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Efficiency gain by using a conceptual residential PVT System in Brazil.

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Environmental concerns and the increasing worldwide demand for energy led the scientific community to develop more efficient and sustainable processes. Solar energy has become an important renewable energy source, considering that it could be used in several ways. The photovoltaic panels (PVs) capture solar radiation and generate electricity, but there is an efficiency loss due to the high temperature of the photovoltaic cells. As a solution, heat exchangers can be used to cool down the PVs and increase electrical power generation. The waste heat can be recovered by employing a solar cogeneration system that provides thermal energy to a secondary system. Solar cogeneration systems are defined as photovoltaic thermal solar collectors (PVTs) and the thermal energy generated by them can be used in several residential, commercial, and industrial processes. In the present work, a PV and a PVT system are modeled, simulated, and analyzed considering a residential installation in Brazil weather conditions. Both systems' efficiency results are compared to verify the differences. The cases are tested throughout the year considering a residential water heating system, with solar irradiance, air temperature, and other climate data obtained from National Meteorology Institute (INMET). Preliminary results show a considerable increase in PVT overall efficiency, over 70%, for different solar irradiances. Considering the approval of the new regulatory framework for distributed solar energy in Brazil, which is encouraging the installation of residential photovoltaic systems this year, the use of PVTs could have a huge impact on residential energy consumption. In addition, the water flow rate in the PVT system is presented as an important parameter to be considered in a PVT design, since the electrical and thermal efficiencies tend to increase by increasing the flow rate. However, the higher the flow rate higher the required pumping power, reducing the impact of the recovered wasted energy by the PVT system.

Keywords: *PVT system, Photovoltaic, Thermal efficiency*

1. INTRODUCTION

The photovoltaic system (PV) is a mature technology that can generate electricity through solar energy, with its installation growing at a 40% average annual rate globally (Zhang *et al.* (2012)). Although some photovoltaic research-cell achieve efficiencies higher than 40% (NREL (2022)), most commercial systems have low efficiencies ($\leq$18%) that causes a heating effect on the PV panel. Besides, it is well known that PV's efficiency is correlated to the cell operating temperature, which can decrease by 0.4-0.5% for each 1K increase (Brinkworth *et al.* (1997)). Therefore, cooling PVs is essential to achieve higher cell efficiencies and increase electricity generation.

The waste heat can also be recovered by employing a solar cogeneration system, which can be defined as a photovoltaic thermal solar collector (PVT) (Chow (2010)), that will provide thermal energy to a secondary system, increasing the overall system efficiency. The PVT modules have a wide range of applications in space heating and cooling, water heating, food processes, agricultural processes, industrial processes, and PV thermal management (Emmanuel *et al.* (2021); Kumar *et al.* (2015)), with several studies been performed in the last years. But these studies have focused on simulations for static conditions or quickly experimental data. Only a few papers couples experimental analyses with 1-year simulation models and none of them presents an integrated approach aiming at comparing PVT vs. PV technologies, from both numerical and experimental points of view (Buonomano *et al.* (2016)). Misha *et al.* (2020) developed a CFD simulation with different solar radiation intensities and an experimental setup tested in Malaysia. The maximum and theoretical efficiency of the PV panel was 15% and the highest cell efficiency achieved with the PVT was 11.71%. These results were collected for 5 days through July 2019. Similar work was performed by Sakellariou and Axaopoulos (2017), where the experimental tests showed only 0.32% of improvement by the PVT over the PV on electric generation. The main gain of the PVT was in water heating, which was enhanced by 20%. Recent studies have shown that a nanofluid-base optical filter can increase the system's thermal power, although this increase is at the expense of a decrease in PV efficiency. This filter narrows the solar radiation light frequency, maximizing the thermal energy absorbed by the fluid, with preliminary results from Otanicar *et al.* (2018) pointing to 61% of thermal efficiency. Slimani *et al.* (2017) showed that a single glass surface over the PV cells, to protect them from the environment, increases the operating temperature, reducing the electric generation efficiency. Again, it was verified that cooling down the cell temperature with passive systems slightly benefits electric generation. However, the thermal energy is highly correlated to the geometry of the PVT system, with a double pass PVT air collector showing advantages over the one with a single pass. Misha *et al.* (2020) have found that a single inlet and outlet PVT can provide more thermal power than the multi-pipe center connected suggested by Abid and Karimov (2011).

In this work, a PV and a PVT system were simulated with real climate data from Brazil, in order to evaluate the power needed to heat water in different country locations. These data were compiled from the automatic weather stations from the National Institute of Meteorology (INMET) and it's available at de Oliveira *et al.* (2021). The dataset consists of 1,840,939 hourly measurements collected from the 589 weather stations, between Jan 1st and Dec 31st, 2020. To move forward, a Quasi-transient simulation could be performed with the support of big data. Brazil has a large territorial extension, with a great variation of Latitude and Longitude and, therefore, a PVT system simulated with real data from Brazil could be used to represent many other locations.

2. Method

In the present paper, the performance of a single solar panel (Case 1) is compared to the PVT system (Case 2), designed to enhance the system efficiency. In case 1, a single solar panel generates electricity to power up a heater on the water pipe. The schematic draw of this system is shown on Fig. 1.

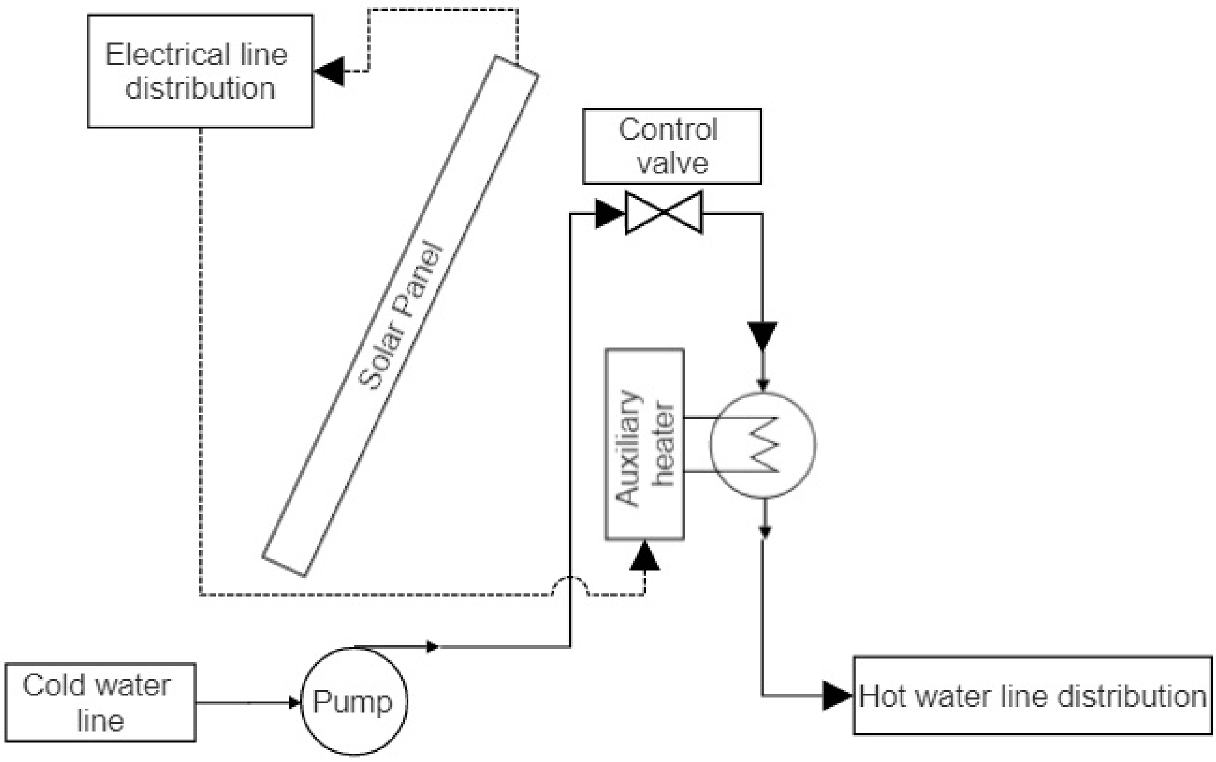

Figure 1. Case 1- PV System with a single solar panel.

In case 2 a PVT is used to cool down the solar panel temperature and increase the heating effect on water. It is expected that a lower temperature increases the solar panel efficiency and the heater efficiency as also. The schematic draw of this system is shown on Fig. 2.

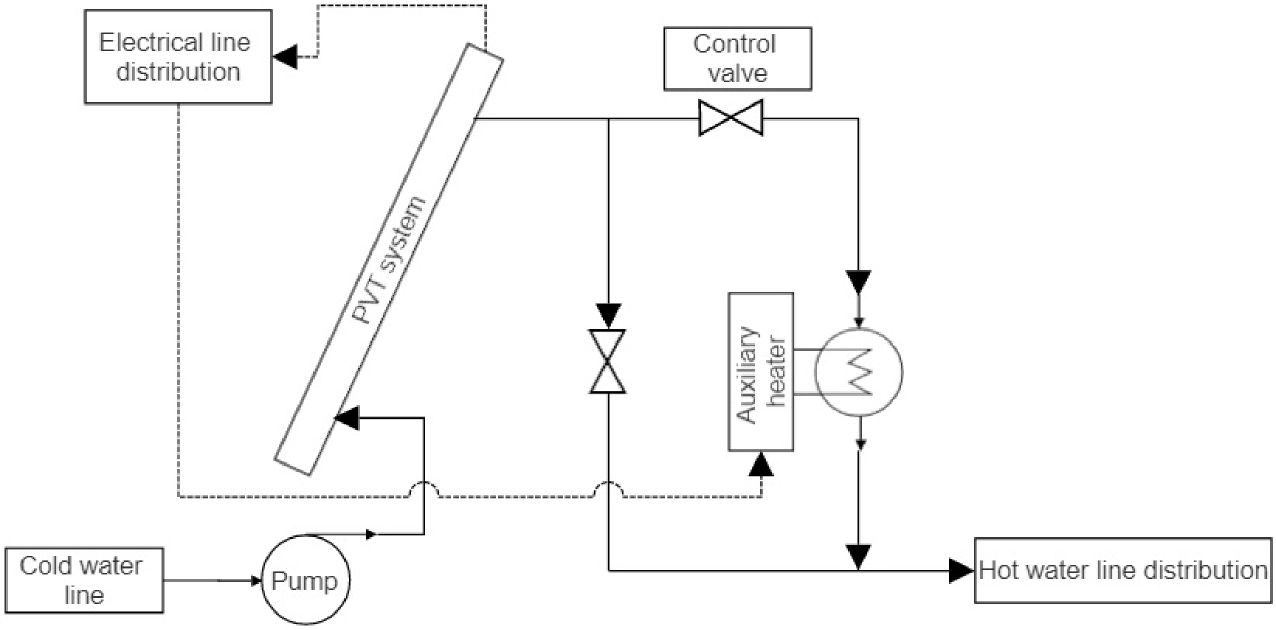

Figure 2. Case 2- PVT System with a single solar panel.

Both cases were simulated considering the same water mass flow rate ($\dot{m}$=0.07kg/s) and the same solar panel, which specifications are presented in Tab. 1.

Table 1. Solar panel specification

Max power	550 W
Max efficiency	21%
Temp. coefficient β	0.0035
Area	2.6 m²
Length	2.26 m

The heater power (P_h) can be described as a function of the reference temperature, T_b=323K, and the heater inlet temperature, T_f. Eq. (1) show this expression, where c_p = 4178 J/kgK is the specific heat coefficient, as Çengel and Ghajar (2009) suggests.

$$P_h = \dot{m}c_p(T_b - T_f) \tag{1}$$

The thermal efficiency (η_t) is the relation between the heater power and the received solar radiation, I_t A_p, shown in Eq. (2), and the electrical generation efficiency (η_e) is the relation between electrical power provided by the PV panel and the received solar radiation, shown on Eq. (3).

$$\eta_t = \frac{\dot{m}c_p(T_b - T_f)}{I_t A_p} \tag{2}$$

$$\eta_e = \frac{I_t \eta_e A_p}{I_t A_p} = \eta_r(1 - \beta(T_p - T_r)) \tag{3}$$

where η_r is the maximum efficiency of the PV panel, β the temperature coefficient, T_r=298 k, which is the Standard Temperature Test and T_p the simulated PV temperature.

2.1 ENERGY BALANCE FOR CASE 1 - PV SYSTEM

A schematic draw for the PV system is shown on Fig. 3. Two energy balance equations are considered for this case: one for the glass and the other for the PV cell. The glass energy balance equation includes the absorbed solar energy and its losses due to the external forced convection, the reflection component, and the heat transferred to the PV cell by conduction. So,

$$I_t A_p \alpha_g - A_g(h_{conv,g} - h_{rad})(T_g - T_a) - A_g h_{cond,g}(T_g - T_p) = 0 \tag{4}$$

where α_g is the absorptance coefficient of the glass, A_p,A_g are the PV cell and glass area, both equal to the area in Tab. (1), $h_{conv,g}$ and $h_{cond,g}$ are the convection and conduction heat transfer coefficient of the glass, respectively, h_{rad} the radiation heat transfer coefficient, T_p, T_g and T_a the temperatures for the PV panel, the glass and the external air, respectively.

The conduction heat transfer coefficient of the glass can be written as

$$h_{cond,g} = \frac{K_g}{L_g} \tag{5}$$

where K_g = 1.8 W/mK is the thermal conductivity and L_g = 0.0032m the glass width. Other properties for the glass are the glass absorptance α_g = 0.12, transmittance τ_g = 0.88 and emissivity ϵ_g = 0.91 (values taken from Siqueira *et al.* (2020)).

The radiation heat transfer coefficient, h_{rad} can be written as

$$h_{rad} = \epsilon_g \sigma (T_g - T_a)(T_g^2 - T_a^2) \tag{6}$$

where σ = 5.67$\times 10^{-8}$ W/m²K is the Stefan Boltzmann coefficient.

The PV cell energy balance equation includes the heat transferred from the glass by conduction and the solar radiation transmitted through the glass, part of which is converted into electrical energy, and the other is lost by natural convection at the back of the PV cell, as shown in Eq. (7).

$$I_t A_p \alpha_p \tau_g - I_t \eta_e A_p + A_g h_{cond,g}(T_g - T_p) - A_p h_{conv,n}(T_p - T_a) = 0 \tag{7}$$

where $h_{conv,n}$ is the natural convection coefficient considered at the back of the PV cell and can be written as the following equations

$$h_{conv,n} = \frac{K_a}{L_p} Nu_L \tag{8}$$

$$Ra_L = \frac{g\beta(T_p - T_a)}{\nu_a \alpha_a} \tag{9}$$

$$Nu_L = 0.68 + \frac{0.670 Ra_L^{0.25}}{(1 + (\frac{0.0492}{Pr})^{9/16})^{4/9}} \tag{10}$$

where K_a=0.02625 W/mK is the air thermal conductivity, L_p=0.0032 m the PV panel width, Ra_L, Nu_L and Pr the Rayleigh, Nusselt and Prandtl, respectively.

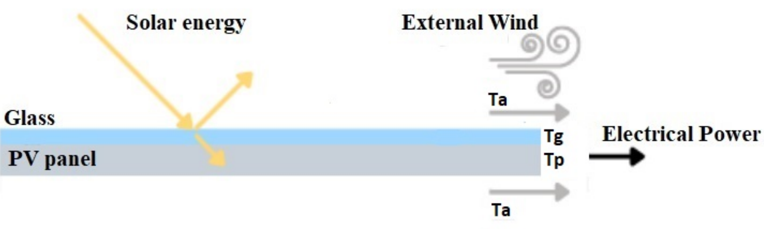

Figure 3. Section plot of the PV system

As suggested by Jürges Apud Duffie and Beckman (2013), the heat loss by forced convection due to the external wind was calculated as

$$h_{conv,g} = \begin{cases} 5.6 + 3.9U, & \text{U<5 m/s} \\ 7.2U^{0.78}, & \text{U} \geq \text{5 m/s} \end{cases} \tag{11}$$

2.2 ENERGY BALANCE FOR CASE 2 - PVT SYSTEM

The main difference between cases 1 and 2 is the PV panel, where case 2 preheats the water using the PV panel as heat exchanger. A schematic draw of the PVT system is shown on Fig. 4.

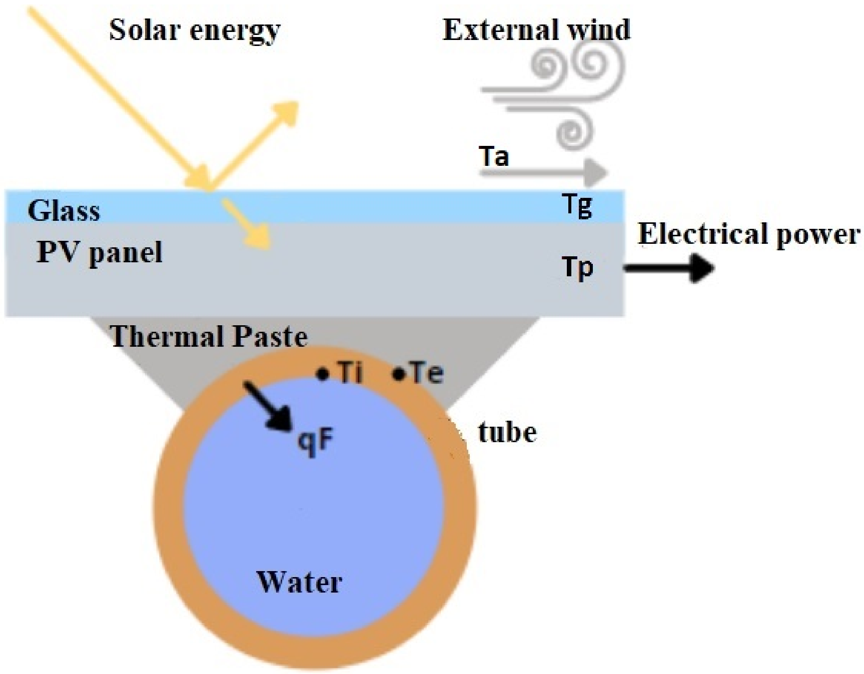

Figure 4. Section plot of the PVT system

Therefore, for case 2, five energy balance equations need to be considered: one for the glass, one for the PV cell, one for the thermal paste, one for the tube, and one for the fluid. As can be seen, the glass energy balance for case 2 can still be represented by Eq. (4). However, the PV cell energy balance in Eq. (7) must be modified to include heat transferred to the tube. Thus, this correction is presented in Eq. (12).

$$I_t A_p \alpha_p \tau_g - I_t \eta_e A_p + A_g h_{cond,g}(T_g - T_p) + A_t h_{cond,tp}(T_e - T_p) = 0 \quad (12)$$

where A_t=0.708 m² is the tube superficial area, T_e is the tube external wall temperature and $h_{cond,tp}$ is the conduction heat coefficient of the thermal paste and can be written as

$$h_{cond,tp} = \frac{k_{pt}}{L_{pt}} \quad (13)$$

where k_{pt}= 3 W/mK is the conduction heat transfer coefficient of the thermal paste and L_{pt} = 0.001 m is the thermal paste width. The thermal paste energy balance equation is straightforward, representing that the heat transferred from the PV cell is equivalent to the heat transferred to the tube.

$$A_t h_{cond,tp}(T_p - T_e) + A_t h_{cond,t}(T_i - T_e) = 0 \quad (14)$$

where $h_{cond,t}$ is the conduction heat coefficient of the tube material and T_i is the tube inner wall temperature. Once the tube has a round shape, $A_t h_{cond,t}$ can be written as

$$A_t h_{cond,t} = \frac{2\pi k_t L_t}{\log(\frac{D_{t,e}}{D_{t,i}})} \quad (15)$$

where K_t is the thermal conductivity of the tube, L_t the length tube, $D_{t,e}$=0.022 m and $D_{t,i}$=0.020 m the external and internal diameter, respectively. The pipe material is copper, where thermal conductivity (k_t) equals to 400.35 W/mK, as suggested by Bergman *et al.* (2011). Thus, the tube energy balance equation can be written as

$$A_t h_{cond,t}(T_e - T_i) - A_t h_{conv,w} \Delta T_{ml} = 0 \quad (16)$$

where $h_{conv,w}$ is the convection coefficient between the tube and the water and ΔT_{ml} the logarithmic difference between the water temperature and the inner wall tube temperature, which can be written as

$$\Delta T_{ml} = \frac{\Delta T_{out} - \Delta T_{in}}{\log(\frac{\Delta T_{out}}{\Delta T_{in}})} \quad (17)$$

where ΔT_{out} and ΔT_{in} can be represented as

$$\Delta T_{out} = T_f - T_i \quad (18)$$
$$\Delta T_{in} = T_i - T_a \quad (19)$$

To finish the case 2 energy balance, the convective heat transfer to the water is assumed to be equal to the heat gain by the PVT system. So,

$$A_t h_{conv,w} \Delta T_{ml} = \dot{m} c_p (\Delta T_{in} - \Delta T_{out}) \quad (20)$$

Properties of air and water are shown on Tab. (2).

Table 2. Properties of air and water, values taken from Çengel and Ghajar (2009) and Fox *et al.* (2020)

Thermal conductivity, K_a	0.02625 W/m²K
Thermal diffusivity, α_a	2.277×10^{-5} m²/s
Specific Heat, c_p	4178 J/kgK
Thermal conductivity, K_w	0.623 W/m²K

3. RESULTS

Brazil has a large territorial area, which means a large variation on Latitude values. The simulation was performed with daylight measurements from 589 weather stations that collected hourly climate data in 2020. These stations are located in all Brazilian states and the air temperature and solar radiation distribution through the year is shown in Fig. 5 and 6. For these figures, the acronyms of Brazilian states are listed on the x-axis, and the y-axis shows the temperature values in Kelvin and solar radiation in W/m². It was chosen to show this climate variables in boxplot graph since is possible to see some important statistics parameters, such as mean, quartiles, minimum and maximum values.

Most States present an air temperature between 293 K (20°C) and 303K (30°C), with an incidence of solar radiation between 250 and 600 W/m². Although those figures shows only the annual statistics, monthly and hourly variations can be observed, where the highest monthly mean values occurs in summer seasons and the maximum solar energy is received at solar noon. So, it is very common for some states to register temperatures above 308 K (35°C) and solar radiation up to 1000 W/m² or even higher. The weather stations also collects wind speed, used to simulate the environmental condition for the PV panel and the PVT system.

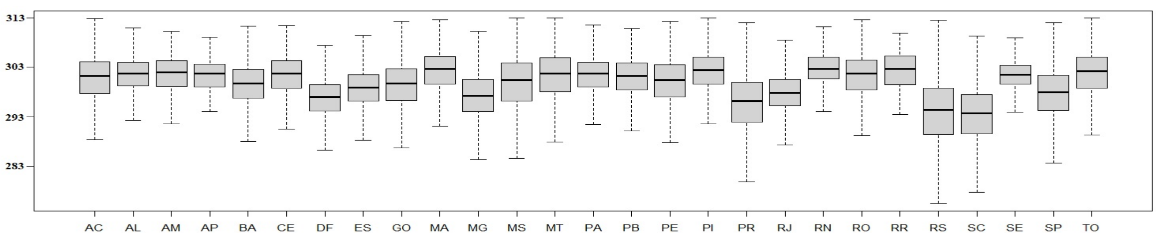

Figure 5. Boxplot for temperature distribution, values in Kelvin

With the equations presented previously and the data collected from the weather stations, the PV cell temperature, and the heat power necessary to reach the temperature T_b, at the heater exit, were simulated for each dataset using Wolfram Mathematica software. For the sake of brevity, only annual average results for each State will be presented, although it is possible to extract seasonal, monthly, or even daily averages. Thus, the annual average temperature of the PV panel, for both cases, is shown in Fig. 7. Without the PVT system, the PV panel reaches high temperatures in all States. Rio Grande do Norte (RN) presented the highest average value, 322 K (49°C), which is consistent since all States in the North, Northeast, and Central-West are characterized by high temperatures. Despite that, by analyzing Fig. 5, 6, even with São Paulo (SP), Maranhão (MA), or Minas Gerais (MG) reaching maximum values of solar radiation, it is clear that RN has the highest solar radiation mean value in the country. The South and Southeast regions presented Tp values 10

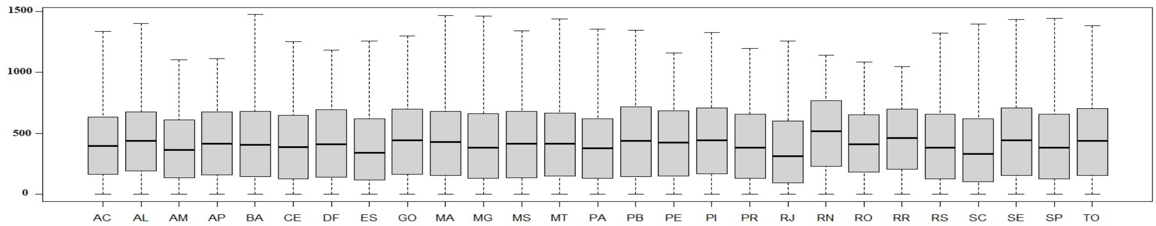

Figure 6. Boxplot for solar radiation distribution, values in W/m²

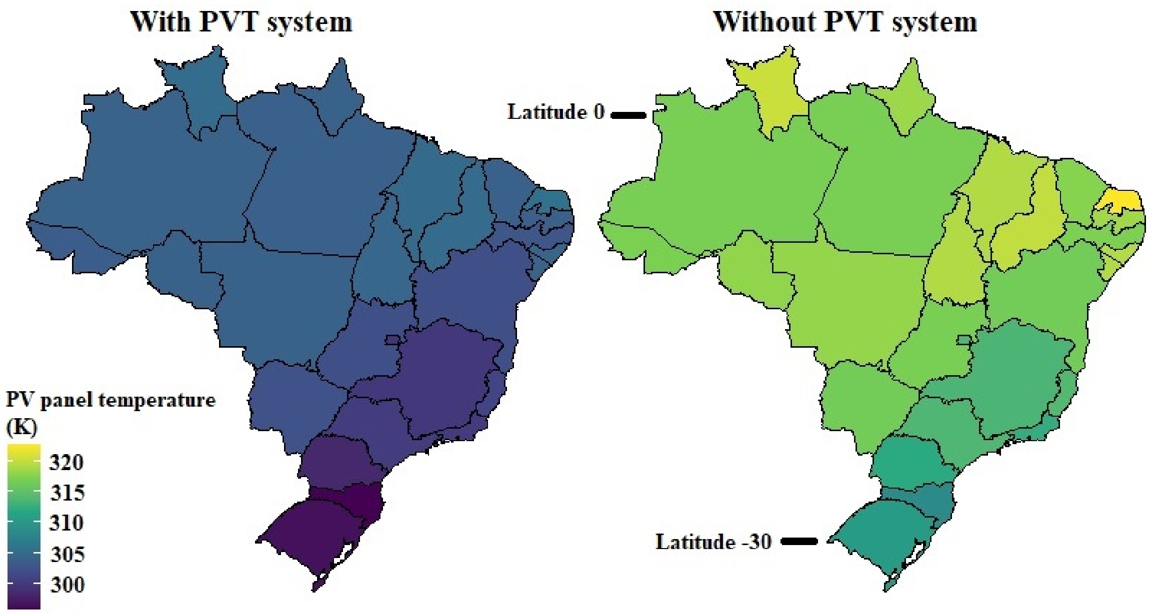

Figure 7. Comparison of PV panel temperature

K lower than other regions, since they can be characterized as regions with high amplitude of solar energy received and intermediary air temperature values.

Fig. 7 shows the map plot for the solar panel temperature (T_p) with respect to the annual mean values. With the PVT system, all the regions presented a significant reduction in T_p, mostly in the northern regions, which suggests a higher electrical efficiency and power generated by the PV plate. The most benefited are the PV panels located on non-south or southeast regions, due to the higher temperature drop. So, it's expected that this locations has more electrical generation efficiency and less power are required from the heater to heat the water up to 323K as can be seen on Fig. 8. Analyzing the annual mean values, South and Southeast demand more heat power than other regions since, in these locations, the PV panel temperature was lower. While other regions had high annual mean values, South states registered a wide range of air temperature, which changes as a function of time. Thus, it is interesting to analyze the hourly mean values at two time instants: Winter and Summer solstices.

Rather than show the required heat power with and without the PVT system, Fig. 9 directly shows the energy saving for the heater. During the Summer season, represented by the December plot, South states were able to reach up to 1000 W of energy saving for the water heater in the noon, but in July, Winter season, the maximum value was 750W. During sunrise, the use of the PVT system had no benefit due to the nearly zero energy saving for the water heating process.

The increasing temperature of the panel implies an efficiency decrease for the generation of electrical energy and a linear relationship can be established from the temperature coefficient, which measures the efficiency drop for each increment in temperature. Due to the attenuation of the local temperatures by the end of the day, the average efficiency of the panel decreases, but the final efficiency observed is relatively high. Locations with higher solar radiation obtained an average efficiency of 19%, and places with lower solar radiation, 20%. When the PVT system reduces the PV panel temperature, the average efficiency increases to 20% and 20.5%, respectively. Those differences between the efficiencies increase the production of electricity by the panels. Fig. 10 shows for each Brazilian state the average produced electricity in the considered period. The overall average gain for the PV panels is 16W, besides the 21 W observed in the Rio Grande do Norte (RN).

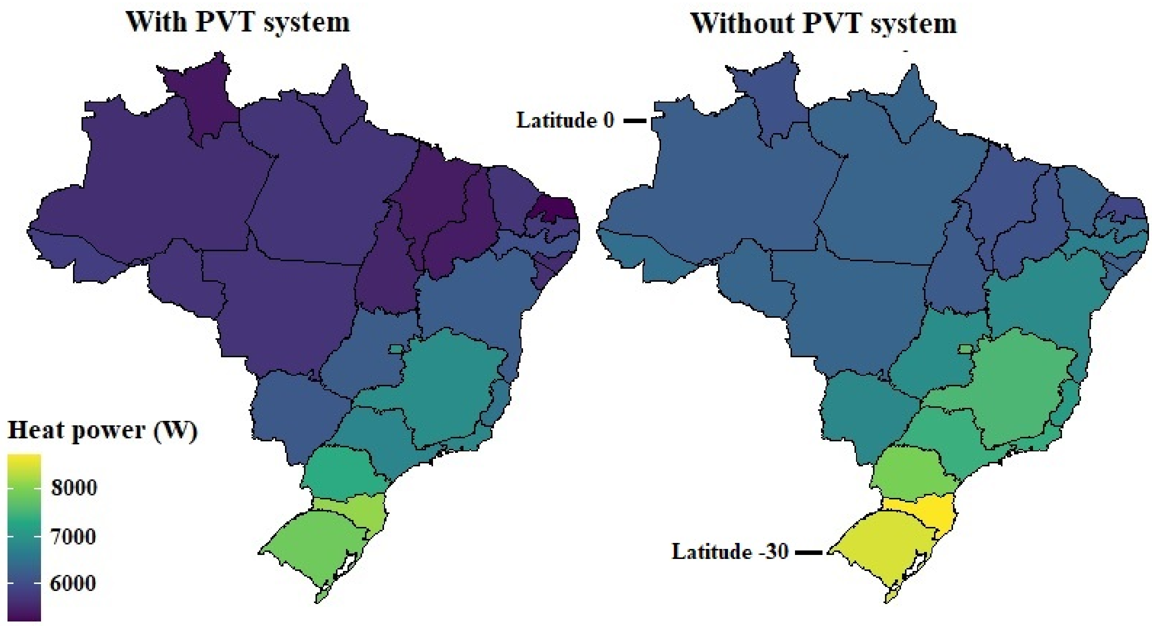

Figure 8. Comparison between the power required from the water heater with the PVT and without it

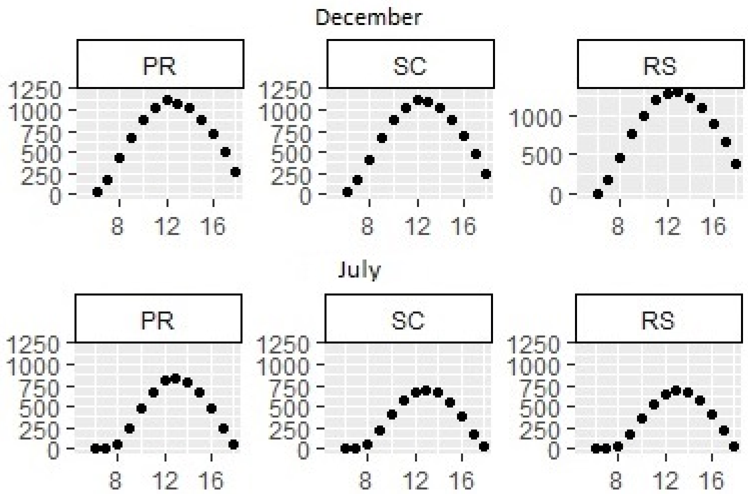

Figure 9. Comparison between the mean hourly energy saving for July (Winter season) and December (Summer season)

4. Conclusions

The present study aimed to simulate a solar panel and a PVT system in the Brazilian territorial area for a full year of climate data. The results showed that the water flow through the panel effectively lowered the temperature, improved the efficiency of electrical generation, and provided effective water heating, which could be used in secondary systems, as it was proposed. It was also possible to visualize the performance in each state of Brazil, which differed according to the climatic characteristics. Considering a PV system with a single solar panel installed, the average electric power production ranged between 180 and 230 W approximately, with an almost negligible increase with a PVT system. However, in the secondary system, the PVT system managed to save up to 1200 W of thermal energy at noon in some States, representing a significant value that could justify its implementation. In future work, we intend to discuss the simulation statistics in more detail and include PV panel arrays installed in series and parallel to the model.

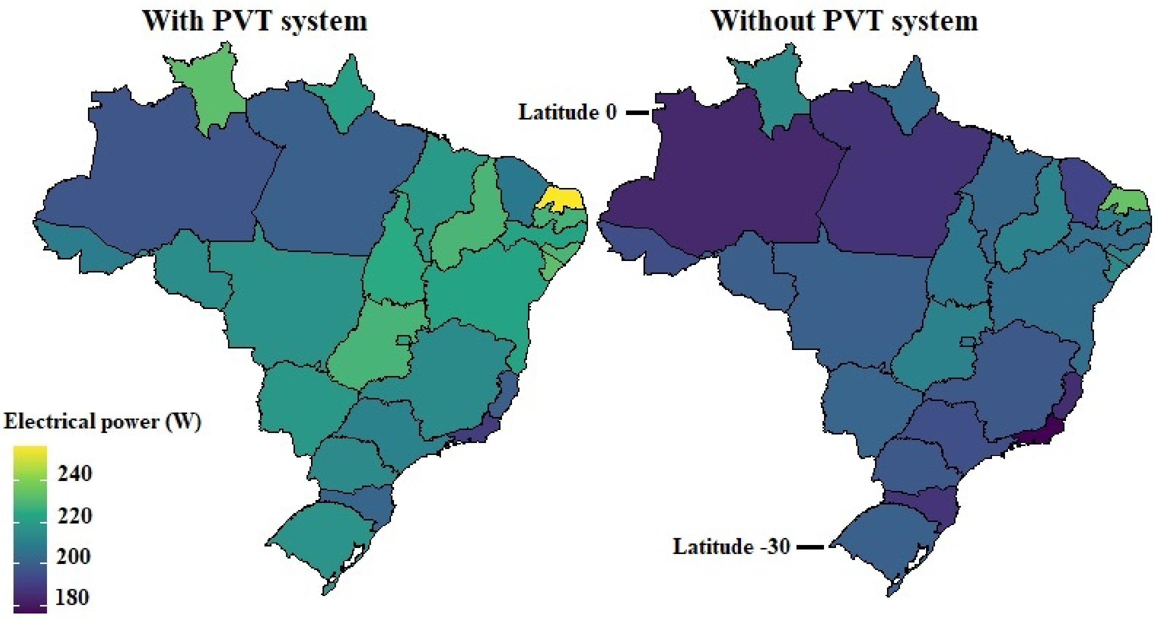

Figure 10. Average of electrical production

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