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COMPARISON OF TEMPERATURE FORECASTING MODELS OF PHOTOVOLTAIC MODULES OPERATING UNDER TROPICAL CLIMATE

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Abstract. Several climatic factors affect the performance of photovoltaic (PV) modules, mainly solar irradiation, ambient temperature, and wind speed. The first two has the greatest impact on PV cell performance, which is directly related to the cells operating temperature. The solar irradiation is converted by PV modules partly into electricity and partly into heat, causing an inversely proportional ratio. Our research compares measured PV modules operating temperature data with theoretical values estimated through models from the literature, aiming to find an equation that best suits the tropical climate of the PV plant site under study. The Skoplaki and Palyvos model, which considers ambient temperature, solar irradiation and wind speed, shows the best adjustment with the thermal behavior of the PV modules under the analyzed climatic conditions. This model showed the lowest average percentage error of 4.41%, with a maximum error of 5.51°C, when compared to the experimental data. The CLEFS CEA and Duffie & Beckman models occupy, respectively, the second and third place of the methods that best suit the data, with similar results, showing an average percentage error of 6.17% and 6.24%, respectively. The largest errors between measured and estimated values occur in the early morning and late afternoon; the smallest errors are between 10:00 a.m. and 02:00 p.m.

Keywords: Renewable energy, Photovoltaic solar energy, PV cells operating temperature, Thermal behavior, PV thermal models

1. INTRODUCTION

Solar energy represents a small piece of the global energy mix. International Energy Agency 2019 report (IEA, 2019) showed exponential PV power growth in several countries. In 2019 alone, solar PV generation showed an increase of 22%, being a year of global record growth in PV capacity. It is expected that between 2019 and 2030, the growth will be 15% per year. 2017 was a year of global growth in solar power, with ca. 25% of the world's total power installed in that year. In that year, according to the Brazilian Solar Photovoltaic Energy Association (ABSOLAR, 2018), global investment in solar energy totaled US$160.8 billion, from these US$86.5 billion were investments from China, being the country that invested the most in solar energy. Figure 1 (a) and (b) brings, respectively, the sustainable development scenario (SDS) of PV power between 2000 and 2030 and the net addition of solar capacity between 2017 and 2019. According to the graphics the importance of PV power in the world energy matrix is increasing.
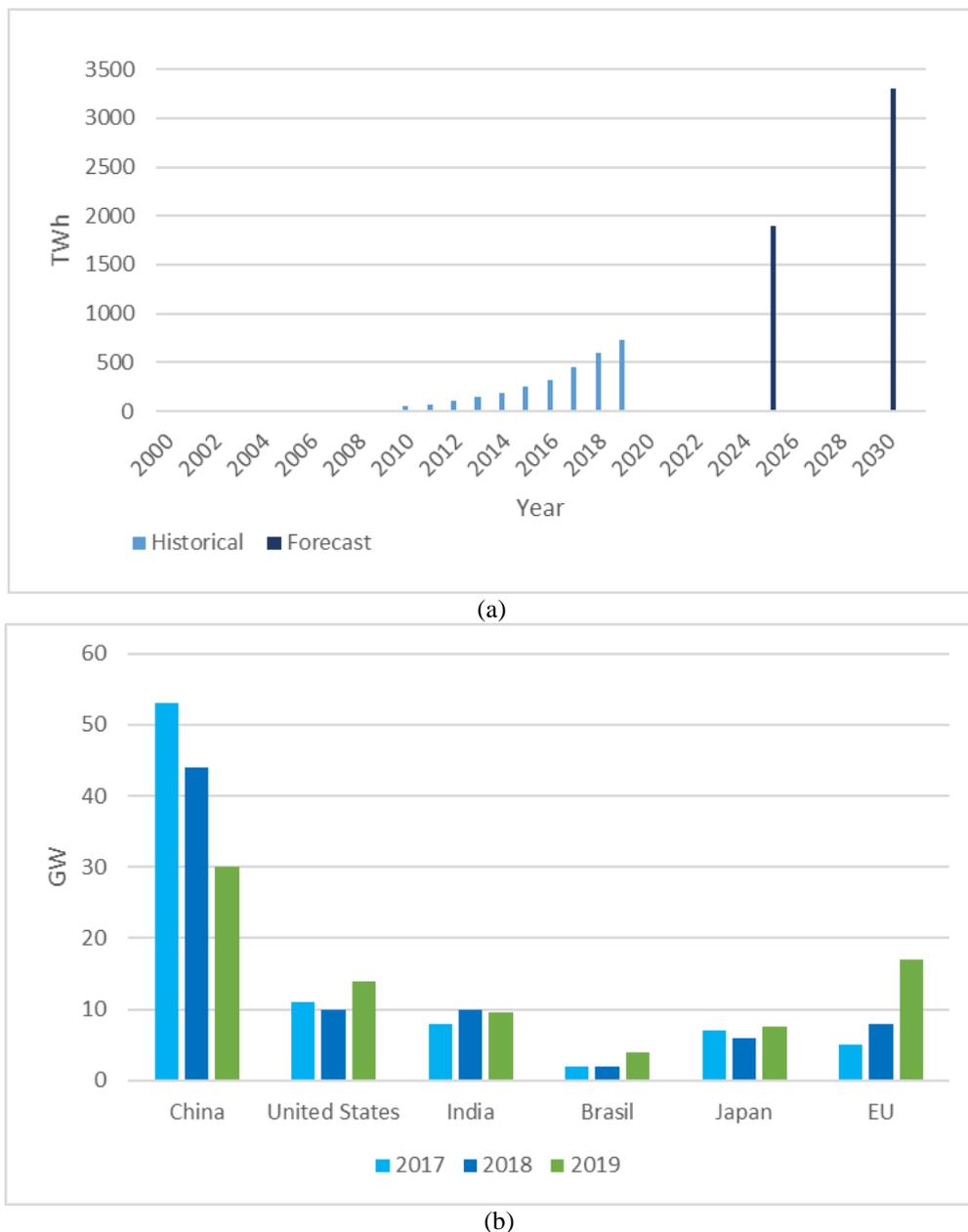
(a)

(b)

Figure 1. (a) PV generation in the Sustainable Development Scenario, 2000/2030 and (b) PV capacity additions, 2017-2019 (IEA, 2019)

At the national level, ABSOLAR announced in May 2021 (ABSOLAR, 2021) that Brazil had 8.1 (GW) of total operational power, the sum of the installed power in centralized generation and in distributed micro and mini generation. These data presented that despite the pandemic of the new corona virus, PV power had an increase of 1 GW in the last year. When compared to 2019, with 4.49 GW of installed power, PV power showed a growth of almost 200%, as shown in Figure 2. Despite representing only 1.8% of the Brazilian energy matrix, PV generation has been growing exponentially in the country. Also according to ABSOLAR, the largest number of systems and installed capacity of Distributed Generation (DG) in the country belongs to the residential consumption class. This is because over the past few years, there has been a large offer of incentives and financing lines, as well as a drop in prices of the systems that together have accelerated the growth in the number of systems in such a way that Brazil already stands out in the international scenario. Hence, PV is one of the most viable solutions for the country's energetic matrix.
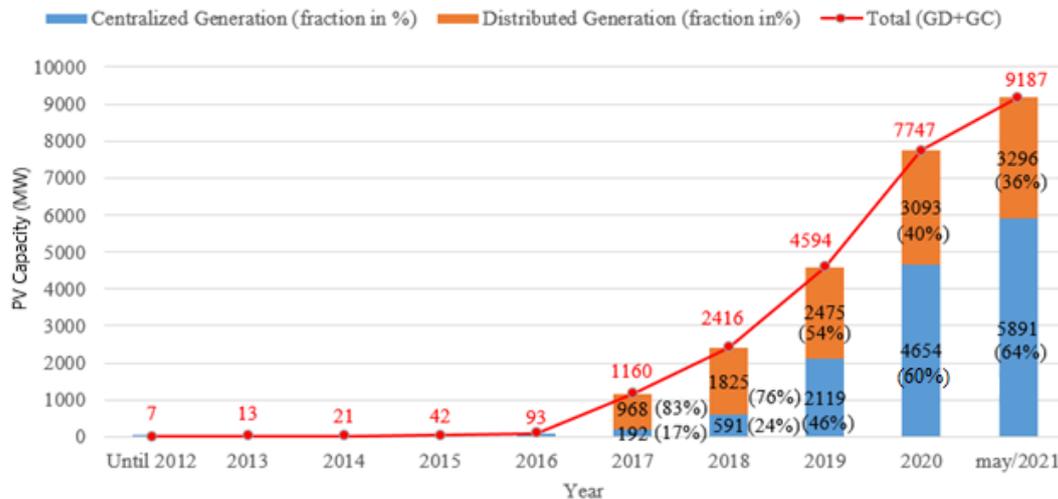
Figure 2. PV power evolution in Brazil – ABSOLAR,2021

Described as having one of the highest solar irradiation rates in Brazil, the state of Ceará, as well as its capital, Fortaleza, are considered one of the main PV generators in the Northeast region. It is the fifth state in terms of installed power in the country. It is important to emphasize that the region in question, according to the energy balance provided by the National Operator of the Brazilian Electric System (ONS,2021) is the one that presents the greatest power of generation of solar energy of the National Interconnected System (SIN).

In view of the scenario presented, it is of utmost importance to know and study the technologies implemented in a PV generation system. As well as knowing the factors that can influence its productivity. PV modules work best in stable, low-temperature climatic conditions. However, it is known that weather conditions in a given region usually vary throughout the day (AMAURY DE SOUZA et.al,2018). With this set up, the PV conversion also varies. The two factors that most affect the PV performance are ambient temperature and solar irradiation. In addition to these, climatic factors such as wind speed, cloudiness, humidity, among others, also influence the variation of Tc throughout the day.

The performance of a PV system is directly related to the climatic conditions to which it is subjected. As these conditions vary not only throughout the day, but also according to the climate prevailing at the site, for each climate there will be a certain prediction model that best suits it. Although there are several studies addressing these models for predicting the operative temperature of PV cells (Tc), studies for semi-arid climates (Santos, 2021), which includes the Brazilian Northeast, are still scarce. This paper aims to verify which model, among some developed by the scientific community over the last decades, best defines the behavior of the change of Tc throughout the day in a PV plant installed in a semi-arid climate. The activities involved consist of measuring the temperature of the modules using sensors installed in them, estimating the temperature using equations developed by researchers over the last decades, evaluating the degree of accuracy of the methods and verifying which of them is the most adequate for the climatic conditions already mentioned.

2. METHODOLOGY

The ratio between the electricity generation and the incident solar irradiation on a PV module determines its conversion efficiency. However, most of the light energy incident on PV cells is lost before it is converted into electrical energy (SIMIONI, 2017), which causes the generated power to be lower than the incident solar irradiation and, consequently, the conversion efficiency of the modules to be lower than 100%. Although each PV module has nominal power and efficiency data, the actual values of these variables vary according to the operational conditions to which the PV system is subjected.

Tc is one of the most influential factors on real-time efficiency during the operation of PV modules, as it affects the electrical properties of semiconductors and other cell components. Having an inversely proportional relationship, the higher Tc is, the lower its electrical efficiency (η). Due to this relationship between the two variables, the prediction of Tc has been receiving attention from the scientific community.

Tc is usually higher than the ambient temperature (Ta) to which the PV system is subjected (CANTOR, 2017). As Tc increases, the output current increases discretely, while the voltage is reduced linearly. This entire process results in a severe reduction in the generation of the PV module (LOCKS, 2019). PV module manufacturers usually release data for their products when they operate under standard test conditions which, speaking of Ta to which the cell is subjected, corresponds to 25°C. The output power of PV modules, presented by the manufacturer, is determined using STC (Standard

Test Conditions). Where Tc operates at a temperature of 25°C. In a real scenario, Tc varies throughout the day and has its value situated between 20°C to 40°C higher than the ambient temperature value of the site (Stambuk, 2017). For a PV plant to be properly sized, the Tc factor must be taken into consideration. Since the PV plant yield can decrease by 0.5% per degree Celsius above STC for crystalline silicon modules (Pinho & Galdino, 2014).

Another factor linked to cell inefficiency is the conversion of solar energy into heat that, if not dissipated, causes an increase in Tc. Due to favoring heat loss by convection, wind speed (Vw) is considered an important factor in the operating temperature of the cells and thus also linked to the efficiency of the PV system. The heat exchange between the modules and the environment occurs by two types of convection: natural and forced. The latter is linked to the wind speed in the vicinity of the modules. Once the wind is able to displace the hot molecules from the surface of the cells, performing a process that aims to balance the temperature around the modules with the ambient temperature.

For modeling operating temperature correlations, the heat transfer mechanisms of conduction, convection, and radiation must also be taken into consideration. As indicated in Figure 3, in PV modules, the dissipation mechanisms occur on both the top face and the bottom face (SKOPLAKI & PALYVOS, 2008). Thus, when installed in metal structures with both faces free, the same installation method taken into account in the NOCT tests, both free faces tend to operate at lower temperatures than those where the bottom face is attached to a surface.

In the literature, several Tc prediction methods are found that correlate the internal temperature of PV modules as a function of environmental variables and their properties. Many of these methods take into account Ta, Vw, irradiance (G), transmissivity (τ), and absorbance (α) (SIMIONI, 2017). There are also the models that make the prediction as a function of the cells' normal operating temperature (NOCT), which is provided by the cell manufacturer and defined with cell operation under conditions of G=800 W/m², Ta= 20°C, Vw=1 m/s, in free installation. Table 1 brings the description of the parameters that will be taken into consideration in the evaluated models.

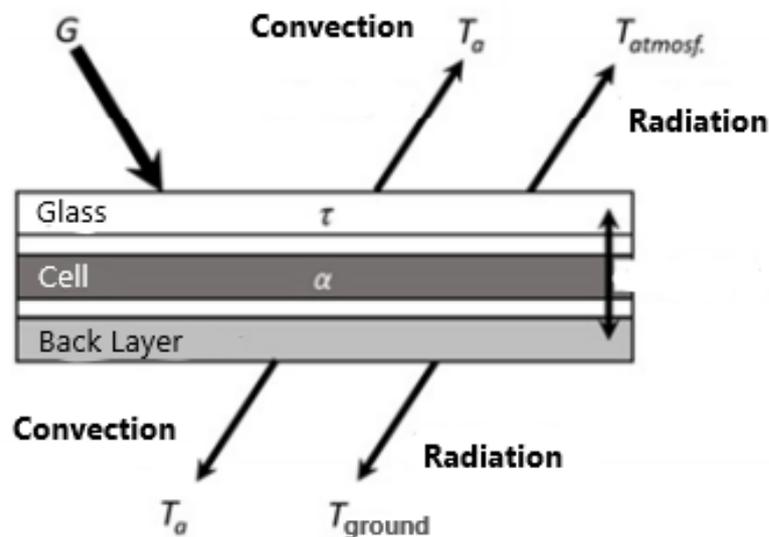Figure 3. Heat transfer mechanisms and typical PV modules layers – Simioni,2017

Table 1. Description of parameters

Parameter	Description
Tc	Cell operating temperature (°C)
Ta	Ambient temperature (°C)
G	Total Irradiance (W/m²)
Vw	Wind speed (m/s)
$T_{C,NOCT}$	PV cell nominal operating temperature, provided by the PV module manufacturer (°C)
$G_{T,NOCT}$	Total irradiance according to SRE, fixed at 800 W/m².
$T_{A,NOCT}$	Ambient temperature according to SRE, set at 20°C
Coefficient ηc	Module conversion efficiency described in the data sheet
Coefficient $\tau\alpha$	Product of transmittance-absorbance, exact value unknown, but estimated to be 0.9
Coefficient ω	Installation mode coefficient, varies according to the fixing mode used in the PV system

There is also the fixing mode coefficient, which is a variable that correlates the arrangement in which the PV module is installed and the different forms of heat dissipation for each of these modes. The use of this coefficient in the Skoplaki and Palyvos (2008) prediction method makes it possible to relate meteorological variables with different fixing arrangements in the calculation of Tc.

Table 2. Fixing mode coefficient

Fixing mode	Coefficient ω
Free installation	1.0
On the roof, with ventilation	1.2
On the roof, without ventilation	1.8
Integrated into the facade	2.4

Duffie & Beckmann (2013) model proposes the calculation of Tc taking into account both the climatic conditions and specific data from the plate and data obtained under standard conditions (NOCT). The model proposed by Pinho & Galdino (2014) consists in the calculation of Tc from Ta and G data.

The methods proposed by Loveday&Taki (1996), Skoplaki and Palyvos (2008), and CLEFS CEA (2004) present different correlations between Tc with Ta, G, and Vw values, all of these data referring to the climatic conditions to which the system is subjected. The estimation proposed by Nusselt-Jürges (1922) was elaborated on top of the Duffie&Beckmann (2013) model when considering some specific operating conditions (CANTOR, 2017). Another form of prediction to be taken into consideration is the standard model of the IEC 61853 (2011) standard, a model that estimates Tc from Ta, $T_{A,NOCT}$, $T_{C,NOCT}$, and $G_{T,NOCT}$. Table 3 shows the models equations used in the comparison.

Table 3: Models for estimating Tc

Authors	Equations
Duffie & Beckmann, 2013	$$Tc = Ta + \left[\left(\frac{G}{G_{T,NOCT}}\right) * \left(T_{C,NOCT} - T_{A,NOCT}\right) * \left(\frac{9.5}{5.7 + 3.8 * Vw}\right) * \left(1 - \frac{\eta c}{\tau \alpha}\right)\right]$$
Pinho & Galdino, 2014	$$Tc = Ta + 0.03 * G$$
Loveday & Taki, 1996	$$Tc = Ta + \left[\left(\frac{0.32}{8.1 + 2 * Vw}\right) * G\right]$$
Nusselt- Jürges, 1922	$$Tc = Ta + \left[\left(\frac{0.25}{5.7 + 3.8 * Vw}\right) * G\right]$$
Skoplaki e Palyvos, 2008	$$Tc = Ta + \left[\left(\frac{0.32}{8.1 + 2 * Vw}\right) * G * \omega\right]$$
CLEFS CEA, 2004	$$Tc = Ta + \left[\left(\frac{1}{22.4 + 8.7 * Vw}\right) * G\right]$$
IEC 61853, 2011	$$Tc = Ta + \left(\frac{T_{C,NOCT} - T_{A,NOCT}}{G_{T,NOCT}}\right) * G$$

3. MEASUREMENT

To perform the Tc prediction, data collected at the LEA - UFC in Fortaleza, Ceará, were used. Its territorial and latitudinal location near the Equator, favors a high insolation throughout the year, characterizing a warm tropical climate, with high temperatures and low temperature ranges (BEZERRA MAGALHÃES et. al, 2011). The year is divided into only two seasons: the rainy period, which occurs in the first half of the year and is marked by precipitation, cloudiness and a lower incidence of winds and solar radiation, and the second half of the year, characterized by being dry and almost cloudless skies, with a higher incidence of winds and solar irradiance, and less precipitation and cloudiness (CAMARGO SCHUBERT ENGENHEIROS ASSOCIADOS et al, 2019)..

The analyzed PV plant was connected to the grid in July 2016, thanks to the partnership between the Center for Teaching and Research in Urban Agriculture (NEPAU), Joazeiro Institute for Sustainable Development and UFC Superintendence of Infrastructure. With a total power of 1500 watt peak (measurement unit for the capacity nominal output of solar modules - Wp), the PV plant is composed of 6 YL250P-29b modules, of 250 Wp each, connected in series and an electronic inverter PHB1500-SS. The installation method used was free-standing and the PV system is oriented towards geographic North with an inclination of 5 degrees.

In order to perform the data collection, sensors and other measuring instruments were used in order to obtain the data acquisition of G, Vw, Ta, and Tc. These measured data were obtained by making use of a Renewable Energy Monitoring System (REMS), developed in Pereira (2018), which informed, in addition to the measured parameters, the day and time at the time of data collection.

Because PV cells are shielded, the exact determination of Tc eventually becomes difficult. In many cases, the temperature of the back side is measured and used as Tc (BUSSON ET. AL, 2018). To obtain Tc of the six PV modules of the LEA-UFC system, six PT 100 sensors were fixed on the central back side of each module that, due to the lower heat flux, is the location of the plate with the highest temperature. For Ta monitoring, a PT100 sensor with radiation shield was used.

In order to obtain the G and Vw measurement data, a pyranometer whose data were validated by the AMPROBE Solar irradiance meter-100 and an NRG #40C anemometer were used. These measuring instruments were installed at the same angle of inclination of the modules in order to perform the measurement of the variables on the surface of the PV modules. Figure 4 shows the PV system along with the sensors and other measurement instruments used to obtain the mentioned parameters.

Figure 4. PV system installed at LEA-UFC, consisting of 6 modules, 1 anemometer, 1 pyranometer and temperature sensors. Top and bottom views of the panels – Santos, 2021

4. RESULTS

Measurements were performed between January and November 2020 in Fortaleza, Ceará. The data were computed and stored in a spreadsheet with 1-minute intervals between each measurement. For the analysis, the measurements taken between 5 a.m. and 6 p.m. were considered, these being the approximated time of the sunrise and sunset in the city.

The data treatment was performed in order to detect and disregard the atypical values (outliers) of the database. The upper and lower limits of the variables were determined based on historical information obtained in studies conducted in Fortaleza, through the National Institute of Meteorology (INMET,2019). The Ta range considered was from 21.7°C to 39°C while the G range was from 0 W/m² to 1250 W/m². In addition to the considerations already mentioned, it was detected that the temperature sensor attached to PV module number 2 presented out-of-calibration values and with measurements with considerable divergence when compared to the sensors of the other PV modules. Therefore, the data obtained by the unbalanced sensor was disregarded in the analysis.

Tc average value was determined from the measurements taken by the 5 temperature sensors attached to the PV modules, being the average value among them. The values calculated from the equations presented in Table 3 were determined from the data measured by the other sensors and measurement instruments.

Comparison between the seven equations and Tc measurements are shown in Figure 5. The curve representing Tc by Skoplaki &Palyvos is the one that best approximates the behavior of Tc measurement. The curves of Pinho & Galdino correspond to those that are most distant from it. Despite presenting the same curve behavior, all the equations analyzed underestimated the value of Tc when compared to the measured value.

It is possible to observe that at times between 5:00 a.m. and 8:00 a.m. and 3:30 p.m. and 6:00 p.m., all the evaluated prediction methods had very similar values. However, the time window outside this range showed a considerable

divergence between the values of the methods, reaching up to 5°C difference between the Skoplaki & Palyvos and Pinho & Galdino methods. Another fact to be observed is that, those methods that did not take into account the wind speed as a parameter, were the ones that most distanced themselves from the behavior of Tc measurement.

Presenting an average percentage error of 4.41%, Skoplaki & Palyvos method corresponds to the one that best estimates Tc when submitted to the climatic conditions of Fortaleza. It is almost completely adequate for the hours between 10:00 a.m. and 2:00 p.m., when the cell temperature curve reaches its maximum values, according to Figure 6, followed by Duffie & Beckman and CLEFS CEA methods, which presented an average percentage error of 6.17% and 6.25%, respectively..
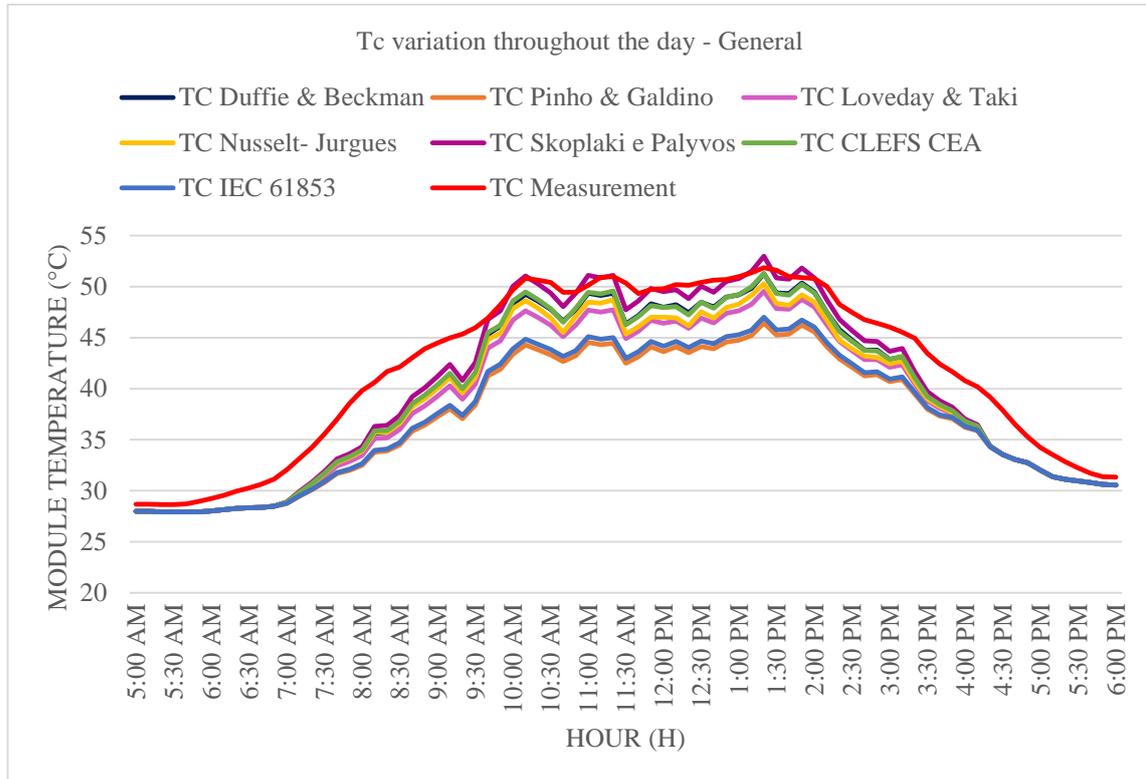

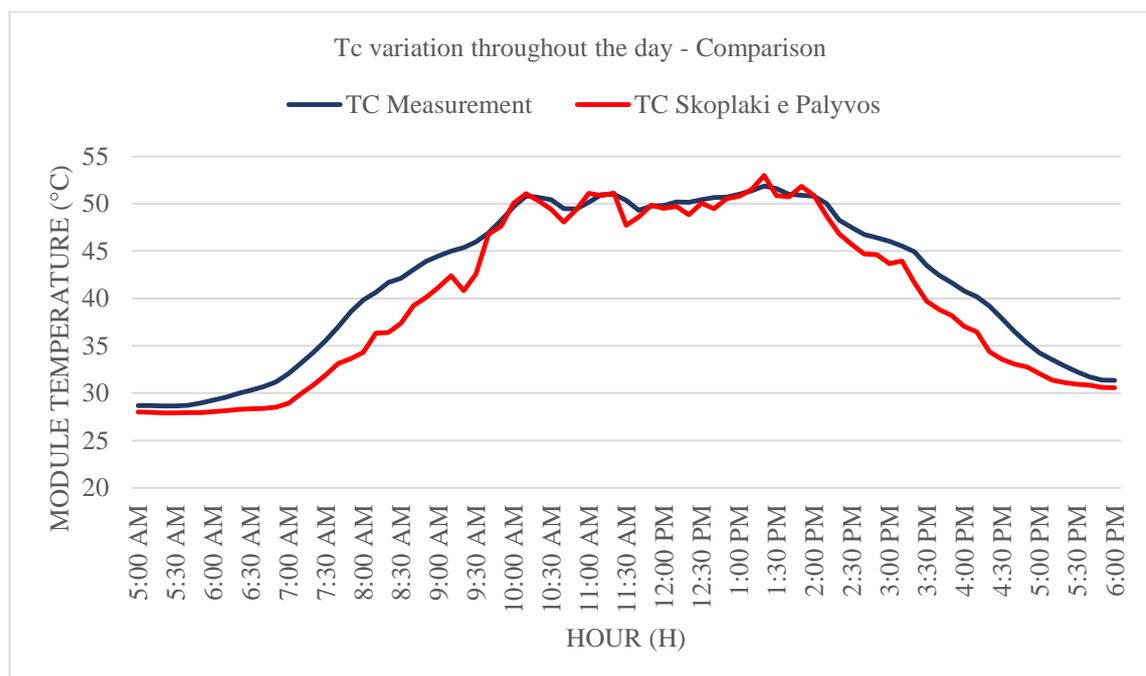Figure 5. Tc variation throughout the day - General

Figure 6. Tc variation throughout the day - Comparison

To corroborate the information already mentioned, Table 4 brings the information of average percentage error, maximum and minimum errors, as well as their respective times, for each of the seven prediction methods evaluated. Skoplaki &Palyvos presents the lowest percentage error when compared to the actual operating temperature. This prediction model is also the one that presents the lowest maximum and minimum error values.

2020						
Order	**Authors**	**Average Error (%)**	**Biggest Error (°C)**	**Biggest Error Time (h)**	**Smallest Error (°C)**	**Smallest Error Time (h)**
1	Skoplaki e Palyvos, 2008	4.41	5.51	08:00:00	0.06	14:00:00
2	CLEFS CEA, 2004	6.17	5.84	08:00:00	0.57	13:20:00
3	Duffie & Beckman, 2013	6.25	6.00	08:00:00	0.53	13:50:00
4	Nusselt- Jürges, 1992	7.21	5.97	08:00:00	0.65	18:00:00
5	Loveday & Taki, 1996	8.04	6.49	08:20:00	0.65	18:00:00
6	IEC 61853, 2011	10.79	7.99	09:20:00	0.65	18:00:00
7	Pinho & Galdino, 2014	11.39	8.29	09:20:00	0.65	18:00:00

Table 4: Errors concerning the measured and estimated temperatures by the analyzed methodologies

5. CONCLUSION

Our paper aims to help researchers to verify which method is the most precise for predicting Tc variation when a PV plant is subjected to a semi-arid climate. Although none of the seven analyzed methods has been completely adequate to describe the thermal behavior of the PV modules in Fortaleza, Skoplaki & Palyvos method showed the best performance. Presenting an average error of less than 5% and a maximum error of 5.51°C, the method becomes, between those analyzed, the most appropriate to describe the thermal behavior of PV modules in the analyzed conditions.

It is possible to note the relevance of considering wind speed as one of the factors to influence the prediction of Tc. Since the wind is responsible for the heat exchange between the PV modules and the environment, it is able to favor Tc reduction and, consequently, the increase of the maximum power. The two methods that did not consider this variable, IEC 61853 and Pinho & Galdino, showed the largest errors, around 8°C, and had the largest average percentage errors, corresponding to 10,79% and 11,39%, respectively

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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