# ANALYSIS OF A THERMAL-PROTOVOLTAIC SYSTEM WITH GLYCERIN-BASED PHASE CHANGE MATERIAL EMPLOYED IN CURITIBA.

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**ABSTRACT**

*Electrical energy from solar energy has risen in the last few decades. When using photovoltaic cells for this transformation, it was found their efficiency is low compared to traditional sources. The efficiency peaks at 19.2% for polycrystalline silicon modules and 22.9% for monocrystalline ones. These low values are a result of the Shockley–Queisser limit. The heating cells reduces that efficiency in 0.4%/°C in crystalline silicon panels. This study has the objective of analyzing different variations of a hybrid photovoltaic-thermal (PVT) system with a phase change material (PCM). The chosen configurations are: standard hybrid PVT system with the passage of water below the panel; hybrid PVT system with PCM (glycerin) reservoir below it and the thermal water system at the bottom (PVT+PCM); hybrid PCM an inversion of the cooling systems, with the water placed above the PCM reservoir (PVT+PCM-I). Tests were conducted in the city of Curitiba-PR for. A mathematical model utilizing the least-square method was made. After analyzing the PVT+PCM-I had temperature reduction than the other two. In all cases, the variation of the open circuit tension mirrors the variation in temperature: as the temperature increases, the tension is reduced. The mathematical model showed itself coherent for all cases.*

## 1. INTRODUCTION

Energy is essential for human survival, after the discovery of electricity, electrical energy become one of the most common and easily accessible forms of energy. However, its generation impacts the environment, often irreversibly. Therefore, other less harmful ways of obtaining energy began to be researched. Solar energy stands out as the most abundant form of energy on the planet and represents the largest source of energy in the world, reaching 1,533 x 109 TWh annually, approximately 65,900 times the world's electricity consumption, estimated at 23,177 TWh in 2020 (ENERDATA, 2022). For this energy can harnessed, it is necessary using photovoltaic panels, which transform solar energy into electrical energy, or thermal panels, which transform solar energy into thermal energy.

Brazilian climatic conditions have been favorable for the generation of electricity by photovoltaic panels. The global average daily horizontal irradiation is 5,483 $Wh/m^2$ in Northeast and 4,444 $Wh/m^2$ in South, with a national average of 5,153 $Wh/m^2$ (Pereira et al., 2017). Currently, photovoltaic energy in Brazil is 14.8%, higher than 1.7% of 2018, with a projection for 2040 of 32% of Brazilian electricity matrix (ABSOLAR, 2018a; ABSOLAR, 2023b).

The loss of electrical efficiency associated with the temperature increase is estimated at 0.45% for each K above 298.15 K in crystalline silicon panels, while for thin-film modules, this loss is about half the value of crystalline silicon (Mau and Jahn, 2006).

The high potential solar irradiation in the country should be positive stimulus for growth this kind of energy. However, excessive heating of photovoltaic panels suffers from reduced energy efficiency. The loss of electrical efficiency associated with the temperature increase is estimated at 0.45% for each K above 298.15 K in crystalline silicon panels, while for thin-film modules, this loss is about half the value of crystalline silicon (Mau and Jahn, 2006). In this way, for photovoltaic plate can maintain an adequate

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temperature, it is necessary to create a cooling device that extracts the excess thermal energy.

Some methods are already being tested, such as the hybrid photovoltaic panel, or thermal photovoltaic (PVT). It uses a heat exchanger between the panel and the fluid. Thermal energy is transferred to the fluid where it cools the plate. Another method uses the phase change material (PCM), it uses the latent phase of this material, from the solid state to the liquid, later it dissipates heat returning to solid state. However, the high cost of commercial materials used as MMF is a problem (Islam et al., 2016). This drives away investment in this research segment. Another possibility is optimized the process to unify the two systems and named it thermophotovoltaic with phase change material (FVT+MMF). This way, there is increase in the efficiency each other. And this study has stood out in recent years.

The objective this article is to evaluate a thermal photovoltaic system with glycerin-based phase change material in laboratory (indoor) and outdoor, comparing its operating temperature and efficiency with a system without cooling, testing in different configurations. Afterwards, elaborate a mathematical modeling of the system and simulate it in different cases.

## 2. PHOTOVOLTAIC SYSTEMS

### 2.1 Photovoltaic cell

The photovoltaic cell directly converts the energy solar radiation into electrical energy, through the photovoltaic effect. This case, electrons are transferred the valence band to conduction, but remain within the material. They can produced from semiconductor materials as silicon, indium phosphide, gallium arsenide and organic materials. To obtain a PN junction in a silicon cell, a junction using boron for the P layer and phosphorus for the N layer.

Just photons with enough energy to go from the valence to the conduction band are used generate electrical energy. The photons energy don't have enough energy to band jump somme the excess energy those that do the band hoppin is transformed into heat. There is a natural limit to the maximum efficiency of photovoltaics, called the Shockley-Queisser limit. In the case of monocrystalline silicon with an energy gap of 1.1 eV this limit is 30%. (Shockley and Queisser, 1961). As this thermal energy increases, the plate efficiency decreases more and more.

Although photovoltaic cells made from other materials have higher efficiencies, silicon cells (amorphous, monocrystalline and polycrystalline) are the most common, representing 95% of the market, as they are abundant and non-toxic materials and their production capacity is on a large scale (Liu et al., 2020).

### 2.2 Thermal photovoltaic system

The FVT system reduces the panel temperature by exchanging heat with the fluid. It can be categorized with several characteristics. In figure 1, acordding Joshi and Dhoble (2018), it shows configurations that have advantages and disadvantages compared others, such as variation in cost and efficiency, as well as ease of installation.

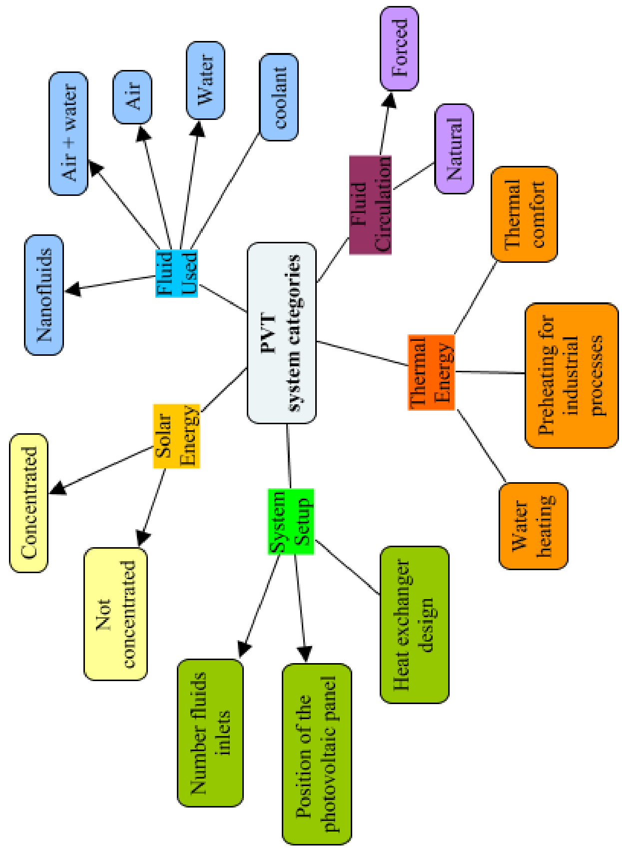


Figure 1. Categories of photovoltaic systems.

Forced circulation has the advantage of better heat convection transfer, having as a negative point the need for a fluid pump system. While convection natural circulates due the difference in specific mass between the heated and cold fluid. The most used cooling fluids are water and air, the first providing greater electrical and thermal efficiency and the second being easier to install (Islam et al., 2016).

Analyzing systems with forced air circulation, global efficiencies of 30% is found in a system with a single passage of fluid and mass flow of 200 kg/h and 35% for a flow of 300 kg/h. In the system with double fluid passage, the efficiencies obtained for these configurations were 40% and 45%, respectively. (Sopian et al., 1996).

Analyzes of PVT systems with amorphous and polycrystalline silicon panels were carried out, analyzing the relevance to using glazing and diffusive reflective surfaces between panels. The performance of the system with water and another one with air was compared. Glazing significantly increased thermal efficiency, but disrupted electrical efficiency. The diffused surfaces increased the energy absorbed by panels, generating more thermal and electrical energy in the system. For all configurations, water was superior to air as a cooling fluid (Tripanagnostopoulos et al., 2002).

Among the cited structures, the one that most resembles the work developed is of Rahaei et al (2021). Where a PVT system was designed with direct contact between the panel and the water that flows through forced circulation on the lower panel surface. Using flow rate of 0.0161 kg/s, the surge electrical efficiency increase over a simple system was 21.5%. The average and maximum thermal efficiency of the system were 49% and 58%. The tests were carried out outdoor and the results presented are from the average results of the test days.

## 2.3 Phase chamge materials

The phase change materials (PCM) absorb energy from the photovoltaic system through latent heat, provides an increase in electrical efficiency.

A phase change material has desirable characteristics: high latent heat; thermal capacity and conductivity; reversible phase shift; consistent melting point; low specific volume and volumetric expansion; overfusion absence; must be stable chemically, non-corrosive, non-flammable, non-explosive, non-toxic and odorless; viable economically and recyclable/reusable (Hasan et al., 2014).

The material melting point must be between the ambient temperature of the place and the panel operating temperature, it is possible to choose a materials mixture to reach desired point.

The estimated increase in annual electrical efficiency using commercially available phase change materials in cold climate regions is between 1% and 3% (Hendricks and Van Sark, 2013).

## 2.4 Combined system PVT with PCM

The union of these two systems proves advantageous, as they supplement each other in the heat extraction from the photovoltaic system. The specific heat by the PCM is used by the thermal system, increasing the thermal, electrical and global system efficiencies.

An energetic and exergetic PVT+PCM analysis of water system was performed, using lauric acid as PCM. The water flow was varied from 0.5 to 4 liters per minute. The temperature reduction when using the PVT+ PCM was 283.25 K, 283.45 K, 286.35 K, 285.55 K and 283.75 K for flows of 0.5, 1, 2, 3 and 4 liters per minute. For the same flows, there was an increase in outlet water temperature of 299.55 K, 288.85 K, 281.85 K, 278.35 K and 277.15 K. The greatest increase in electrical efficiency was obtained with 4 liters per minute setting with a value of 14.42%, 4.72% above the conventional system. However, the setting with the highest average exergy efficiency value was 1 liter per minute, reaching 12.19% (Houssain et al., 2019).

Tests were carried out outdoor with a PVT+PCM system, comparing it to a conventional photovoltaic system. In this system, a coiled copper wire was inserted into the PCM reservoir in order to avoid temperature stratification. A finned heat exchanger was also used to ensure better heat exchange between the panel and the PCM. The result was a system capable of producing 7.43% more electricity during the day compared to the simple module. The global average efficiency of the system was 31.35% (Carmona et al., 2021).

## 2.5 Phase chamge materials

Finding an PCM with the desired thermal energy storage characteristics and is sustainably produced is a challenge. Glycerin, didactic name for glycerol/propanetriol with purity greater than 95%, is a byproduct of biodiesel with potential application as phase change material.

Osaka (2019) developed a PVT+PCM system using glycerin as a phase change material. In this system, a 10W polycrystalline silicon panel was used. The open circuit voltage (VOC) and short circuit current (ISC) by manufacturer are 17.1 V and 0.59 A respectively. The glycerine-based PCM melting temperature was measured in a calorimeter, evaluating two material samples. In the analysis results, there is a PCM temperature jump at end of the experiment, approaching water temperature and showing that the phase change begins when the material is between 313.15 K and 318.15 K and ends approximately 10 K above this temperature. This point is suitable for an operation system in the city of Curitiba, considering conditions climatic. Through this analysis it is also possible to see this PCM does not have a defined temperature phase, which is expected from not pure substance. Comparing a conventional system, the maximum system temperature reduction with water flow was 9.63°C, with insignificant variation between the two flows. The system voltage obtained with water flow was 3% higher than the system without flow and 10% higher than the conventional system.

# 3. RESULTS AND DISCUSSION

The proposed PVT+PCM system with glycerin is a study sequel by Osaka (2019) initially carried out at laboratory to develop the mathematical model. Then the work analysis outdoor. The analyzes were done with cooling panels and a reference panel. The panel used for the tests is a Yingli YL010-17b model, with electrical power of 10W, electrical efficiency of 10% and loss of 0.45% for each Kelvin above ambient temperature.

The cooling system consists of a heat exchanger through which the water passes and a reservoir where the PCM is contained. This intensifies the heat conduction of the phase change material and maintains a more homogeneous temperature. In the upper part of the reservoir, a heat exchanger is installed with 7 fins of 14 mm in length, with equal spacing. Figure 2 shows a system diagram with its four components in the arrangements: PVT+PCM system (original arrangement, with the PCM above thermal system): PVT and PVT+PCM-I (inverted arrangement, with the PCM below thermal system).

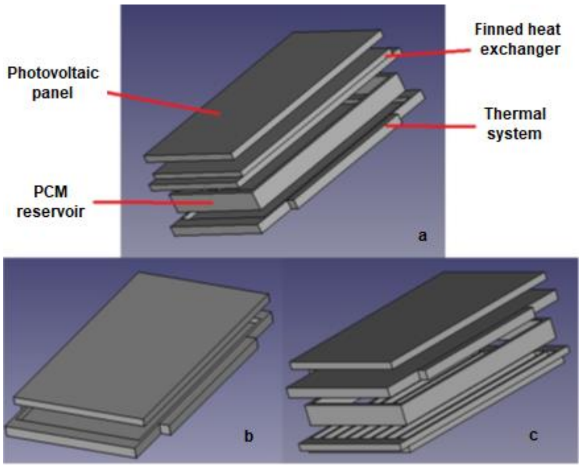


Figure 2. a. PVT+PCM system b. PVT system c. PVT+PCM-I system.

Figure 3 shows the photovoltaic panel, the phase change material reservoir and the thermal system covered with thermal paste.

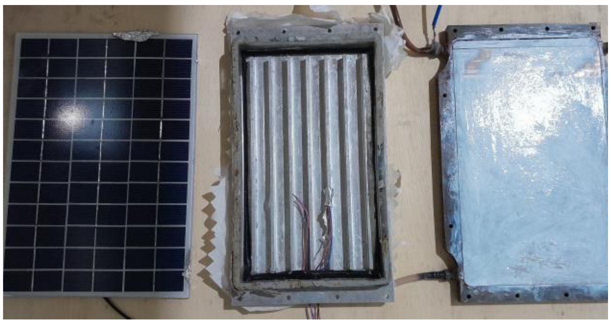

Figure 3. PVT+PCM system components.

The reservoir with a depth of 30 mm was filled with glycerin, to measure the temperature a fixed thermocouple was installed on the central fin and another at reservoir medium height. The thermal system is a copper coil placed between two steel plates. Water is pumped from 8.5 liters reservoir into the system pump with a flow rate of 0.014 l/s.

### 3.1 Lab test

The tests were carried out in a thermal chamber at thermal systems laboratory PUC PR (Pontifical Catholic University of Paraná). They were carried out under STC (Stardard Testing Conditions) with irradiance of 1000 W/m2, wind speed of 1 m/s and ambient temperature of 298.15 K. Nine 500 W lamps were used, arranged in such a way where the global irradiance reaches the desired value measured with a Kipp & Zonen CMP 11 pinamometer. The measurement of 960 W/m$^2$ was less than ideal, so there was a value stored compensation in the acquisition. The wind was caused by a system of fans and exhausters in series and measured with hot wire anemometer. The test was carried out in three proposed configurations: PVT system; PVT+PCM system and PVT+PCM-I system. Thermocouples were used to measure the panel temperature, water inlet and outlet of the thermal system, at fins tip and at PCM reservoir center. The open voltage produced by the panels is also measured by connecting the panel wiring acquisition system.

### 3.2 Outdoor test

It was carried out on the roof of PUC PR shown in figure 4, in this test the PVT+PCM configuration was used. Data acquisition was performed with two T-type thermocouples for ambient temperature, a pyranometer to measure global irradiance, analogue blade anemometer to mesure wind.

Figure 4. Outdoor test.

Measurements were taken in June and December, so one can observe the system operating at two extremes: when the sun is at maximum latitude, both north and south, then having the irradiance at its most extreme states. In June, measurements were taken on a frosty sunny day, on a cloudless day and on a cloudy day. In December, measurements were taken on two unstable days, one with a high temperature (303.15 K throughout the day) and the other with a high peak temperature, but with milder values in the afternoon and at night. Thus, only measurements of the climatic variables were made, simulating the panels behavior through mathematical models.

## 4. MATHEMATICAL MODEL

Through the methods of least squares, non-measurable parameters were calculated, such as: contact resistance, convection heat transfer coefficients and PCM properties. Obtaining the parameters was done through the SLSQP (Sequential Least SQuares Programming) the Python SciPy library function, which interactively solves the equation with different parameters values until obtaining the best result with tolerance of $10^{-6}$.

The performance in Nevada desert at Las Vegas - USA was analyzed, due to the easy access of meteorological data through the NREL (National Renewable Energy Laboratory) and extreme conditions for analysis (Stoffel et Andreas, 2006). The perform data the simulation are global irradiance, wind speed and ambient temperature. The models are obtained in relation to the data obtained in the laboratory and then compared with the experimental results in an outdoor. The differential equations that describe the system are solved by the First Order Euler method, step of 10 seconds for the PVT and PVT+PCM-I and of 60 seconds for the PVT+PCM. The basic equation was the Energy Conservation Equation.

### 4.1 Thermal photovoltaic system

Figure 5 represents the PVT circuit where the green arrow indicates solar energy input and the orange arrows the electrical energy, the heat dispersion to the environment and the cooling system components. The temperature was considered the average of the input and output measurements.

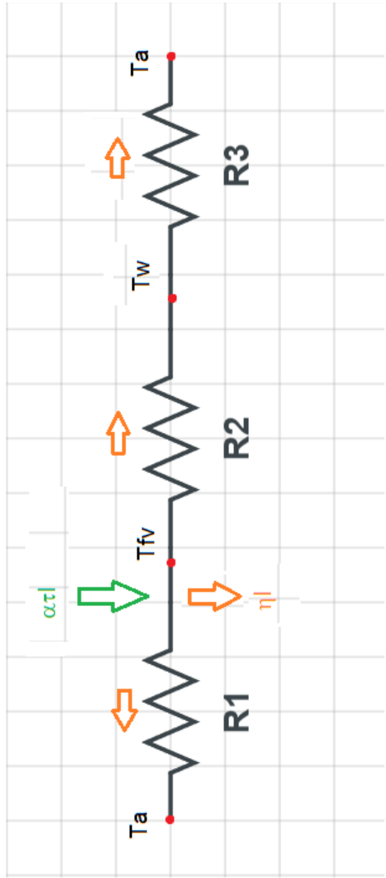


Figure 5. PVT circuit thermal circuit.

The equations below represent the system mathematical modeling:

$$\left.\frac{dT}{dt}\right|_{fv} = \left[(\alpha\tau - \eta)I - U_1\left(T_{pv} - T_a\right) - U_2\left(T_{pv} - T_a\right)\right]\frac{A_{fv}}{C_{fv}} \quad (1)$$

$$U_1 = h_a = 0.664\,\frac{k_a Pr^{1/3}}{L_p}\,Re_L^{0.5} \quad (2)$$

$$U_2 = \left(\frac{1}{h_b} + \frac{L_{pv}}{k_{pv}} + \frac{L_v}{k_v}\right)^{-1} \quad (3)$$

$$\eta = 0.1 - 0.0045\left(T_{pv} - 25\right) \quad (4)$$

This system represents the panel and water temperature variation, where U1 is the convection heat exchange with air, U2 is the heat exchange between the panel and the thermal system and U3 is the thermal system exchange with base. The determined parameters were hb, hw1, hw2 and R” being respectively: heat transfer to base; convection coefficient with material above and below water and contact resistance between panel and thermal system.

### 4.2 Thermal photovoltaic system with phase change material

Figure 6 represents the PVT+PCM circuit, in this case the heat flow goes from PCM fins, subsequently to the thermal system.

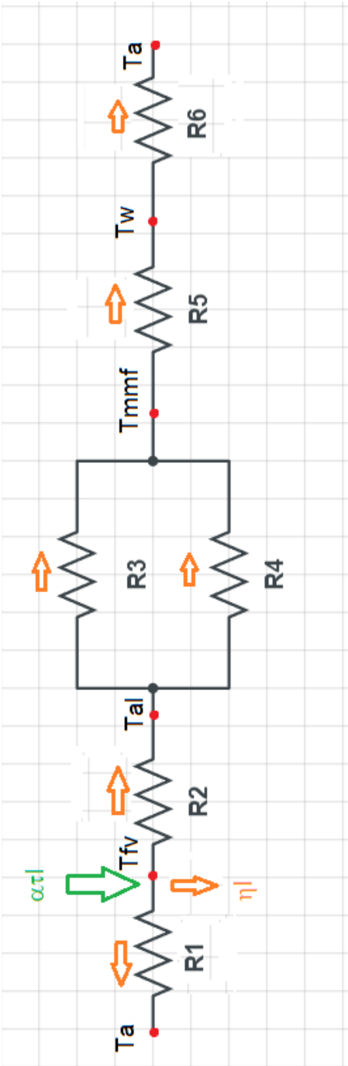


Figure 6. PVT+PCM system thermal circuit.

The equations below represent the circuit mathematical modeling:

$$\left.\frac{dT}{dt}\right|_{fv} = \left[(\alpha\tau - \eta)I - U_1\left(T_{pv} - T_a\right) - U_2\left(T_{pv} - T_a\right)\right]\frac{A_{fv}}{C_{fv}} \quad (5)$$

$$\left.\frac{dT}{dt}\right|_{al} = \left[U_2\left(T_{fv} - T_{al}\right) - \frac{U_3U_4}{U_3 + U_4}\left(T_{al} - T_{pcm}\right)\right]\frac{A_{fv}}{C_{al}} \quad (6)$$

$$\left.\frac{dT}{dt}\right|_{pcm} = \left[\frac{U_3U_4}{U_3 + U_4}\left(T_{al} - T_{pcm}\right) - U_5\left(T_{pcm} - T_w\right)\right]\frac{A_{fv}}{C_{pcm}} \quad (7)$$

$$\left.\frac{dT}{dt}\right|_{w} = \left[U_6\left(T_{pcm} - T_{al}\right) - U_6\left(T_w - T_a\right)\right]\frac{A_{fv}}{C_w} \quad (8)$$

$$U_2 = \left(\frac{L_{al1}}{k_{al}} + \frac{L_{pv}}{k_{pv}} + \frac{L_p}{k_p} + \frac{L_v}{k_v} + R"\right)^{-1} \quad (9)$$

$$U_3 = \frac{k_{al}}{L_{al2}}\frac{A_{cel}}{A_{al}} \quad (10)$$

$$U_4 = \frac{k_{pcm}}{L_{pcm2}}\frac{A_{cel}}{A_{pcm}} \quad (11)$$

$$U_5 = \left(\frac{L_{pcm2}}{k_{pcm}} + \frac{1}{h_w} + \frac{L_{al3}}{k_{al}}\right)^{-1} \quad (12)$$

$$U_6 = \left(\frac{1}{h_b} + \frac{1}{h_{w2}}\right)^{-1} \quad (13)$$

The global coefficient U1 is equal the first model, the other coefficients are calculated in the described equations. For PCM, it was considered that it completely changes phase when reaching the Tsl temperature, which generates an system inaccuracy because this material does not have a defined phase change temperature. The determined parameters were, in addition to those already PVT, Tsl, kmmf and cmmf system defined, respectively phase change temperature, thermal conductivity and material specific heat.

### 4.3 Thermal photovoltaic system with inverted phase change material

In this case there is a PCM reservoir inversion and heat exchanger with water, the circuit represents is in figure 7. As the fins are at the reservoir bottom, its temperature will not be evaluated in this case.

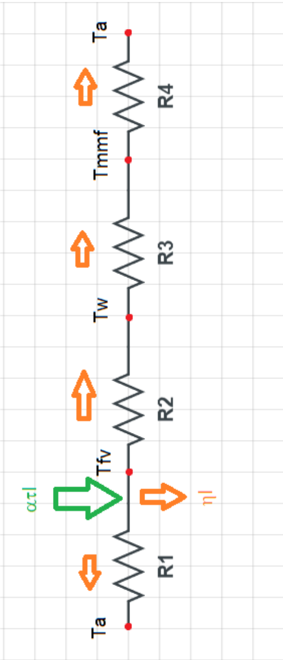


Figure 7. PVT+PCM-I system thermal circuit.

The equations below represent the circuit mathematical modeling:

$$\left.\frac{dT}{dt}\right|_{fv} = \left[(\alpha\tau - \eta)I - U_1(T_{pv} - T_a) - U_2(T_{pv} - T_w)\right]\frac{A_{fv}}{C_{fv}} \quad (14)$$

$$\left.\frac{dT}{dt}\right|_{w} = \left[U_2(T_{fv} - T_w) - U_3(T_w - T_{pcm})\right]\frac{A_{fv}}{C_w} \quad (15)$$

$$\left.\frac{dT}{dt}\right|_{pcm} = \left[U_3(T_w - T_{pcm}) - U_4(T_{pcm} - T_a)\right]\frac{A_{fv}}{C_{pcm}} \quad (16)$$

The coefficients U1 and U2 are the same found for the thermal photovoltaic system, U3 represents the interaction between water and the MMF and U4 the PCM heat loss to the environment.

## 5. RESULTS AND DISCUSSION

The individual results for each of the systems are shown in figures 8, 9 and 10. In the PVT+PCM system, there is a significant temperature reduction while the fins absorb the heat from the panel and the PCM is still in a solid state, but as the fins temperature approaches the panel, the PCM melts. Systems where the panel is in direct contact with water, reduction is not as pronounced in initial period, but becomes considerably greater in steady state (SS), as the water temperature is lower than that of fins, allowing a more efficient heat exchange for a longer period. This means the PCM does not undergo fusion even with an irradiance higher than the standard.

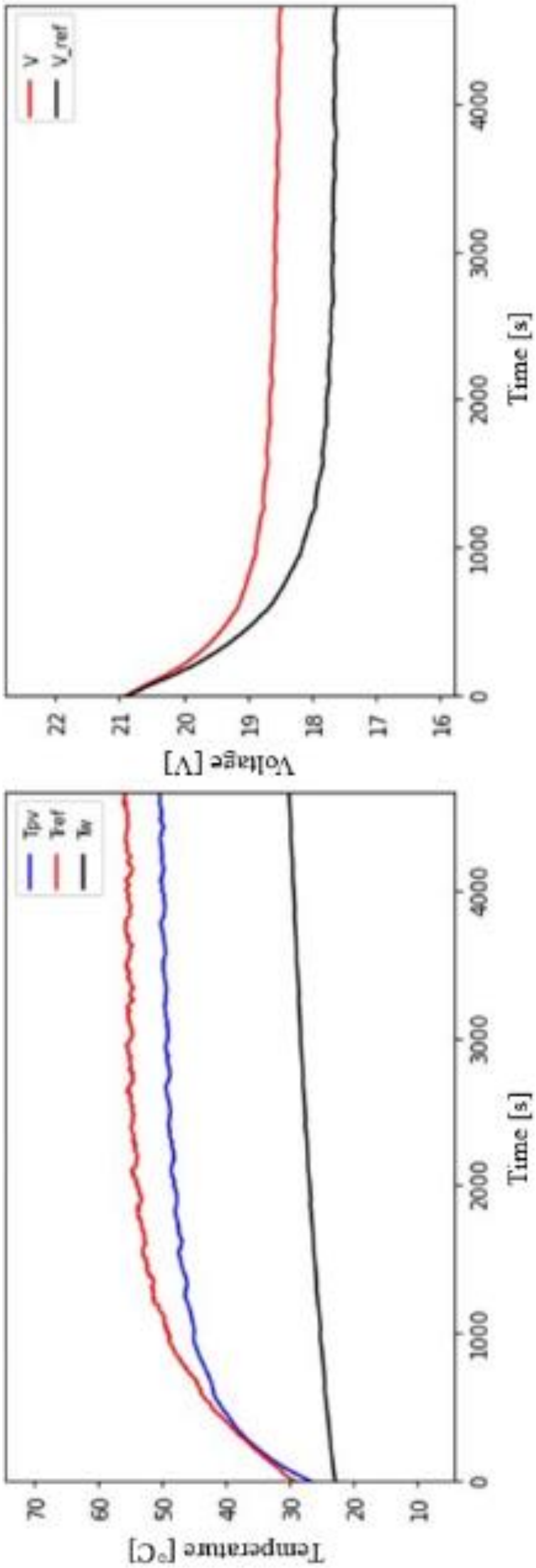


Figure 8. PVT system open temperature and voltage.

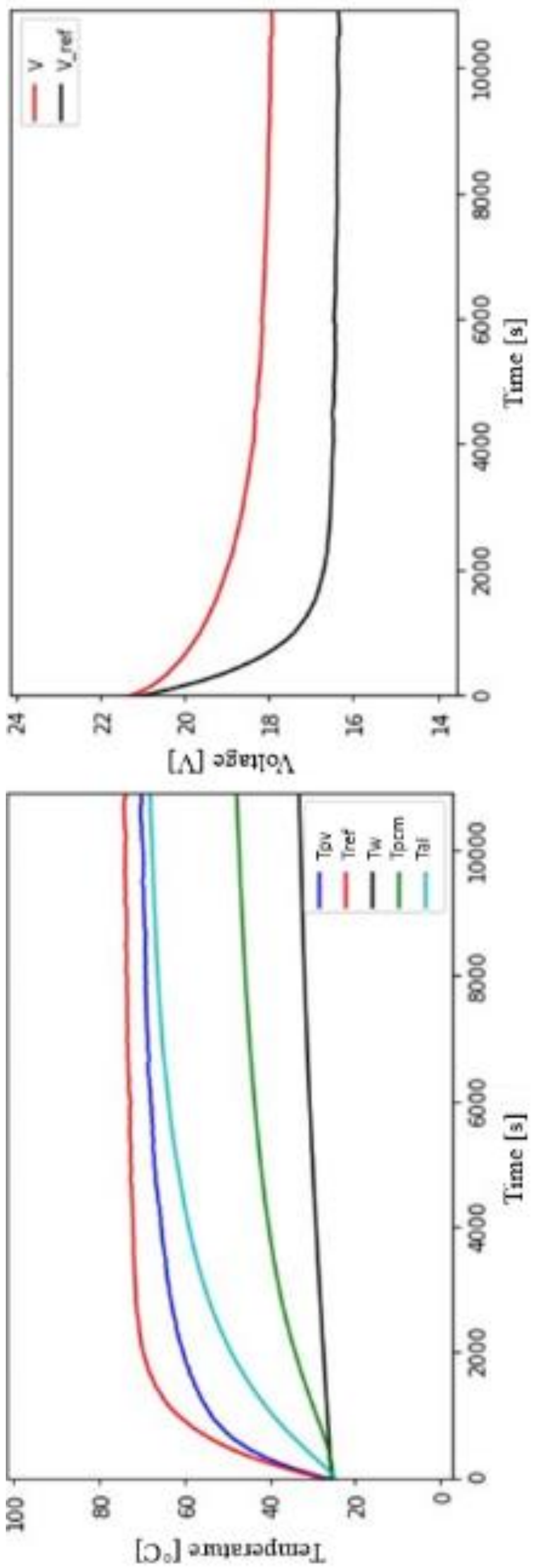


Figure 9. PVT+PCM system open temperature and voltage.

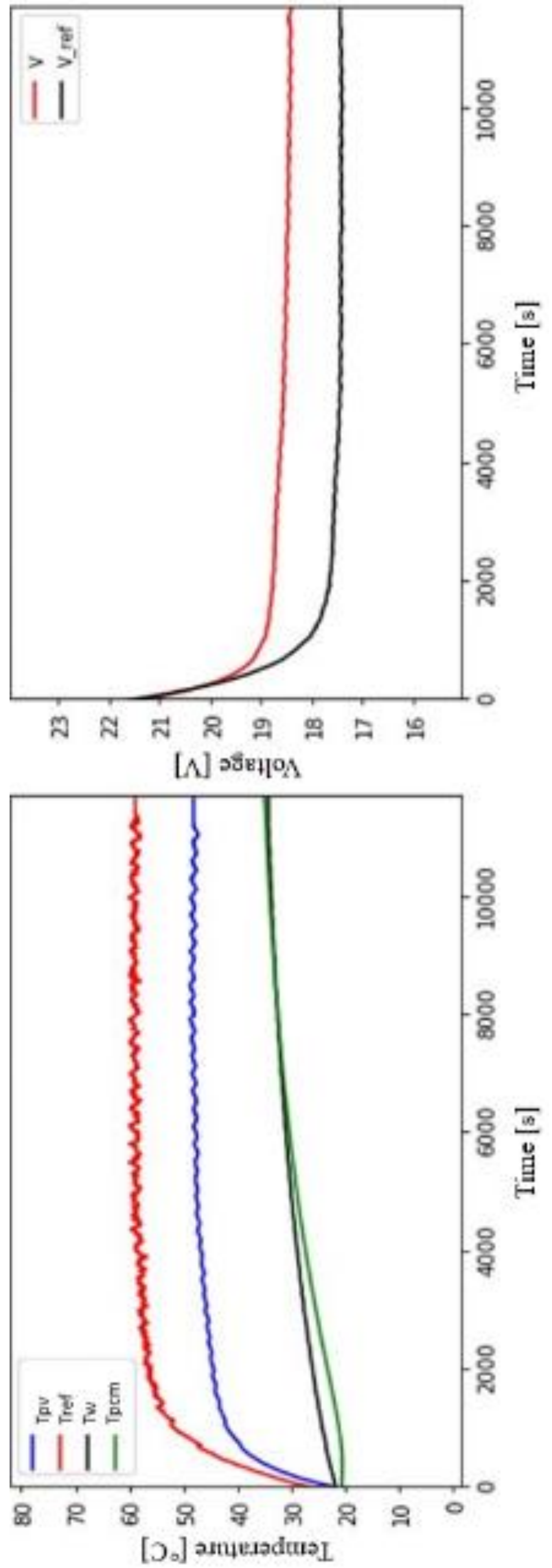


Figure 10. PVT+PCM-I system open temperature and voltage.

The Table 1 shows the graphs shown overall result.

Table 1. Difference of systems with cooling in relation to the original system.

| | Unit | PVT | PVT + PCM | PVT + PCMI |
|---|---|---|---|---|
| **Temperature reduction in SS** | ºC | 5,53 | 3,87 | 10,83 |
| **Maximum temperature reduction** | ºC | 6,35 | 9,63 | 12,61 |
| **Open voltage increase** | % | 4,89 | 9,65 | 5,67 |
| **Thermal energy generated after 1h** | KJ | 175,86 | 93,81 | 190,84 |

The graphs represented in Figure 11 compare the results obtained through mathematical modeling with the results in the laboratory.

The modeling is adequate, with more accentuated errors amount during the transient regime, where the values are higher than the real ones for the PV and PVT+PCM systems and below for the PVT+PCM-I. In the latter case there is also divergence for the cooling system after temperatures a certain point, due to fins heat absorbed and conducted to the PCM not being accounted by the model.

## 6. CONCLUSIONS

Through laboratory tests, the FVT+PCM-I configuration had a more significant temperature reduction than others. In all cases, the open voltage variation follows the temperature variation. The reservoir water temperature increase was higher for the configurations with the thermal system immediately below the panel. The mathematical modeling was consistent, with an average error of less than 2% for all configurations.

The outdoor analysis showed low temperature reduction in winter. Even so, at times when there was a reduction in temperature, there was a gain in VOC proportional to this variation. Temperature of the cooled system remained well below the reference panel while the sunny weather, but in cloudy periods the cooled system has difficulty cooling down, and may even reach a higher temperature than the uncooled system. Although there is this effect, the use of cooling is beneficial.

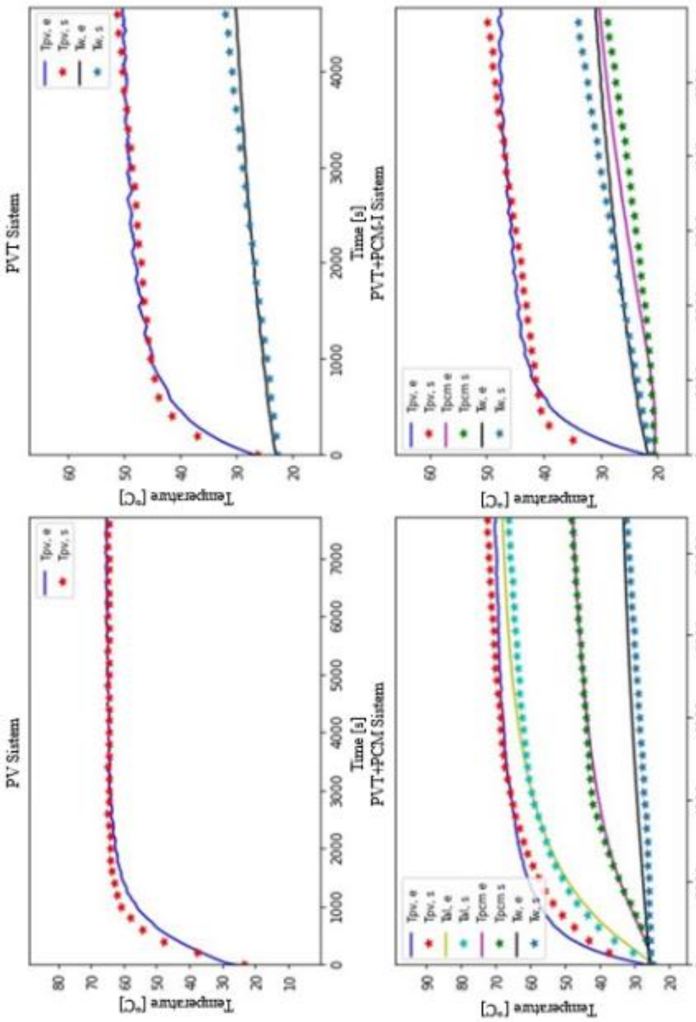

Figure 11. Comparison between simulation and experimental data.

## 7. REFERENCES

ABSOLAR. ABSOLAR projeta fonte solar liderando matriz em 2040. [S.l.: s.n.], 2018. Disponível em: https://www.absolar.org.br/noticia/absolar-projeta-fonte-solarliderando- matrizem-2040/. Acesso em: 16 nov. 2022.

ANEEL/ABSOLAR. Panorama da solar fotovoltaica no Brasil e no mundo. [S.l.: s.n.], 2022. Disponível em: %3Chttps://www.absolar.org.br/mercado/infografico/. Acesso em: 10 fev. 2022.

Carmona, M., Bastos, A. P., Garciéa, J. D., 2021, Experimental evaluation of a hybrid photovoltaic and thermal solar energy collector with integrated phase change material (PVT-PCM) in comparison with a traditional photovoltaic (PV) module. Renewable Energy, Elsevier, Vol. 172, p. 680–696.

ENERDATA. Consumo energetico mundial. [S.l.: s.n.], 2022. Disponivel em: https://yearbook.enerdata.net/electricity/electricity-domestic-consumption-data.html. Acesso em: 7 jul. 2022.

Hasan, A., Sarwar, J., Alnoman, H., Abdelbaqi, E. S., 2017, Yearly energy performance of a photovoltaic-phase change material (PV-PCM) system in hot climate. Solar Energy, Elsevier, Vol. 146, p. 417–429.

Hendricks, J. H. C., Van Sark, W. G. J. H. M., 2013, Annual performance enhancement of building integrated photovoltaic modules by applying phase change materials. 58 Progress in Photovoltaics: Research and Applications, Wiley Online Library, Vol. 21, n. 4, p. 620–630.

Hossain, M., Pandey, A., Selvaraj, J., Abd Rahim, N., Islam, M., Tyagi, V., 2019, Two side serpentine flow based photovoltaic-thermal-phase change materials (PVT-PCM) system: Energy, exergy and economic analysis. Renewable Energy, Elsevier, Vol. 136, p. 1320–1336.

Islam, M., Pandey, A., Hasanuzzaman, M., Rahim, N., 2016, Recent progresses and achievements in photovoltaic-phase change material technology: a review with special treatment on photovoltaic thermal-phase change material systems. Energy Conversion and Management, Elsevier, Vol. 126, p. 177–204.

Joshi, S. S., Dhoble, A. S., 2018, Photovoltaic-Thermal systems (PVT): Technology review and future trends. Renewable and Sustainable Energy Reviews, Elsevier, Vol. 92, p. 848–882.

Mau, S., Jahn, U., 2006, Performance analysis of grid-connected PV systems. Arsenal Res., Bus. Area Renew. Energy Technol., Vienna, Austria, Tech. Rep. IEA-PVPS, Vol. 2, pp. 2006.

Rahaei, A., Rafee, R., Zargarabadi, M. R., 2021, A photovoltaic thermal system with a complete contact between water and PV modules suitable for district heating and electric power generation. Sustainable Energy Technologies and Assessments, Elsevier, Vol. 47, pp. 101325.

Saluja, G., 1984, Potential of solar hot water heating systems at higher latitude locations. In: ENERGY Developments: New Forms, Renewables, Conservation. [S.l.]: Elsevier, pp. 199–2.

Shockley, W., Queisser, H. J., 1961, Detailed balance limit of efficiency of p-n junction solar cells. Journal of applied physics. Vol. 32, n. 3.

Sopian, K., Yigit, K., Liu, H., Kakac, S., Veziroglu, T., 1996, Performance analysis of photovoltaic thermal air heaters. Energy Conversion and management, Elsevier, Vol. 37, n. 11, p. 1657–1670.

Stoffel, T., Andreas, A., 2006, Nevada Power: Clark Station; Las Vegas, Nevada (Data). [S.l.].

Tripanagnostopoulos, Y., Nousia, T., Souliotis, M., Yianoulis, P., 2002, Hybrid photovoltaic/thermal solar systems. Solar energy, Elsevier, Vol. 72, n. 3, p. 217–234.

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