwari and Sodha I	$T_c = \frac{pG(\tau\alpha - \eta) + (U_i T_a + U_T T_b)}{(U_i + U_T)}$	0	$\frac{U_i}{(U_i + U_T)}$	$\frac{p(\tau\alpha - \eta)}{(U_i + U_T)}$	0	$\frac{U_T}{(U_i + U_T)}$
Tiwari and Sodha II	$T_c = \frac{\tau[\alpha_C p + \alpha_\gamma(1 - \beta_C)G - \eta_C G \beta_C + U_i T_a + U_T T_b]}{(U_i + U_T)}$	0	$\frac{\tau\alpha_C p}{(U_i + U_T)}$	$\frac{\tau\alpha_\gamma(1 - \beta_C - \eta_C \beta_C)}{(U_i + U_T)}$	0	$\frac{\tau U_T}{(U_i + U_T)}$
Almonacid	$T_c = T_a + d_1 G + d_2 V_w$	0	1	$\frac{d_1}{U_L}$	$d_2$	0
Markwart	$T_c = 0.943T_a + 4.3 + 0.028G - 1.528V_w$	4.3	0.943	0.028	-1.528	0
Muzathik	$T_c = 0.943T_a + 0.3529 + 0.0195G - 1.528V_w$	0.3529	0.943	0.0195	-1.528	0
Akyuz <i>et al.</i>	$T_c = 0.957T_a + 3.1 + 0.025G - 0.3V_w$	3.1	0.95	0.025	-0.3	0
NOCT-1p model	$T_c = T_a + \left( \frac{G}{G_{NOCT}} \right) (T_{c,NOCT} - T_{a,NOCT}) + a(V_w - V_{w,NOCT})$	0	1	$\left( \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{NOCT}} \right)$	$a$	0
NOCT-2p model	$T_c = T_a + b \left( \frac{G}{G_{NOCT}} \right) (T_{c,NOCT} - T_{a,NOCT}) + c(V_w - V_{w,NOCT})$	0	1	$b \left( \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{NOCT}} \right)$	$c$	0
ISFOC method	$T_c = T_b + \left( \eta C_g \sum \frac{L_k}{\lambda_k} \right) G$	0	0	$\left( \eta C_g \sum \frac{L_k}{\lambda_k} \right)$	0	1

TABLE VI  
TERMS OF THE NONLINEAR CORRELATIONS WHEN EXPRESSED BY (5)

Correlations name	Formulation	$b_0$	$b_1$	$C_1$	$d_1$	$d_2$	$e_1$	$C_2$	$e_2$	$f_1$	$g_1$	$e_3$	$f_2$	$g_2$	$e_4$	$f_3$	$g_3$
Faiman	$T_c = T_a + \frac{G}{T_{a,ref} V_w}$	0	1	0	-	-	-	1	1	0	1	0	1	1	$U_0$	$U_1$	-1
Skoplaki and Palyvos	$T_c = T_a + \frac{0.32}{8.91 + 2V_w} G$	0	1	0	-	-	-	1	1	0	1	0	0.32	1	8.91	2	-1
Skoplaki <i>et al.</i> I	$T_c = T_a + \frac{0.25}{8.7 + 3.8V_w} G$	0	1	0	-	-	-	1	1	0	1	0	0.25	1	5.7	3.8	-1
Duffie and Beckman I	$T_c = T_a + \left( \frac{G}{G_{NOCT}} \right) \left( \frac{9.5}{(8.7 + 3.8V_w)} \right) (T_{c,NOCT} - T_{a,NOCT}) \left[ 1 - \left( \frac{\eta}{\tau\alpha} \right) \right]$	0	1	0	-	-	-	1	1	0	1	0	$\frac{9.5(T_{c,NOCT} - T_{a,NOCT})}{\tau\alpha G_{NOCT}(\tau\alpha - \eta)}$	1	5.7	3.8	-1
Skoplaki <i>et al.</i> II	$T_c = T_a + \frac{G}{G_{NOCT}} (T_{c,NOCT} - T_{a,NOCT}) \left[ 1 - \frac{\eta}{\tau\alpha} \right] \left[ 1 - \frac{\beta_{STC}}{\tau\alpha} (1 + \beta_{STC} T_{STC}) \right]$	0	1	0	-	-	-	1	1	0	1	0	$\frac{9.5(T_{c,NOCT} - T_{a,NOCT})}{G_{NOCT}[\tau\alpha - \beta_{STC}(1 + \beta_{STC} T_{STC})]}$	1	$a$	$b$	-1
Chennai <i>et al.</i>	$T_c = T_a + 0.0138G(1 + 0.031T_a)(1 - 0.042V_w)$	0	1	0	-	-	-	0.0138	1	0.031	1	0	1	1	1	-0.042	1
Sandia's model	$T_c = T_b + \left( \frac{G}{G_{ref}} \right) \Delta T$ and $T_b = G(e^{a+bV_w}) + T_a$	0	1	1	-	$\frac{\Delta T}{G_{ref}}$	$a$	$b$	0	0	-	-	-	-	-	-	-
Kurtz <i>et al.</i>	$T_c = T_a + G e^{-3.473 - 0.0594V_w}$	0	1	1	-	-3.473	-0.0594	0	0	-	-	-	-	-	-	-	-
Hornung <i>et al.</i>	$T_c = T_a + m \left[ e^{\left( \frac{-0.5V_w}{V_{w0}} \right)} + c \right] G$	0	1	$m$	0	$\frac{-0.5}{V_{w0}}$	$c$	0	-	-	-	-	-	-	-	-	-
Coskun <i>et al.</i>	$T_c = 1.4T_a + 0.01(G - 500) - V_w^{0.8}$	-0.01	1.4	0.01	0	0	0	-1	1	0	1	1	0	1	0	1	0.8

If  $C_1 = 0$ , the terms  $d_1$ ,  $d_2$ , and  $e_1$  that depend on  $C_1$  are disregarded and represented by “-.” The same occurs with the terms  $e_2$ ,  $f_1$ ,  $g_1$ ,  $e_3$ ,  $f_2$ ,  $g_2$ ,  $e_4$ ,  $f_3$ , and  $g_3$  when  $C_2 = 0$ .

TABLE VII  
TERMS OF THE NONLINEAR CORRELATIONS 32 AND 33 WHEN EXPRESSED BY (6)

Correlations name	Formulation	$h_1$	$h_2$	$m_1$	$n_1$
Duffie and Beckman II	$T_c = \frac{T_{a,NOCT} + \frac{G}{G_{NOCT}}(T_{c,NOCT} - T_{a,ref}) \left\{ 1 - \frac{\eta_{STC}}{\tau_{\alpha}} (1 + \beta_{STC} T_{STC}) \right\}}{1 - \frac{\beta_{STC} \eta_{STC}}{\tau_{\alpha}} \frac{G}{G_{ref,NTE}} (T_{c,NOCT} - T_{a,ref})}$	1	$\frac{(T_{c,NOCT} - T_{a,ref})}{G_{NOCT}} \left\{ 1 - \frac{\eta_{STC}}{\tau_{\alpha}} (1 + \beta_{STC} T_{STC}) \right\}$	1	$-\frac{\beta_{STC} \eta_{STC}}{\tau_{\alpha}} \frac{(T_{c,NOCT} - T_{a,ref})}{G_{ref,NTE}}$
Mattei	$T_c = \frac{UT_a + G(\tau_{\alpha} - \eta_{STC} - \beta_{STC} \eta_{STC} T_{STC})}{U - \beta_{STC} \eta_{STC} G}$	$U$	$(\tau_{\alpha} - \eta_{STC} - \beta_{STC} \eta_{STC} T_{STC})$	$U$	$-\beta_{STC} \eta_{STC}$

## ACKNOWLEDGMENT

Leticia de Oliveira Santos would like to thank “Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)” for a M.Sc. scholarship. Paulo Cesar Marques de Carvalho would like to thank “Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq)” for a researcher scholarship.

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