THE INFLUENCE OF WIND SPEED ON THE PV MODULE OPERATING TEMPERATURE: A CASE STUDY FOR FORTALEZA

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Abstract. *The photovoltaic (PV) module operating temperature influences its electrical efficiency, a fundamental parameter for PV power forecasting. The present research is divided into two stages and aims to use some classic models, based on the temporal analysis of the data, applying them to the meteorological conditions of Fortaleza, Ceará, to predict the PV module operating temperature in a real arrangement. Initially, our study uses the programming language R to build linear regression plots based on the data. In the second step, the R programming language is used to estimate possible operating temperature values of the PV module based on the input data: solar irradiation, wind speed, ambient temperature and the PV module structure material. The influence of wind speed on the PV plant is analyzed, as it acts as a natural cooler for PV cells. It is important to note that both the position of the PV modules in relation to the wind and the magnitude of the wind speed influence the operating temperature. The models are tested with data from the Alternative Energies Laboratory of the Federal University of Ceará (LEA - UFC), checking for each model which are the predictors and the operating temperature of the PV module, as each model has an application depending on humidity, irradiation, magnitude of wind speed and PV module material. Based on the models results, a graphical analysis is proposed in order to compare their performance and improve the algorithm in R, so that the PV module operating temperature value can be more quickly and objectively applied.*

Keywords: *photovoltaic module, operating temperature, wind speed, R language*

1. INTRODUCTION

Solar energy is a renewable source and has great potential to be used by both residential users and large industries. Photovoltaic (PV) electricity production has grown in recent years. As an example of use, there are consumers who utilize this type of electricity production in their residences, obtaining a reduction in their energy bill, in addition to using a sustainable source of energy; the same motivation is valid for the industry sector.

An important issue for PV generation is the performance, as some factors should be taken into account. One of these factors is the PV modules operating temperature, as high temperatures influence negatively the PV efficiency. The standard approach commonly used to model PV module temperature is based on ambient air temperature and in-plane irradiance measurements; the influence of wind on the PV cell temperature is not considered. Aiming to expand the analysis, our article considers the influence of wind according to certain theoretical models. Additionally, many papers are found focusing on the PV modules temperature, but few studies analyze the process in semiarid regions, as the Brazilian Northeast.

As the PV share in the electricity production grows, there is an increasing demand for high-quality energy yield forecasts. Considering the importance of predicting the PV module operating temperature, our article compares data from polycrystalline silicon PV modules at the Alternative Energies Laboratory of the Federal University of Ceará (LEA – UFC), collected in the period November 2019 to November 2020, with data from models, aiming to analyze which theoretical model best describes the thermal behavior. Along with the analysis using the R language, an application was developed in the R language using the theoretical models equations. According to our review, Santos (2020) used machine learning; the theoretical models were chosen based on the simplicity in calculating the temperature and the easy of putting the algorithms in R. Furthermore, these models are very known in the literature for studying the PV modules temperature.

Nomenclature

h_w	wind convection coefficient	*Greek symbols*	
G	irradiance	α	absorption coefficient of the solar
T_a	ambient temperature		cells
T_c	cell/module temperature	β	temperature coefficient of PV
U_0, U_1	Faimann coefficients		cells maximal power
U_{PV}	heat exchange coefficient	η	efficiency of the PV cells
v	wind speed	τ	transmittance of the cover system
T_{est}	temperature estimated by models		
T_{mea}	temperature measured *in situ*	*Subscripts*	
v_w	local wind speed close to the module	a	ambient
		c	cell/module
		NOCT	nominal operating cell temperature
		STC	standard test conditions

2. METHODS

A total of 32,666 observations data were collected in the period November 2019 to November 2020 from the LEA-UFC, in Fortaleza (latitude: -03° 43', longitude: -38° 32', elevation: 21 m): wind speed, PV module operating temperature, ambient temperature, and solar irradiation. For each set of observations, the day and hour of collection were recorded. The first semester of the year in Fortaleza is considered the rainy season, while the second is the dry season, with greater incidence of winds and solar irradiance. These data of our study were obtained using a Renewable Energy Monitoring System - REMS developed in Pereira (2018).

2.1 Experimental Apparatus

The LEA's PV plant was connected to the UFC's electrical grid in July 2016 in partnership with the Center for Teaching and Research in Urban Agriculture (NEPAU), Joazeiro Institute Sustainable Development and UFC Infrastructure Superintendence. The PV plant is composed by 6 modules of 250 Wp, with a total power of 1500 Wp, that are oriented to geographic north with a 5 degree tilt. Figure 1 shows the PV modules seen from top and bottom, as well as the sensors installed for acquisition of G, V_w, T_a and T_c data. A Hukseflux LP02 pyranometer is used at the same inclination angle as the PV modules for G measurements on the inclined plane. Pyranometer measurement data were validated using the AMPROBE brand Solar-100 irradiance meter. A NRG #40C anemometer also in the same slope of the PV modules was installed aiming to measure V_w on the surface of the modules. For T_a measurement, a PT100 sensor with a radiation shield is used. For T_c monitoring of the six modules PV, PT100 sensors were fixed in the central rear part of each module, which is the place with the highest temperature, due to the lowest heat flow. The validity of the temperature data is conduced using a FLIR infrared thermal camera ONE.

Figure 1: PV system at the LEA-UFC, consisting of 6 modules, 1 anemometer, 1 pyranometer and temperature sensors. Source: adapted from (Santos, 2020)

2.2 Choosing the best theoretical model

The present study used as input G, V_w, T_a data; sequentially, we compared PV module operating temperature *in situ* and temperature predicted by eight theoretical models. Based on the RMSE (Root Mean Square Error), expressed by Equation 1, it was possible to observe which model best suited UFC's PV modules.

$$RMSE = [\frac{1}{n}\sum_{i=0}^{n}(T_{est} - T_{mea})^2]^{1/2}, \qquad (1)$$

Where n = 32666, T_{est} is the temperature estimated by the theoretical model and T_{mea} is the measured in situ temperature. The smaller the RMSE, the better is the prediction model. Each theoretical model has an equation for calculating the PV module operating temperature T_c. Not all models consider the wind speed; however, all models consider G and T_a as input data. With the collected data, the histogram shown in Figure 3 was produced to express the magnitude of the wind. Most of the winds data are of low intensity ($V_w \leq 1$ m/s); according to Santos (2020), the PV modules are in a place surrounded by trees and consequently poorly ventilated. Using the R language, a simple application was developed based on theoretical models, in which the PV module operating temperature is given based on ambient temperature, material type, wind speed, and solar irradiation; Figure 2 shows the steps.
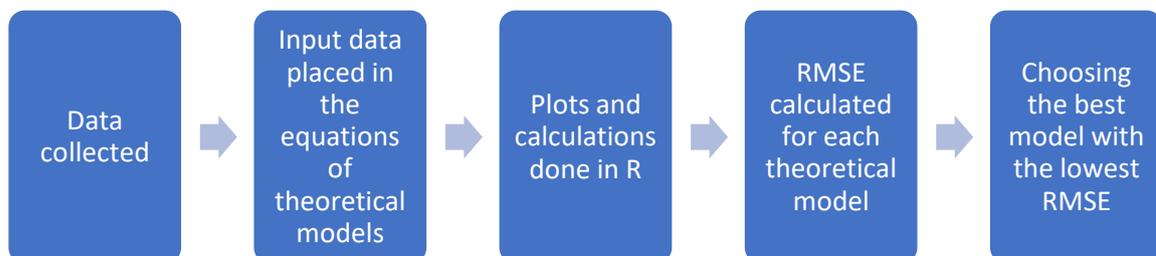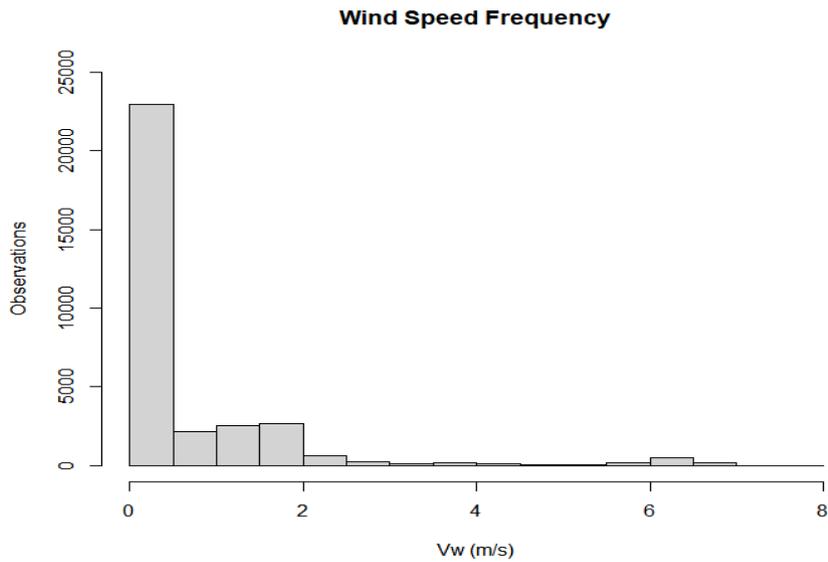

Figure 2: Process steps

Figure 3. Histogram of wind speed

Table 1 shows some characteristics of the materials used in the manufacture of PV modules. Table 1 contains the material type, Normal Operational Conditions Temperature (NOCT), constants U_0 and U_1 (specified by Koehl et al. for selected PV cell technologies).

Table 1: Characteristics of some PV materials

PV technology	NOCT (°C)	Module efficiency η_{STC} (%)	Temperature coefficient of maximal power β_{STC} (%/K)	U_0 (specified by Koeh et al.)	U_1 (specified by Koeh et al.)
Monocrystalline Silicon (m-Si)	45	18.4	-0.38	30.02	6.28
Polycrystalline Silicon (p-Si)	46	14.1	-0.45	30.02	6.28
Amorphous Silicon (a-Si)	46	6.0	-0.19	25.73	10.67
Microcrystalline Silicon (μc-Si)	44	9.5	-0.24	30.02	6.28
Cadmium Telluride (CdTe)	45	10.7	-0.25	23.37	5.44

Source: adapted from (Schwingshackl *et al.*, 2013).

3. THEORETICAL MODELS

3.1 Standard

Input variables are G, T_a data; a wind temperature around 1 m/s is assumed (Markvart, 2000).

$$T_c = T_a + \frac{G}{G_{NOCT}}(T_{NOCT} - T_{a,NOCT}),$$
(2)

T_{NOCT} is 46°C for polycrystalline silicon, $T_{a,NOCT}$ is 20°C and G_{NOCT} is 800 W/m². The PV module operating temperature depends only on G, T_a data, as all other parameters are constant.

3.2 Skoplaki

This model has an equation similar to the Standard model, with additional terms (Skoplaki *et* al, 2008):

$$T_c = T_a + \frac{G}{G_{NOCT}}(T_{NOCT} - T_{a,NOCT}).\frac{h_{w,NOCT}}{h_w(v)}.[1 - \frac{\eta_{STC}}{\tau.\alpha}(1 - \beta_{STC}T_{STC}),$$ (3)

β_{STC} = -0.45%/K; η_{STC} = 14.1 % (Table 1); τ is the transmittance of the solar panel; α is the absorptivity; such that $\tau.\alpha$ ≈ 0.9; T_{STC} = 25°C = 298.15 K, is the temperature under standard test conditions. The term that appears by multiplying temperatures works as a correction factor for the prediction of the PV panel in relation to the Standard model, as now the wind speed is also in the equation. h_w is the wind convection coefficient, which can take the following parameterization:

$$h_w = 5.7 + 2.8v_w$$ (4)

$h_{w,NOCT}$ = 8,5 W/m^2.K (v_w = 1 m/s).

h_w varies linearly with the magnitude of the wind speed.

3.3 Faimann

This model considers U_0 = 30.02 W/m^2.K and U_1 = 6.28 J/m^3.K which are heat loss coefficients and can be consulted in Table 1 (Faimann, 2008).

$$T_c = T_a + \frac{G}{U_0 + U_1 v_w},$$ (5)

Where v_w is the wind speed in m/s.

3.4 Mattei

This model for PV temperature was proposed by Mattei *et* al, 2006:

$$T_c = \frac{U_{PV}(v)T_a + G[\tau.\alpha - \eta_{STC}(1 - \beta_{STC}T_{STC})]}{U_{PV}(v) + G.\beta_{STC}T_{STC}},$$ (6)

$$U_{PV}(v_w) = 24.1 + 2.9v_w,$$ (7)

$U_{PV}(v)$ is the heat exchange coefficient given in W/m^2.K and varies linearly with the magnitude of the wind speed.

3.5 Sandia

Kurtz *et* al, 2009 used this equation for PV temperature:

$$T_c = T_a + G.e^{-3.473 - 0.0594.v_w},$$ (8)

This model does not use the properties of the PV module material.

3.6 Muzathik

Muzathik, 2014 used this regression equation for PV temperature:

$$T_c = 0.943T_a + 0.0195G - 1.528v_w + 0.3529,$$ (9)

A model with statistical parameterization; material properties are not considered.

3.7 Markvart

Markvart, 2000 used the following equation:

$$T_c = 0.943T_a + 0.28G - 1.528v_w + 4.3, \tag{10}$$

A model with statistical parameterization, similar to Muzathik; material properties are not considered.

3.8 Ross

This model considers

$$T_c = T_a + rG, \tag{11}$$

Table 2 summarizes the parameters. We consider a Ross parameter of 0.034 km²/W, since the observation site is a sloping roof that is not so well ventilated. The place of the studied PV panels is surrounded by tall trees, and with that, high magnitude winds can hardly act on them.

Table 2: Ross parameter for various installation types

| Type of arrangement PV	r (k m²/W)
Independent	0.021
Flat roof	0.026
Well ventilated sloped ceiling	0.020
Sloped ceiling not so well ventilated	0.034
Highly integrated sloped roof, poorly ventilated	0.056
Transparent PV integrated into the facade	0.046
Opaque PV integrated into the facade	0.054

Source: adapted from (SKOPLAKI *et al.*, 2008).

4. RESULTS AND DISCUSSION

Figure 4 shows dispersion plots of the PV modules temperature versus wind speed compared to the actual data collected. A very large dispersion of PV module temperature is observed, which indicates that other variables such as irradiation and ambient temperature need to be considered to predict module temperature. However, some similarity between the plots of Markvart, Muzathik, Ross and Sandia is observed.
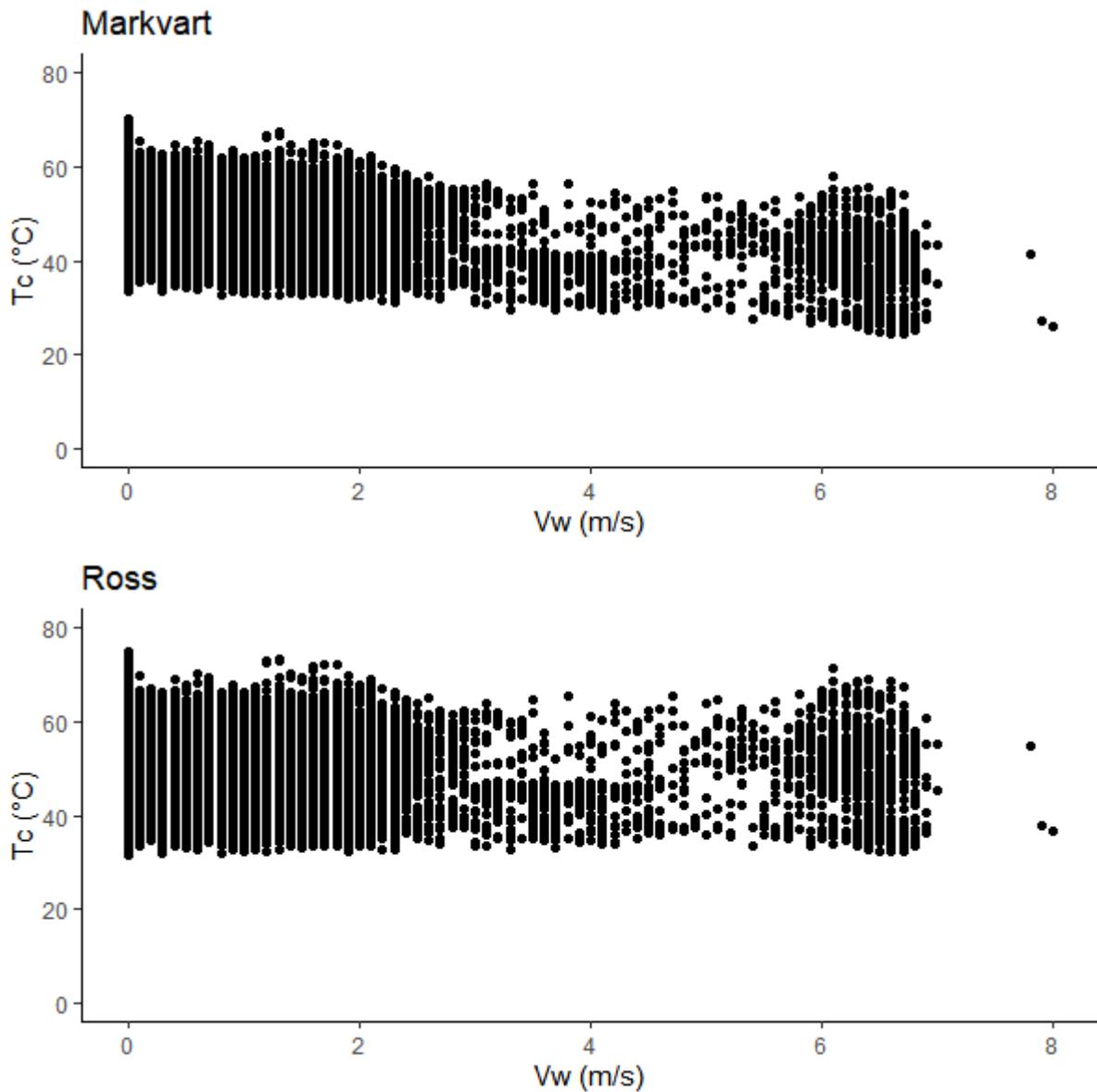
Mattei

Sandia

Muzathik
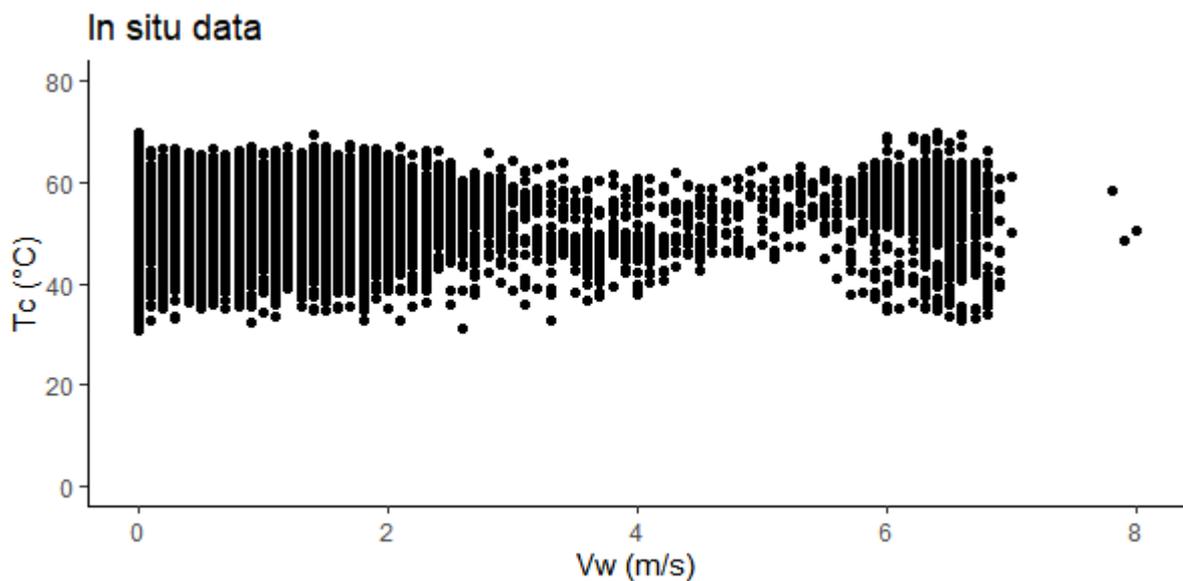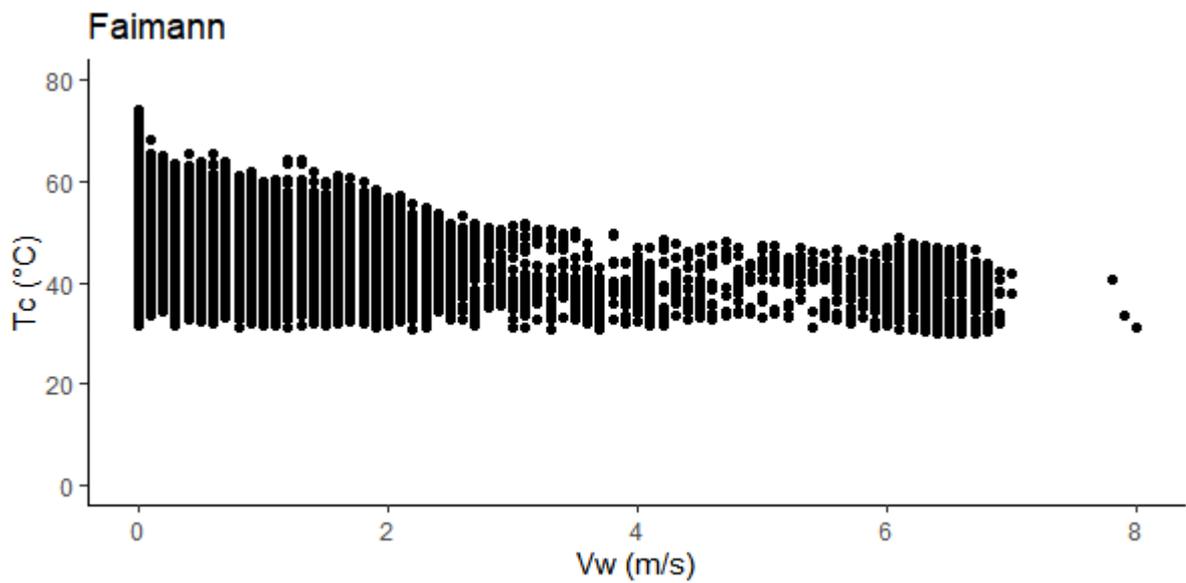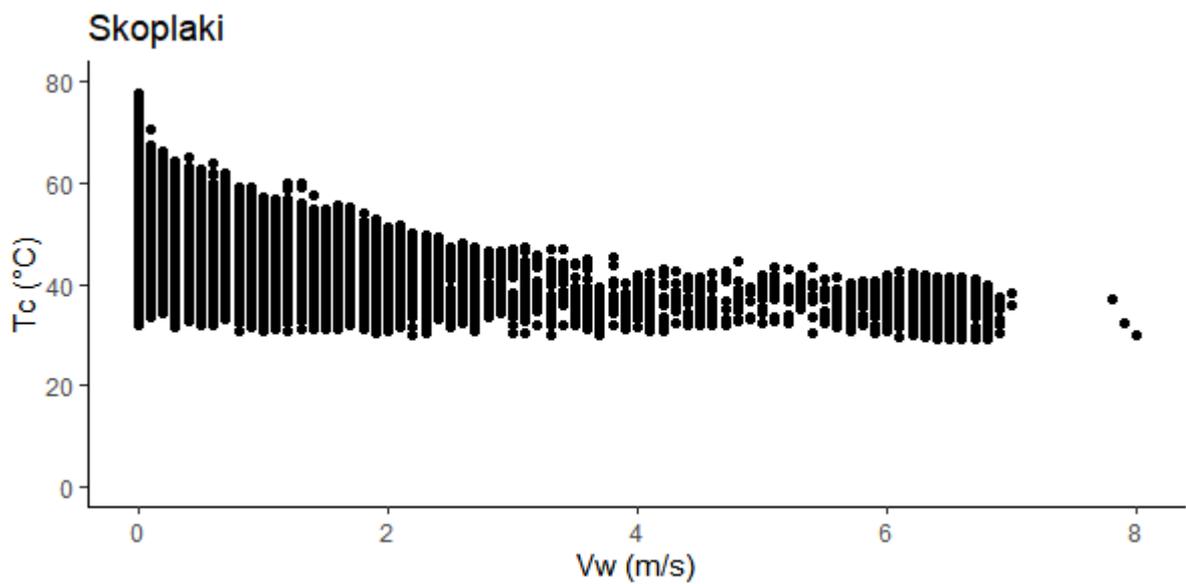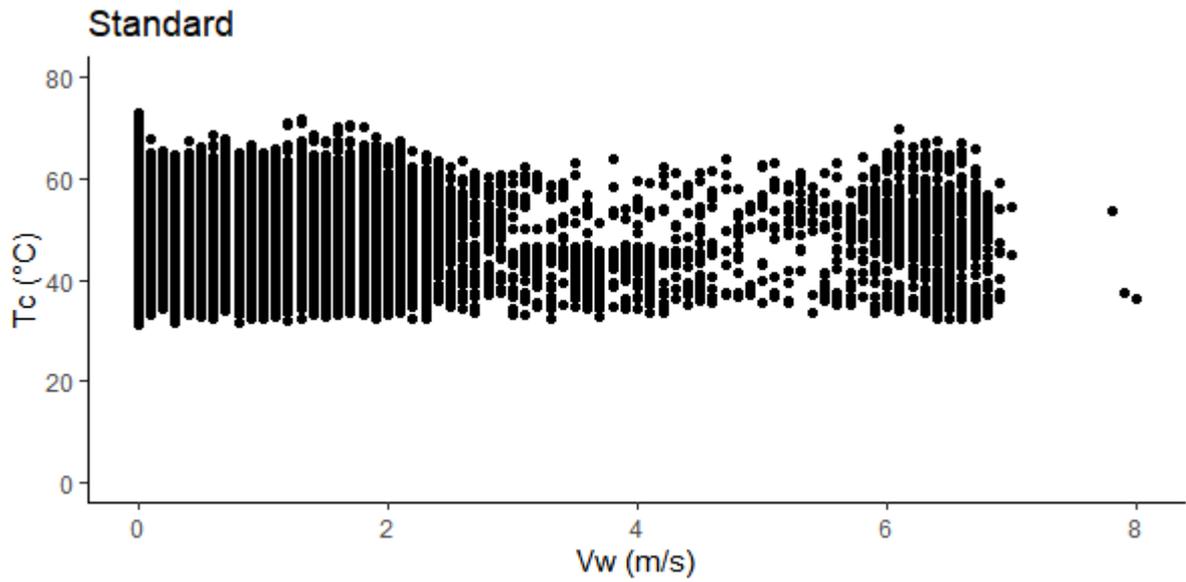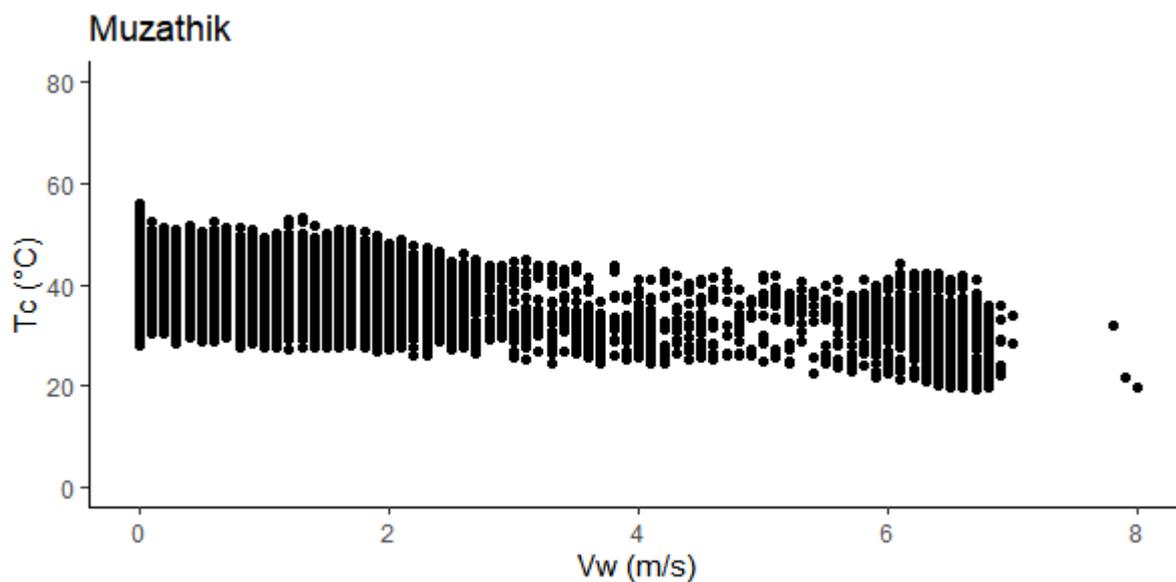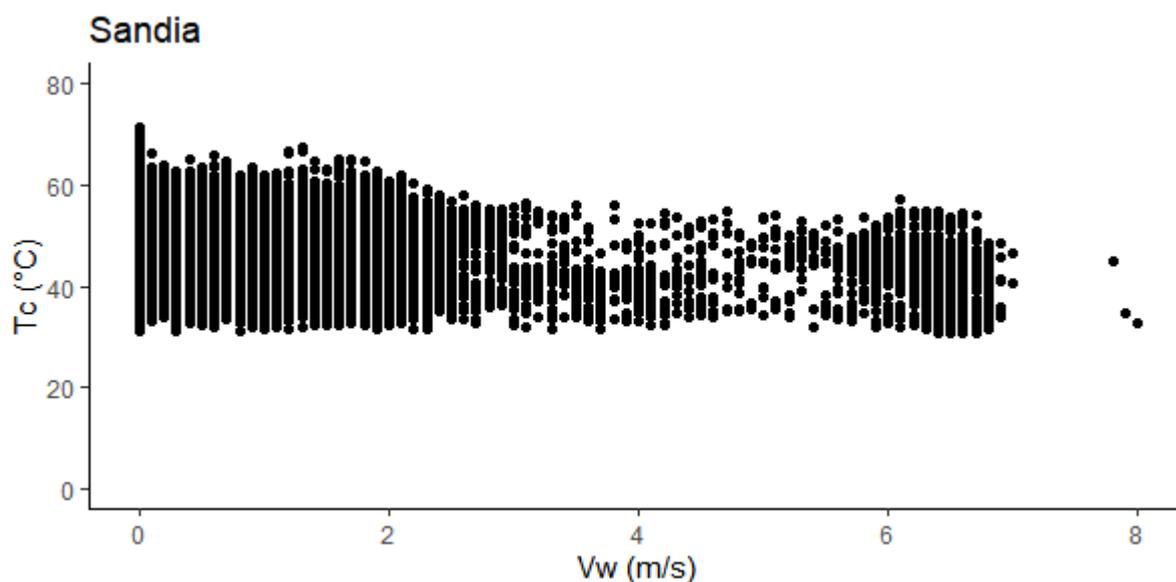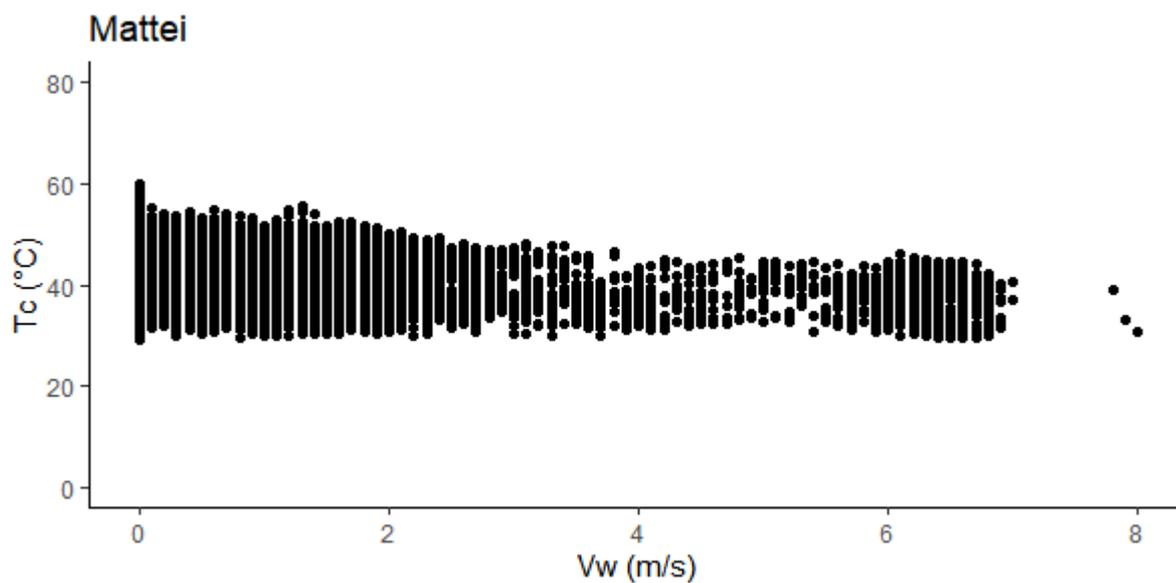
Figure 4: Scatterplot of theoretical models showing temperature behavior as a function of wind speed.

Using the equations of the theoretical models for predicting the PV modules operating temperature, Table 3 shows the results obtained from the observations and comparison of the models with real data using RMSE.

Table 3: Theoretical models and RMSE

Theoretical Models	**RMSE**
Standard	8.0832
Skoplaki	9.4057
Faiman	8.8747
Mattei	11.9767
Sandia	8.6618
Muzathik	14.1197
Markvart	8.0285
Ross	7.8986

Ross model is the one that best fits the prediction of the operating temperature of the UFC PV module, considering only G, T_a data. The second best model is Markvart, in which wind speed is included, but material properties are not.

This is because it is a statistical model. The model with the lowest performance was Muzathik. This model resembles Markvart, since what changes from one to the other are only the free coefficients and the coefficients that multiply the solar radiation. In general, models that consider the wind speed to be low, such as the Standard, or that do not consider it, such as Ross, performed well considering RMSE.

5. CONCLUSION

Our objective was to evaluate, among eight theoretical models, the one that best describes the temperature behavior of PV modules and whether wind speed has a great influence in the case of the PV modules in Fortaleza. Ross model is the one that best describes the behavior of the operating temperature of the PV modules, with a RMSE of 7.8986, even not considering the wind speed as an input variable. This model is followed by the statistical parameterization of Markvart, with RMSE of 8.0285, which considers wind speed, but does not consider material properties in its forecast equation. The model with the lowest performance is Muzathik model, with RMSE of 14.1197, which is also a statistical parameterization, similar to Markvart, but with some different coefficient values. Hence, for our case study, wind speed does not have a significant influence on the temperature of the PV modules. This can be explained considering that the PV modules are in a place surrounded by tall trees and consequently poorly ventilated.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE