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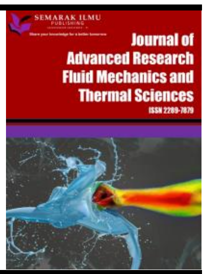

Uncertainty Estimate and Sensitivity Analysis of Lumped Thermal Model of Photovoltaic Modules

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ABSTRACT

The present work explores the assessment of lumped thermal modelling of solar PV modules and its convective heat transfer terms. The model of solar energy conversion in PV modules requires an accurate description of the electrical and thermal mechanisms involved in energy conversion. The variability of the heat flux over the surface is observed. It allows the uncertainty in the predicting of PV cell temperature and consequently to the conversion efficient is propagated to converted power, inducing an observed error in the efficiency of order of 0,1% for each °C (degree Celsius) and an error of 1W for each °C (degree Celsius). This error was estimated in the generation of a solar plant located in Pilar community in Rio de Janeiro and the possibility of a generation error of 0.6% was observed.

1. Introduction

The conversion of solar energy to electricity through photovoltaic (PV) cells is a well-known physical phenomenon, in which the efficiency decreases with its temperature. In a framework of solar PV modules, composed of set of interconnected solar cells, its thermal behavior determines the temperature of all components and consequently the overall efficiency of the energy conversion. Therefore, the dependence of the PV modules' efficiency on its temperature can be explained by the physical aspects of energy conversion on cells, as can be seen in review papers by several authors [1-3]. It can be formulated also by the behavior of an adjoining simple electrical equivalent circuit (using one or two diodes), where the model parameters vary with the temperature (T) and irradiance (G) [4-6]. In this way, a typical I-V curve changes for each condition {G, T}. Alternatively, a module operating with a maximum power point tracking (MPPT) electrical control system and conversion efficiency relations, expressed in terms of irradiance and module temperature, can be used with a relatively good accuracy [7].

The reliable models of solar energy conversion in PV modules require a good accuracy on the description of the electrical and thermal mechanisms involved in the energy conversion. Hence,

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realistic estimates of the performance of solar PV installations can be achieved by employing properly integrated models. It is critical in situations where the temperature of the modules is high, as a consequence of unfavorable climate conditions at an installation site (high ambient temperature and low wind) or in tracked and low-concentrated solar-PV systems (with high G). In those situations, the cell's temperature can attain values around 70°C to -90°C, lowering the module efficiency. Therefore, the energy conversion models (both electrical and thermal) must demonstrate estimates of accurate and realistic levels of converted power, properly establish a power plant energy assessment [8].

The modeling of the thermal behavior of PV modules and their efficiency has been extensively explored in the literature, by using lumped models [9-11] and benchmarking them through the monitoring of the efficiency of installations in onsite or laboratory experiments [12-14]. The modeling involves thermal balances (in steady or unsteady conditions), considering convective and thermal radiation heat transfer modes. Classically, the lumped models employ the estimates of convective heat transfer coefficients using empirical relations for an inclined flat plate, in free and forced convection [12]. The mixed convection coefficient is obtained through a power-law additive relation using the independent estimates for free and forced coefficients [11]. The uncertainty on the convective heat transfer coefficient is inherent to the use of general empirical relations for the specific conditions of the arrangement of a solar panel in real power plant configurations. The wind speed condition and the geometrical mounting of the modules are far from the ideal laboratory configuration, where the general formulas were obtained.

The uncertainty of the Nusselt number is obtained to determine the errors of the lumped model approaches, in predicting the conversion efficiency in the solar PV system. This problem was formulated in Cornils *et al.,* [15].

Furthermore, other studies discuss the analysis of uncertainty and sensitivity. The research by Hansen *et al.,* [16] evaluated the uncertainty and sensitivity analysis of two DC power models of PV systems. The authors quantified the uncertainty in the output of each model by empirical residual distributions. The research results indicated that the uncertainty in the output of the PV system is of the order of 1% for daily energy (relatively small). In the irradiance modeling step of the POA (Plane-of-array), a bias of about 5% of the daily energy in the irradiance model of the POA was observed, which consequently translates directly into a systematic difference in the predicted energy. In the sensitivity analyses, it was observed that the residues resulting from the POA irradiance and the effective irradiance models are the main contributors to the daily energy residues, both for the technology and for the considered location.

Using natural sunlight and calibrated secondary reference cells, Whitfield and Osterwald [17] established an uncertainty estimation procedure for measuring PV systems electrical performance. Blakesley *et al.,* [18] developed a simulation tool that includes an uncertainty model developed from research of test and calibration laboratories. Through a sensitivity analysis, it was concluded that the most important uncertainty factors are related to the irradiance measurement and the nominal operating temperature of the module. Liu *et al.,* [19] proposed an uncertainty and sensitivity analysis method to identify important uncertainties in the power system optimization process. The model was tested through a case study carried out for a classic district power system on a typical transition season day. The results of this research show that the proposed framework can effectively analyze the uncertain parameters of the system. This research aims to analyze the convection heat transfer coefficients through a dynamic and non-linear modeling of the electrical and thermal system of the photovoltaic module and its impact on the expectation of electrical generation from the determination and evaluation of the error in the module surface. The numerical model was applied and validated through experiments carried out in a photovoltaic solar plant in Frei Caneca in Rio de

Janeiro, Brazil. It is important to emphasize that so far, the literature survey has not shown any approach to this problem.

This article is organized as followed: the first section presents the problem formulation accompanied by a brief literature review. In the second section, the lumped model is developed, and the error analysis is performed to determine the efficiency sensitivity and converted power of the photovoltaic module. In the third section, the plant in Frei Caneca is presented. In the fourth section, numerical results are obtained for various configurations of photovoltaic systems and a more profound discussion is presented on the estimates for the uncertainty of the convection heat transfer coefficients. The error values applied to the plant in Frei Caneca are also highlighted in section 4. Finally, the conclusion of the work is presented.

2. Lumped Thermal Model

The thermal modeling is based on the formulation of the energy balance in a PV solar module, considering all system mechanisms of heat exchange and converted electricity. In this way, a differential nonlinear equation can be obtained for the time evolution of the module temperature. The input parameters for this problem are the climate conditions of irradiance (G) (on the plane of the inclined panel), and the ambient temperature ($\mathrm{T_a}$). All those conditions vary in the daytime.

From a practical point of view, generally the temperature of the solar PV model (T), is computed by a very simple model denominated Nominal Operation Cell Temperature (NOCT) given by Eq. (1)

$$T = T_a + \frac{NOCT-20}{800}.G \tag{1}$$

The NOCT parameter is a technical data given in the datasheet of the module. It is obtained from standard panel tests (zero wind and controlled module temperature). Naturally, Eq. (1) is too restrictive and fails in most of situations of module operation. If accuracy in the results of the module temperature is needed, the use of this equation would be completely inappropriate.

Therefore, the description of the temperature evolution of a solar PV module is better formulated by a complete energy balance model, which has been extensively explored in the literature [9-11, 20, 21].

Following this formulation, let us consider a solar-PV panel installed with an inclination angle of β with the horizontal plane, oriented to the north (in southern hemisphere) or south (in northern hemisphere). The energy balance, considering the heat exchange from both module surfaces (upward and downward), can be written as Eq. (2)

$$\mathrm{C}\frac{\mathrm{dT}}{\mathrm{dt}} = \mathrm{Q_{r,sw}} - \mathrm{Q_{r,lw}} - \mathrm{Q_c} - \mathrm{P_e} \tag{2}$$

In this equation, C denotes the thermal inertia coefficient. On the right- hand side of the equation, is taken into account the terms of incoming short-wave radiation ($Q_{r,sw}$), long-wave emitted thermal radiation ($Q_{r,lw}$), convection losses (Q_c) and converted electrical power (P_e).

The inertia term is computed considering the mass (m_i) and specific heat (c_i) of each module component i (glass, back-sheet, solar cells, etc.). Following Jones and Underwood [9] it can be calculated as Eq. (3)

$$C = \sum_i m_i c_i \tag{3}$$

The inertia term is extremely important in the condition of rapid variations in climate conditions, in particular for the ramps in the solar irradiance. In simulations performed for unsteady intraday conditions, with high temporal resolution, this term must be preserved.

In Eq. (2), the incoming solar radiation absorbed by the module upward surface is either modelled $Q_{r,sw}$, by Eq. (4)

$$Q_{r,sw} = (\tau\alpha)_{eff}A\left[\left(\frac{1+\cos\beta}{2}\right)I_d + \left(\frac{\cos\theta}{\cos\theta_z}\right)I_b + \left(\frac{1-\cos\beta}{2}\right)\rho_r(I_d + I_b)\right] = (\tau\alpha)_{eff}AG \quad (4)$$

where $(\tau\alpha)_{ef}$ is the effective transmissivity-absorptivity product of the module and *A* is its area. This term accounts for the effective solar energy absorbed by the module components, the beam component of radiation is represented by I_b, and the diffuse component is I_d, θ denotes the incident angle of beam radiation, θ_z is the zenith solar angle, the reflectivity coefficient denoted by ρ_r.

The long-wave thermal radiation emitted from the heated surfaces is formulated by the Stefan-Boltzmann law, using the proper view factors in the exchange between the module surfaces with the ground and sky. It can be expressed by Eq. (5)

$$Q_{r,lw}=\sigma\varepsilon A\left(\frac{1+\cos\beta}{2}\right)\left(T^4 - T_{sky}^4\right) + \sigma\varepsilon A\left(\frac{1-\cos\beta}{2}\right)\left(T^4 - T_\infty^4\right) + \sigma\varepsilon A\left(\frac{1+\cos(\pi-\beta}{2}\right) + \sigma\varepsilon A\left(\frac{1-\cos(\pi-\beta}{2}\right)\left(T^4 - T_\infty^4\right) \quad (5)$$

In this equation σ and ϵ are respectively the Stefan-Boltzmann constant and the emissivity of the module surfaces. T_∞ and T_{sky} are the ambient temperature (using air temperature equal to ground temperature) and the effective sky temperature which corrects the long-wave hemispheric radiation heat transfer to environmental conditions. Here a simple model is employed Swinbank [22] in Eq. (6)

$$T_{sky} = 0.0552T_\infty^{1.5} \quad (6)$$

The convection heat transfer is modelled by the classical Newton's cooling law using in Eq. (7)

$$Q_c = 2hA(T - T_\infty) \quad (7)$$

The same convective heat transfer coefficient (h) was considered for both downward and upward surfaces. To evaluate it, empirical relations are used, where the standard dimensionless dependence is employed in Eq. (8)

$$Nu = Nu(Re, Ra, Pr) \equiv \frac{hL}{k} \quad (8)$$

Here the Nusselt number (Nu) represents a typical length of the panel noted by L. Eq. (8) involves Reynolds (Re), Grashof (Gr), Prandtl (Pr) and Rayleigh (Ra) dimensionless numbers, defined respectively by Eq. (9).

$$Re \equiv \frac{\rho L U_\infty}{\mu}; Ra \equiv \frac{g\beta_T(T-T_\infty)L^3}{v^2}.Pr; PR \equiv \frac{\mu C_p}{k} \quad (9)$$

In the Eq. (9), the air properties $\{\rho, \upsilon, \mu, C_p, \kappa, \beta_T\}$ (density, kinematic viscosity, viscosity, specific heat, thermal conductivity and thermal expansion coefficient) are computed for the film temperature ($T_f \equiv 0.5(T + T_a)$).

Finally, the electrical converted power is calculated by a simple model for the efficiency given by Eq. (10)

$$P_e = \eta(G, T)GA \tag{10}$$

2.1 Converted Electrical Power

The modeling of electrical power is based on the simple model formulated by Eq. (10) for its efficiency. If the electrical operating system employs the Maximum Power Point Tracking (MPPT) strategy, a proper formulation for the efficiency as a function of the irradiance and the module temperature can achieve a good accurate. Consequently, the conversion efficiency in MPP is calculated by Eq. (11)

$$\eta = \eta_{ref}\left(1 + \alpha_4(T - T_{ref})\right) \tag{11}$$

where η_{ref} is the conversion efficiency of reference, T is the temperature of module and T_{ref} is the temperature of reference.

which the efficiency in nominal Temperature (Tn) is expressed by Eq. (12)

$$\eta_{ref} = a_1 + a_2 G + a_3 \log(G) \tag{12}$$

In those equations, $\{a_1, a_2, a_3, a_4\}$ are constants obtained from the data issued from the complete electrical model (presented below) under MPPT conditions. Complementary, $\{T_n, G_n\}$ denotes the nominal irradiance and temperature, equivalent respectively to 25°C and 1000W/m^2.

The electrical conversion behavior of a PV module can be represented by an equivalent circuit of one-diode, illustrated in the Figure 1. From the Kirshoff law, the I-V curve of this circuit can be expressed by Eq. (13)

$$I = I_{PV} - I_0\left[\exp\left(\frac{V + R_S I}{a\,V_T}\right) - 1\right] - \frac{V + R_S I}{R_P} \tag{13}$$

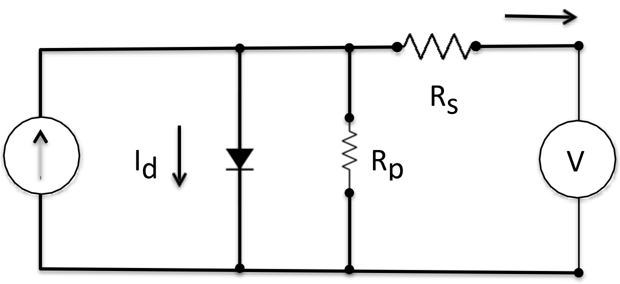

Fig. 1. One diode equivalent circuit

In this equation, I and V are respectively the electrical current and the voltage from the module. I_{PV} and I_0 are respectively the current of the photovoltaic conversion and the circuit saturation current. The constant a is the diode ideal factor (close to 1). R_s and R_p are the series and shunt resistances. V_T is the term associated with the reference voltage of the N_s solar cells at temperature T, computed by Eq. (14)

$$V_T = \frac{N_S KT}{q} \tag{14}$$

where K = 1.38065 × 10^{-23}J/K (Boltzmann constant) and q = 1.60217646 ×10^{-19}C (Electron charge). In this equation, the temperature T, has to be expressed in Kelvin. The converted power and efficiency of the module is computed by Eq. (15)

$$P = VI;\ \eta = \frac{VI}{GA} \tag{15}$$

To complete the model, the electrical currents are formulated by (see Ref. [4], for instance)

$$I_{PV} = \left(I_{PV,n} + K_I \Delta T\right)\frac{G}{G_n} \tag{16}$$

and

$$I_0 = \frac{I_{SC,n} + K_I \Delta T}{\exp\left[\frac{(V_{OC,n} + K_V \Delta T)}{aV_T}\right] - 1} \tag{17}$$

In those equations ΔT = T − Tn and the set of the model constants {$I_{PV,n}$, K_I, $I_{SC,n}$, V_{OC},n, K_v} are often available in the datasheet of the commercial modules. The resistances R_s and R_p are extracted from the PV module data, using the approach proposed in some works [23,24]. Here the ideal factor for the diode is considered as a fixed value of a = 1.3.

2.2 Linearization of The Thermal Radiation Term

The linearization of the Stefan-Boltzmann term given in Eq. (5) is not needed for solving of the nonlinear initial value problem formulated by Eq. (2). Most of the numerical methods do not present any difficulty to integrate the problem with the complete fourth-order term as written in Eq. (5). On the other hand, the linear formulation is employed here to estimate the magnitude of error in the lumped formulation, simplifying this analysis.

Therefore, alternatively the thermal radiation term can be re-written as Eq. (18)

$$Q_{r,lw} = 2Ah_r(T - T_\infty) \tag{18}$$

where the radiation heat transfer coefficient is given by Eq. (19)

$$h_r = 4\sigma\epsilon(T + T_\infty)(T^2 + T_\infty^2) \tag{19}$$

Here the reference means environmental temperature T_∞ is considered in Eq. (20)

$$T_\infty = \frac{1}{2}\left(T_a - T_{sky}\right) \tag{20}$$

In Figure 2 the comp comparison between linear and nonlinear equations are presented, for typical characteristics of solar PV modules and considering a tilted angle β = 15^o. The temperature of the module varies in the range of 22^{o}C – 70^{o}C and the ambient temperature is maintained in 20^{o}C. The emissivity of the module surfaces is equal to 0.9.

For h_r computed for all conditions of module temperature a perfect adherence of the estimates of the dissipated heat computed by the complete Stefan-Boltzmann equation is observed. If a mean value of the radiation heat transfer coefficient, h_r = 5.65W/m^2. K is used, the linear model has a small difference to the complete model, with a R^2 = 0.972. Hence, for the estimation of the magnitude error in section 2, the linear model proposed by the Eq. (18-20) can be definitively employed.

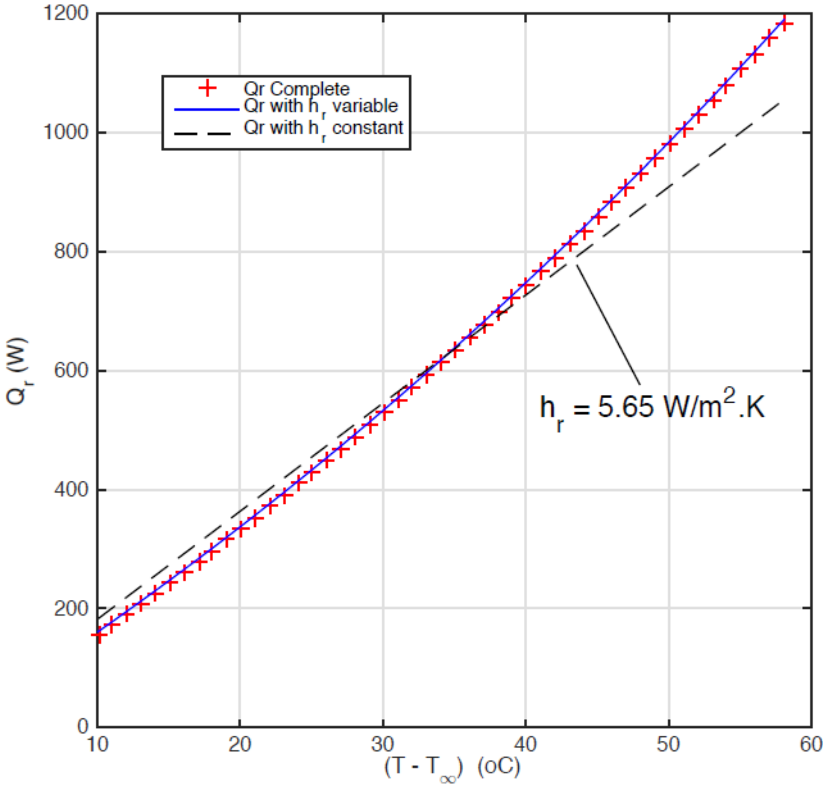

Fig. 2. Long-wave thermal radiation from a typical panel with A = 1.6m^2 and T_a = 20^o C – Complete and linearized models

3. Lumped Thermal Model Linearized and Sensibility Analysis

After defining each term, linearize and consider the transient state, therefore Eq. (2) can be written as Eq. (21)

$$0 = Q_{r,sw} - Q_{r,lw} - Q_c - P = GA(ra)_{eff} - 2h_fA(T - T_\infty) - 2hA(T - T_\infty) - GA\eta_{ref}[1 + a_1(T - T_n)] \quad (21)$$

Thus, the temperature of the module can be expressed by Eq. (22)

$$T = \frac{G[(ra)_{eff} + \eta_{ref}[1 + a_1(T - T_n)] + 2h_fT_\infty + 2hT_\infty}{2(h + h_f) + G\eta_{ref}a_1} \quad (22)$$

Firstly, the uncertainty for the module efficiency and power can be estimated through the model for the electrical conversion, considering its dependency to the module temperature. It can be determined by Eq. (23)

$$\delta\eta^2 = \left(\frac{\partial\eta}{\partial T}\right)^2 \delta T^2 \tag{23}$$

From Eq. (11)

$$\frac{\partial\eta}{\partial T} = \eta_{ref} a_1 \tag{24}$$

Consequently, the uncertainty can be calculated by Eq. (25)

$$\delta\eta^2 = (\eta_{ref}\, a_1)^2\, \delta T^2 \tag{25}$$

and for the converted power in Eq. (26)

$$\delta {P_e}^2 = (GA\eta_{ref}\, a_1)^2\, \delta T^2 \tag{26}$$

Thus, considering that the magnitude of the terms in those equations can be estimated as Eq. (27)

$$O(GA) \sim 10^3; O(\eta_{ref}) \sim 10^{-1}; O(a_1) \sim 10^{-2} \tag{27}$$

These estimates allow the following results in Eq. (28) and Eq. (29) [21]

$$\frac{\delta\eta}{\delta T} \sim 0{,}1\%/^{\circ}C \tag{28}$$

$$\frac{\delta P}{\delta T} \sim 1 W/^{\circ}C \tag{29}$$

This first result shows a low influence of the temperature in the module efficiency. On the other hand, the estimated power has an error order around 1 W for each 1°C of uncertainty in the module temperature.

Using this, the work of Junior [20] simulations for the unsteady power output are obtained for typical variations of irradiation (ramps and valleys) and other real climate inputs. A comparison between the dynamic and steady state models is discussed and the main differences for the temperature and power levels have shown the of applicability of the proposed model. In this way, the results are used to estimate the error by making a comparison between a model simulated with the computational tool Hybrid Optimization of Multiple Energy Resources (HOMER) and a 160 kWp solar power plant in Frei Caneca in Rio de Janeiro. HOMER's average monthly power generation forecast data was compared with power generation data from the power plant at Frei Caneca.

4. Model application to The Frei Caneca Plant
4.1 Frei Caneca Plant

The Solar Pilar project is a pilot project that aims to provide low-cost energy to 90 families divided into two groups. The first group involves 30 families who instead benefitting from installations of residential solar systems of 3.28 kWp each, which are made up of photovoltaic modules, hybrid inverter, batteries, controller and smart meters. The second group has 60 families that are connected through a 160 kWp plant installed on the premises of the LIGHT energy concessionaire in Frei Caneca (see Figure 3).

Solar Pilar aims to provide low-carbon, high-quality, low-cost electricity to vulnerable families living in Pilar, a community in Duque de Caxias, in the metropolitan region of Rio de Janeiro in southeastern Brazil.

Assessments were carried out and indicate the various costs of the residential facilities at Pilar and the Frei Caneca plant and the monthly average amount of energy to be generated by these systems. To estimate the cost of the amount of energy to be generated by the systems, simulations were carried out using the computational tool HOMER, considering the solar potential of the region and the load profile of the community. The total cost of installations in Frei Caneca is estimated at US$ 88,367.20 and the total cost for each residential installation in Pilar is US$9,985.85. The average monthly generation of the Frei Caneca plant is 18,633.60 kWh/month and residential generation in Pilar is estimated at 378.34 kWh/month. For the model application, the Frei Caneca plant was considered.

Fig. 3. The photovoltaic modules in the Frei Caneca Plant located near the Pilar community

5. Results

In this section, the sensibility analysis was performed using the results from the Frei Caneca plant and the results of a simulation performed in the paper of Junior [20].

5.1 Sensibility Analysis of Frei Caneca Plant

The estimated temperature error for a 500W/m^2 panel was 3°C leading to a 3W generation error per panel, in this model the assumed percentage error was ±0.6% for monthly generation [20]. This estimate error due to the monthly temperature variation of the HOMER software estimate is presented monthly.

The values of losses do not seem to cause great impact in a month, but for the estimate of total generation of the plant considering estimates of return on investment can generate major impacts. The plant can be accessed remotely to track the performance of your system, and the comparison of the values.

Since November 2022, the plant has been yielding generation results through the CSI cloud application. Figure 4 below illustrates the monthly electricity generation pattern of the simulated model using the HOMER computational tool, excluding the influence of temperature on the photovoltaic modules. Additionally, this Figure 4 demonstrates the generation of electric energy with the incorporation of the assumed uncertainty.

Table 1 shows a comparison between the actual power generation data from the plant in Frei Caneca and the simulated model data with and without error application. The data used takes into account only the last three months of electricity generation at the plant (November and December 2022 and January 2023). Therefore, the analysis carried out for these three months indicates an average percentage variation of reduction of 0,6% between the monthly energy generation of the plant in Frei Caneca and the simulated model with the application of the assumed error. This discrepancy may be related to an error in the model.

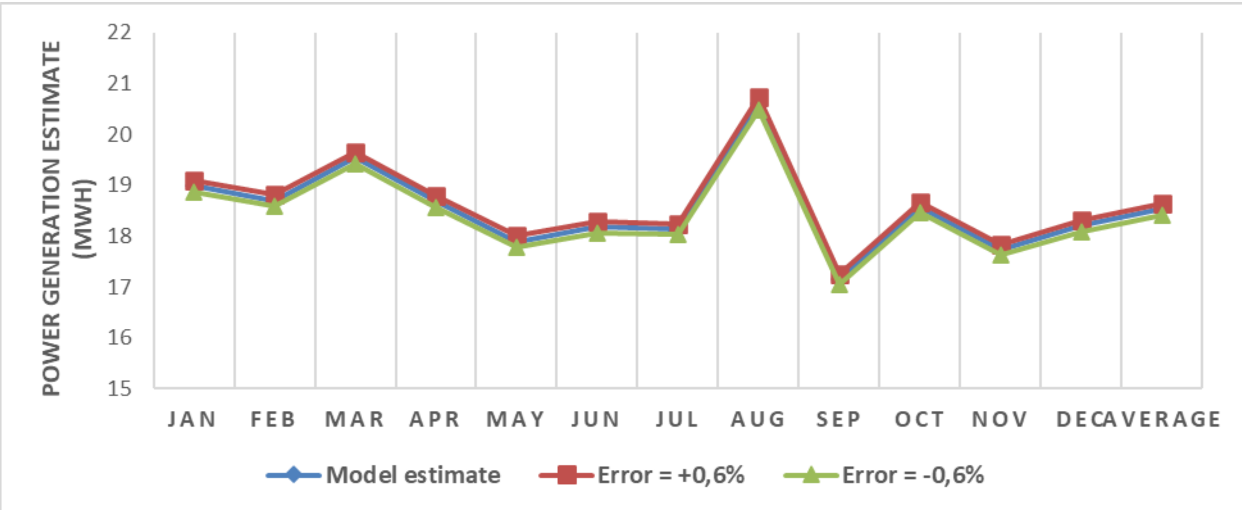

Fig. 4. The power generation estimate in Frei Caneca Plant

As can be seen in Table 1, in the months of December (2022), November (2022) and January (2023) the generation was higher than estimated, this can be attributed to several factors such as climate conditions, or even the need to review HOMER simulation parameters.

Part of the divergence between the estimated and actual generation of the plant can be explained by uncertainty in the identification of the NOCT of the solar panels, other factors such as intense solar irradiation with milder temperatures than usual may also have contributed to the increase in generation. Comparing the realized values at the plant in operation with the estimates plus 0.6%, differences of 1.11, 1.10 and 1.75 MWh were obtained in the months of December, November and January respectively. Therefore, the analysis carried out for these three months indicates an average percentage variation of reduction of 6.59% between the monthly energy generation of the plant in Frei Caneca and the simulated model with the application of the assumed error.

Using the error values, it can be analyzed which modifications should be made in the simulation model and which climate situations and system configurations promoted a generation greater than expected.

Table 1
Comparison between measured generation values in the application, calculated estimates and possible estimation errors based on the temperature variation

	Nov	Dec	Jan	Average
Frei Caneca Plant (MWh)	18.90	19.41	20.85	19.72
Model estimate (MWh)	17.74	18.2	18.99	18.31
Error = +0,6%	17.85	18.31	19.10	18.42
Error = -0,6%	17.63	18.09	18.88	18.20
Frei Caneca plant vs estimated model error (%)	5.57	5.67	8.37	6.59

6. Conclusions

The impact of the temperature in photovoltaic systems continues to be a challenge in operating plants and academic research.

This study focused on the development and evaluation of a mathematical model aimed at estimating the generation behavior of photovoltaic modules. The model considered various factors, such as the energy conversion process, thermal balance, and their interactions with the environment. Additionally, it examined the sensitivity of parameters to understand how their behavior influenced the operating conditions of the module.

The model described in this study was implemented at a photovoltaic power plant situated in the Pilar community in Rio de Janeiro. The obtained results represent actual generation values observed during a three-month operational period of the plant.

This result indicates that it is necessary to observe the impacts of temperature in generation, as errors can be avoided in generation estimates. The important thing in this case is to provide errors ranges in the final estimate of the converted power that allowing a good evaluation and its associated uncertainty range. This is a relevant fact for the design of the plants and the economic studies of photovoltaic systems. More experiments are needed to verify the impacts of temperature in photovoltaic generation using the NOCT temperature in a non-permanent state.

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