Representativeness of an experimental photovoltaic-thermal (PVT) system prototype in relation to a residential PVT system operating under real conditions

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Abstract

Photovoltaic-thermal (PVT) systems consist of a photovoltaic (PV) module with a heat exchanger attached to its rear, allowing the simultaneous generation of electricity and thermal energy, thus maximizing the use of solar energy. This study assesses the representativeness of a PVT system prototype with polypropylene (PP) heat exchanger in relation to a residential PVT system. Results showed that the prototype generated 72% of the electrical energy per unit area compared to the residential system. The thermal energy per unit area in the prototype was 15.5% higher than the residential. However, thermal energy per unit area showed that prototype's thermal losses were higher, reaching 51.25% compared to only 13.25% in the residential. Therefore, although the prototype underestimates the residential PVT system's performance, it remains useful for testing consumption profiles and demonstrating system feasibility.

Keywords: PVT system prototype, residential PVT system, thermal performance, electrical performance.

1. Introduction

Although PV cell convert radiation directly into electrical energy, its conversion efficiency is still limited. Commercial modules operate with efficiency between 5% and 25%, depending on the material of the PV cell (Tiwari et al., 2023). This limitation implies that most of the solar incident radiation is absorbed and dissipated as heat through the layers of the PV cell. The heat accumulation is prejudicial, as the temperature rise decreases the cell electrical efficiency in 0.45% for each degree Celsius of temperature in the monocrystalline silicon cell (c-Si) and polycrystalline (pc-Si) cells (Kalogirou and Tripanagnostopoulos, 2006). Additionally, the thermal stress accelerates the material degradation, compromising the operational life-span of the system (Saidi et al., 2025).

The operating temperatures of a PV module can reach 80°C in summer in some regions, causing a significantly reduction in electrical efficiency (Reddy et al., 2015). In this way, an effective cooling of the PV modules creates the possibility not only of rising electrical efficiency as a greater durability of the PV cells. A solution for this problem can be the PVT system, which consists of a heat exchanger coupled to the rear of a PV module, collecting useful heat that would otherwise be lost to the environment (Chow, 2010). This thermal energy can be applied to diverse scenarios, such as climatization and to provide hot water for domestic use (Almoatham et al., 2024).

In domestic applications water is the most applied thermal fluid in PVT systems to extract heat from the PV modules (Alshibil et al., 2023). For the residential sector, the water-based PVT modules can supply up to 50% of the total demand for electricity and up to 70% of the hot water demand, depending on the region of the installation and the system sizing (Herrando et al., 2019).

Abdul-Ganiyu et al. (2020) compared the annual performance of a PV module and a PVT module operating under real conditions in the hot and humid tropical climate of Ghana. The authors found that the total annual energy output per unit area of the PV module was 194.9 kWh m^{-2}, while the PVT module produced 149.92 kWh m^{-2} of electrical energy and 1087.79 kWh m^{-2} of thermal energy, respectively. A study realized in the climatic environment of Iraq, evaluated numerically the thermal and electrical performance of a PVT system for a house with five occupants. The authors concluded that the PVT system could provide between 61.7 %

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and 83 % of the total hot water demand, with also an electricity generation between 24.5 % and 43.9 % of the electrical demand (Hamdoon et al., 2020).

Busson et al. (2022) estimated through the simulation in software Transient System Simulation Tool (TRNSYS) that the heated water shower consumption in a four-person residence and a total demand of 700 kWh, depending on the Brazilian region, can represent 45% of the annual electricity demand. Therefore, the residential sector shows promising scenarios for the utilization of sustainable technology to contribute with the thermal and electrical supply.

In the present work, the heat exchanger used is made of polypropylene (PP) with multiple parallel rectangular channels and is installed on the back of conventional PV modules using aluminum spring clamps. The PVT system prototype uses a PVT module with a PP heat exchanger connected to a 100-liter thermal storage tank, a pump, and a consumption simulator. The residential system, with three PVT modules and seven PV modules, is installed in a residence with three occupants, operating under real consumption conditions. The objective of this study is to compare the prototype with the residential system to evaluate the representativeness of the first in relation to the second and, thus, use the PVT system prototype in future studies to predict the performance of PVT systems under real operating conditions.

2. Methodology

2.1. PVT system prototype

The PVT system prototype is installed at the Laboratory for Conversion Engineering and Technology (LEPTEN/UFSC) in Florianópolis, Santa Catarina (SC). Figure 1 presents a complete view of the prototype, highlighting some of the devices that make up the test bench.

Caption:
1 – PV module
2 – PVT module
3 – Pyranometer
4 – Anemometer
5 – Thermal storage tank
6 – Dry-cooler
7 – Water tank

Figure 1: PVT system prototype.

Figure 2 schematically presents the prototype operation. Through pump 1, water from the water tank is circulated in the PVT module, removing heat from the back surface of the module and, consequently, reducing the operating temperature of the PV cells. The heated water is then conducted to a thermal storage tank, where it is stored. Pump 2 is activated to simulate the previously programmed consumption profile, conducting the hot water to the dry-cooler where it is cooled and returned to the water tank, completing the cycle.

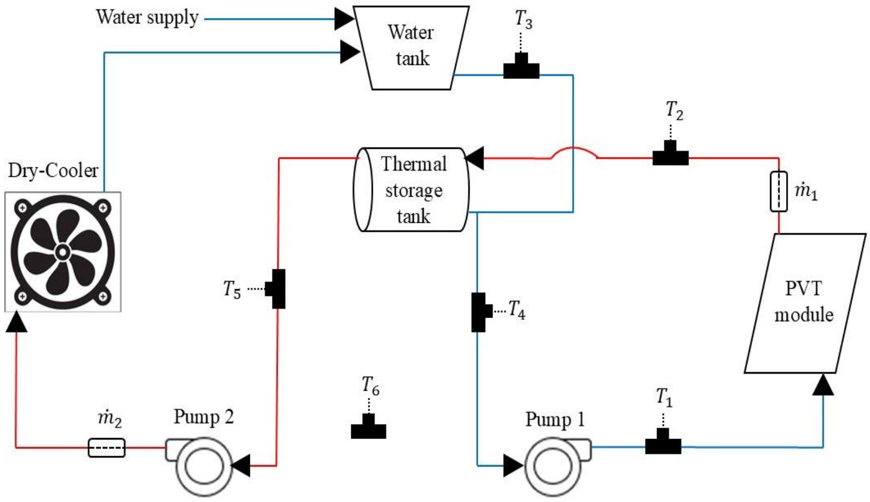

Figure 2: Schematic PVT prototype presentation.

Table 1 presents the specifications for the modules and Table 2 shows the instrumentation specifications and other equipment of the PVT prototype. There is also an electrical control panel for operating the pumps and dry-cooler, a data acquisition system that records data every 10 seconds, and a consumption simulator using an Arduino microcontroller.

Table 1: Specifications of PVT and PV modules.

Parameters	PV module	PVT module
Model	CS3W-405P	CS3W-405P
Nominal power	405 Wp	405 Wp
Module efficiency	18.33 %	18.33 %
Area	2.21 m^2	2.21 m^2 PP heat exchanger = 1.64 m^2
Temperature coefficient ($P_{máx}$)	-0.35% °C^{-1}	-0.35% °C^{-1}
Temperature coefficient (V_{oc})	-0.29% °C^{-1}	-0.29% °C^{-1}
Temperature coefficient (I_{sc})	0.05 % °C^{-1}	0.05 °C^{-1}
$(\tau\alpha)_c$	0.95	0.95
ε_g	0.95	0.95

Table 2: PVT bench equipment description.

Variables	Instrumentation	Quantity	Specifications
Solar irradiation	Pyranometer	1	Model EKO MS-60
Wind speed	Anemometer	1	Model VSensDB-V
Temperature	Temperature Sensor	6	PT100 AA Class
Flow rate	Flux sensor	2	Electromagnetic (PICOMAG DMA25-AAAAA1)
Hot water	Thermal storage tank	1	100 liters
Cold water	Water tank	1	100 liters
-	Pumps	2	Pump 1 – Model Solaris 100 Pump 2 – Model BCL6
Voltage	Voltage transducer	1	Model 50V420ADC-UNIV
Current	Current transducer	1	Model 20C420ADC-UNIV
-	Microinverter	1	Model SUN-1300G
-	Dry-Cooler	1	Model FCR16D61H

2.2. Residential PVT system

The residential PVT system is installed in a house inhabited by three people in Florianópolis-SC. The system has 3 PVT modules connected in parallel. Figure 3 provides a schematic diagram of the system, while Table 3 lists the module specifications and Table 4 summarizes the instrumentation and other equipment used in the residential PVT system.

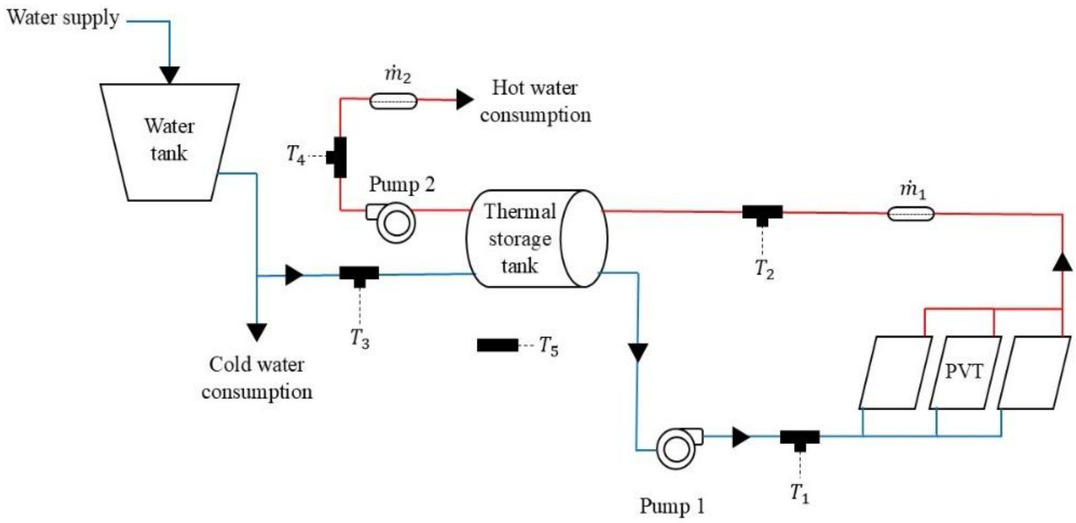

Figure 3: Schematic residential PVT presentation.

Table 3: Specifications of PVT and PV modules.

Parameters	PV module	PVT module
Model	Q.Peak L-G5.0.G Q.ANTUM	Q.Peak L-G5.0.G Q.ANTUM
Nominal power	360 Wp	360 Wp
Module efficiency	18.5 %	18.5 %
Area	1.942 m^2	1.94 m^2 PP heat exchanger = 1.56 m^2
Quantity	7	3
Temperature coefficient ($P_{máx}$)	-0.39% °C^{-1}	-0.39%°C^{-1}
Temperature coefficient (V_{oc})	-0.28% °C^{-1}	-0.28% °C^{-1}
Temperature coefficient (I_{sc})	0.04 % °C^{-1}	0.04 % °C^{-1}
$(\tau\alpha)_c$	0.95	0.95
ε_g	0.95	0.95

Table 4: PVT residential equipment description.

Variables	Instrumentation	Quantity	Specifications
Solar irradiation	Solarimetric station	1	-
Wind speed	Solarimetric station	1	-
Temperature	Temperature Sensor	5	PT100 AA Class
Flow rate	Flux sensor	2	Turbine type (YF-B5)
Hot water	Thermal storage tank	1	500 liters
Cold water	Water tank	1	500 liters
-	Pumps	2	Model BCL6
Electrical energy generated	Inverter	1	Model Sunny Boy 3.0 1AV-40

Similar to the prototype's operation, in the residential system, water is circulated through the PVT modules by pump 1. The heated water is stored in the thermal storage tank until it is used by the residents. Pump 2 is used to increase or decrease the consumption flow, being controlled by a flow switch that activates it only when there is flow. The hot water consumption of the residence is associated with two electric showers and a kitchen faucet. The data acquisition system is identical to that used in the PVT prototype.

Based on meteorological data obtained from the solarimetric station at LEPTEN/UFSC, the Pérez model for an anisotropic sky, presented by Duffie and Beckmann (2006), was used to convert global horizontal solar radiation into tilted global solar radiation tilted at an angle of 14°. The electrical production was measured by the MPPT (Maximum Power Point Tracking) inverter.

To quantify energy production, the electrical generation of the PVT prototype was monitored directly using voltage and current transducers installed in the system. In the residential PVT system, the electrical generation data were obtained through the power inverter. The energy density is calculated as the ratio between the electrical energy generated and the total area of the modules that make up each system.

2.3. Representativeness

A consumption profile, defined by the residents of the house, was programmed using an Arduino to verify the representativeness of the PVT prototype in relation to the residential PVT system. The results compared were energy per unit area, electrical generation and thermal generation.

The test consumption profile was established between 06:00 and 20:00 h. Within this time interval, specific periods were set for the use of the showers and kitchen faucet by the residents, and the same profile was programmed into the PVT prototype. Table 5 presents the simulated schedule.

Table 5: Set times for the simulation.

Equipment	Schedules
Electric shower	10:00 AM - 10:05 AM
Faucet	11:00 AM - 11:10 AM
Faucet	13:00 PM - 13:10 PM
Electric shower	15:05 PM - 15:10 PM
Electric shower	17:15 PM - 17:20 PM
Faucet	17:30 PM - 17:40 PM
Electric shower	18:40 PM - 18:45 PM
Electric shower	19:30 PM - 19:45 PM

The thermal energy output of the PVT modules was obtained based on the instantaneous thermal power generated. This power was calculated using the water flow rate circulating through the PP heat exchanger and the difference between the inlet and outlet water temperatures. The values were determined according to Eq. 1. In both test benches, the pumps that circulate water in the PVT modules are controlled by a temperature differential between the water outlet and inlet, remaining activated until this differential is less than or equal to 0.5 °C.

$$\dot{W}_{th,module} = c\,\dot{m}_1\,(T_{out} - T_{in}) \qquad \text{(eq. 1)}$$

Where c (J kg^{-1} K^{-1}) is the specific heat of water, $\dot{m}_1$ (kg s^{-1}) is the mass flow rate of the water circulating through the PP heat exchanger, T_{out} (°C) is the water outlet temperature and T_{in} (°C) is the water inlet temperature in the PP heat exchanger, T_1 e T_2 , from Figure 2 and Figure 3 respectively.

For the total thermal generation of the systems, Eq. 2 was used.

$$\dot{W}_{th,system} = c\,\dot{m}_2\,(T_{out} - T_{in}) \qquad \text{(eq. 2)}$$

Where T_{out} and T_{in} correspond to the temperatures T_5 and T_4 for the prototype, as in Figure 2, and T_4 and T_3 for the residential PVT, as in Figure 3.

3. Results

The tests were conducted on a day with total solar irradiation of 6.30 kWh m⁻². Figure 4 presents a comparison between the tilted solar irradiance estimated using the Pérez model—applied to direct normal, global, and diffuse irradiance data measured on the horizontal plane by the solarimetric station—and the values measured by the pyranometer installed on the prototype, tilted at 27°. The Pérez model was used to convert the irradiance measured on the horizontal plane into the irradiance incident on a surface tilted at 14°, corresponding to the tilt of the residential PVT system modules. In the morning, the model overestimates the measured values, while in the afternoon it underestimates them, a behavior expected due to the difference in tilt angles.
Although the model presented limitations in reproducing short-term irradiance fluctuations caused by the sudden appearance of clouds, an analysis of the coefficient of determination ($R^2 = 0.98$) and the root mean square error (RMSE = 55.3 W m^{-2}) indicated good agreement between the model estimates and the experimental data, demonstrating that the Pérez model, when applied to the solarimetric station data, provides a satisfactory estimation of the solar irradiance incident on the residential PVT system.

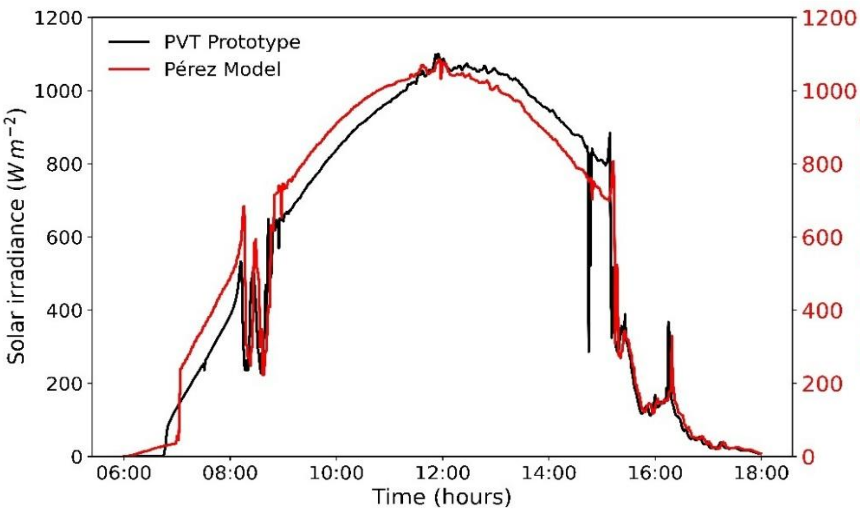

Figure 4: Solar irradiation measured on the prototype and estimated by the Pérez model.

The comparison of the consumption profiles measured in the residential and prototype systems on the test day is presented in Figure 5. It is possible to observe that the residents did not perform the test at some of the established times. However, although small synchronization variations were observed in the simultaneous activation times, resulting from the manual control carried out by the residents, the capability of the PVT prototype's consumption simulator to replicate established profiles is evident. This characteristic is important as it allows for the validation of theoretical models and the sizing of PVT systems with PP heat exchangers under different operational conditions.

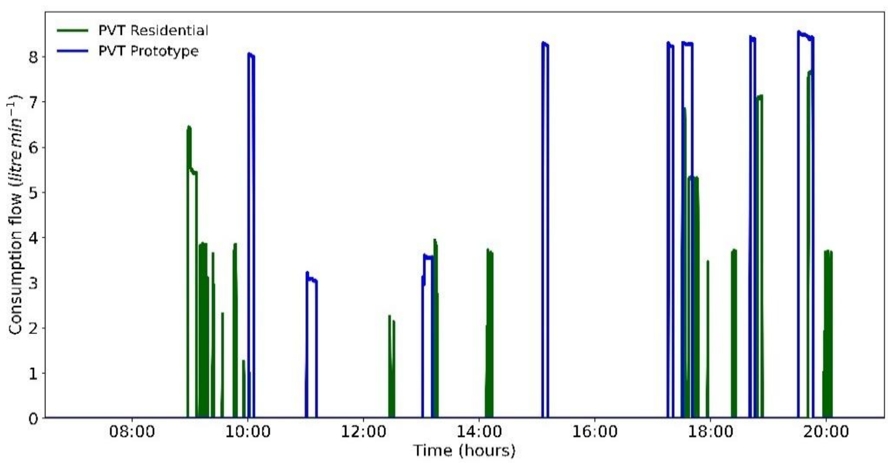

Figure 5: Consumption profiles measured in the residential and prototype systems in a day.

Figure 6 presents the inlet and outlet temperature results in both systems. The constructive differences between the residential system and the prototype resulted in higher outlet temperatures for the residential system, as expected. It can also be observed that the outlet temperature curves of both systems follow the irradiance behavior shown in Figure 4, since these variables are directly proportional. These results also demonstrate the PP heat exchanger in the PVT module capacity of extracting thermal energy that would otherwise be lost to the environment to heat water.

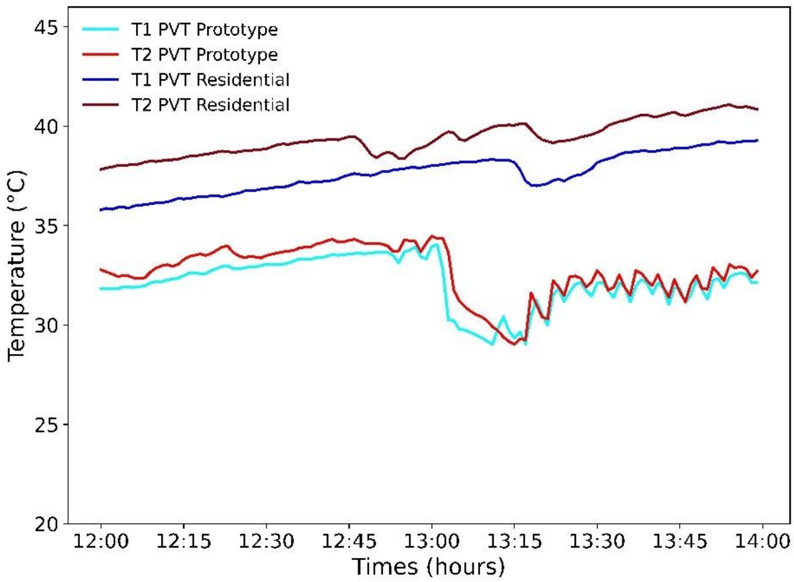

Figure 6: Inlet and outlet temperatures for both systems.

The results of the energetic point of view to verify the representativeness of the PVT system prototype in relation to the PVT residential system is presented in Table 6. The prototype showed being able to generate approximately 72% of the electrical energy per unit area compared to the residential system. This analysis revealed a similarity between the systems, confirming a good agreement in the electrical performance by area, although the construction and scale differences. As the residential configuration including 10 modules total of which only 3 are PVT, the total electrical generation is substantially higher.

Table: 6 Energy performance of the PVT prototype and of the residential PVT system.

Variables	PVT prototype	PVT residential
Electrical energy per unit area	1017.0 Wh m^{-2}	1421.9 Wh m^{-2}
Electrical generation	2247.7 Wh	27585.7 Wh
Thermal Generation PVT module	1898.6 Wh	4333.4 Wh
Thermal Generation PVT system	925.6 Wh	3763.6 Wh
Thermal energy per unit area of the PVT module	859.0 Wh m^{-2}	744.7 Wh m^{-2}
Thermal energy per unit area of the PVT system	418.8 Wh m^{-2}	646.7 Wh m^{-2}

When comparing the thermal energy generated by the PVT modules, the prototype produced approximately 44% of the total energy generated by the residential system modules. This result suggests a good performance of the prototype PVT module, which is even more notable when it is observed that it generated 31.4% more thermal energy than the average residential module.

When analyzing thermal energy per unit area of the PVT module, it is observed that the prototype presents a 15.5% higher in thermal energy conversion per unit area compared to the residential PVT system. This performance difference is directly related to the construction and dimensional differences between the systems, especially regarding the thermal storage tank. These differences influence the temperature gradient between the inlet and outlet of the PVT modules, resulting in a longer circulation pump activation time, since control is based on the thermal differential. Furthermore, the water flow rates in the PP heat exchangers also differ while in the residential system the flow rate is 0.16 kg s^{-1}, in the prototype it is 0.11 kg s^{-1}, parameters directly proportional to thermal generation.

Although the PVT prototype demonstrates higher efficiency in converting thermal energy per unit area, the total thermal output indicates considerable losses throughout the system. A percentage analysis of thermal losses, based on the ratio between the thermal energy per unit area of the PVT modules and that of the complete systems, shows that while the residential PVT system exhibits losses of only 13.15%, the prototype reaches 51.25% of thermal energy losses at the end of the cycle.

The distinct installation conditions of each system help explain the observed heat losses. While the PVT prototype installed outdoors is subject to greater convective losses, the residential system, located under the roof, operates in a more protected environment. Although no loss model was incorporated into the calculations to individually quantify the contribution of each system component, the results indicate the need for improved thermal insulation, particularly along the tubulation of the PVT prototype. It is worth noting that the test as carried out on a day with winter-like weather conditions, which contributed to the heat losses observed in the prototype.

Despite underestimating the overall thermal performance of the residential PVT system, the prototype comparison remains relevant, as it enables the application and validation of heat loss models reported in the literature, helping to identify the one that best represents PVT systems employing PP heat exchangers. Consequently, this analysis directly contributes to the optimization of future PVT system designs through controlled testing of the prototype under varying operating conditions.

4. Conclusions

This study compared the energy performance of a PVT system prototype with a residential PVT system based on a consumption profile established by the residents. The results highlighted the potential of PVT systems with PP heat exchangers for thermal energy generation, harnessing heat that would be lost to the environment, resulting in a higher overall efficiency compared to a purely PV system.

Testing with a programmed consumption profile demonstrated the practicality and capability of the PVT prototype’s simulator to replicate different usage scenarios. This enables the evaluation of PVT system performance under varying family usage patterns and climatic conditions.

The prototype's representativeness in simulating real-world operation scenarios is fundamental for the correct sizing of residential PVT systems. This is due to its ability to estimate, based on demand, how much thermal energy can be generated, in addition to verifying how much the electrical efficiency is improved. The prototype's ability to simulate different profiles and conditions makes it useful for applying and validating heat loss models available in the literature, enabling the identification of those that best represent PVT modules with PP heat exchangers.

The results contribute to improving thermal insulation, optimizing component sizing, and developing more efficient PVT systems. The PVT prototype also proves useful for optimizing flow rates in PP heat exchangers, enabling better analysis of thermal performance when comparing systems. Furthermore, flow control and adjustment contribute to the design sizing process of PVT systems.

In general, the prototype underestimated the performance of the residential PVT system, a result expected due to differences in the number of PVT modules, the dimensions of the thermal storage tank, and certain operating conditions. These differences, particularly the size of the thermal storage tank and the water flow rates in the PP heat exchangers, directly influence the heat transfer to the working fluid and, consequently, the systems’ thermal output. Nevertheless, the prototype proved to be an effective tool for evaluating the thermal performance of PVT systems under real operating conditions, enabling reproduction of typical consumption profiles.

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6. References

Abdul-Ganiyu, S., Quansah, D. A., Ramde, E. W., Seidu, R., Adaramola, M. S., 2020. Investigation of Solar Photovoltaic-Thermal (PVT) and Solar Photovoltaic (PV) Performance: A Case Study in Ghana. Energies, v. 13, p. 2701.

Almoatham, S., Chiasson, A., Mulford, R., Moreno-Pena, M., 2024. Development of experimentally-validated models for nocturnal cooling of thermal systems with photovoltaic thermal (PVT) modules. Solar Energy. 268, 112279.

Alshibil, A. M. A., Farkas, I., Víg, P., 2023. Sustainability contribution of hybrid solar collector towards net-zero energy buildings concerning solar cells wasted heat. Energy for Sustainable Development, v. 74, p. 185–195, 2023.

Busson, B. O., Pigozzo Filho, V. C., Leyton Mopan, A., Gomide, D. S., Passos, J. C., Tachon, L., Hipólito, H., Araújo, F. C., Gabiatti, M., 2022. Economic feasibility simulation and thermal performance of a heat exchanger for photovoltaic module. *Proceedings of the IX Brazilian Solar Energy Congress (CBENS 2022)*, Florianópolis, Brazil, 23–27 May. [in Portuguese].

Chauhan, A., Tyagi, V. V., Anand, S., 2018. Futuristic approach for thermal management in solar PV/thermal systems with possible applications. Energy Conversion and Management. 163, 314–354.

Chow, T. T., 2010. A review on photovoltaic/thermal hybrid solar technology. Applied Energy. 87, n. 2. 365–379.

Duffie, J. A., Beckman, W. A., 2006. Solar engineering of thermal processes, third ed. John Wiley & Sons, New Jersey.

Hamdoon, O. M., Alomar, O. R., Salim, B. M., 2020. Performance analysis of hybrid photovoltaic thermal solar system in Iraq climate condition. Thermal Science and Engineering Progress, v. 17, p. 100359.

Herrando, M., Ramos, A., Zabalza, I., Markides, C. N., 2019. A comprehensive assessment of alternative absorber-exchanger designs for hybrid PVT-water collectors. Applied Energy, v. 235, p. 1583–1602.

Kalogirou, S. A., Tripanagnostopoulos, T., 2006. Hybrid PV/T solar systems for domestic hot water and electricity production. Energy Conversion and Management, v. 47, p. 3368-3382.

Reddy, S. R., Ebadian, M. A., Lin, Cheng-Xian., 2015. A review of PV–T systems: Thermal management and efficiency with single phase cooling. International Journal of Heat and Mass Transfer, v. 91, p. 861-871.

Saidi, S., Brahim, T., Jemni, A., 2025. Experimental advances in photovoltaic-thermal (PVT) systems: a comprehensive review of cooling technologies, materials, and performance optimization. Solar Energy, Vol 298, p. 113650.

Tiwari, A, K., Chatterjee, K., Agrawal, S., Singh, G. K., 2023. A comprehensive review of photovoltaic-thermal (PVT) technology: Performance evaluation and contemporary development. Energy Reports, v. 10, p. 2655–2679.