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Analysis of a photovoltaic-thermal with heat pump system for engine heating in thermal power plants

Análise de um sistema fotovoltaico-térmico com bomba de calor para aquecimento de motores em usinas termoelétricas

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ABSTRACT

This study performed a computational analysis and experimental validation of a hybrid photovoltaic-thermal (PVT) system combined with a heat pump for engine heating in thermal power plants. Using the Ansys Fluent software for computational fluid dynamics simulations, the research examined the thermal performance and efficiency of the PVT system under real operating conditions. The simulations confirmed that the PVT system could achieve high thermal efficiency, especially during periods of maximum solar radiation. The mesh model used in the simulations comprised 6,589,347 elements, refined to capture the details of fluid flow and heat transfer. The results indicated that the maximum outlet water temperature reached 315 K, while the experimental tests showed a maximum temperature of 328.15 K. The maximum thermal efficiency observed was 73% at noon. The study also demonstrated the feasibility of scaling up the system from a bench-scale prototype to industrial applications. By employing the Boussinesq approximation and maintaining the dimensionless Reynolds, Nusselt, Prandtl, Grashof, and Rayleigh numbers, the downscaled simulations were shown to be reliable and comparable to full-scale systems. The integration of the PVT system with a heat pump proved to be effective in reducing fossil fuel consumption, enabling simultaneous generation of electricity and heat, thereby improving energy efficiency and reducing operating costs in industrial settings. The PVT system faces climate constraints, high costs, and industrial integration challenges. The present study acknowledges the challenges in the widespread adoption of PVT systems and suggests future research to optimize these systems in diverse climatic and geographic contexts.

Keywords: bench-scale prototype; computational fluid dynamics; thermal efficiency; scale-up; solar energy; industrial applications.

RESUMO

Este estudo realizou uma análise computacional e validação experimental de um sistema fotovoltaico-térmico (PVT, *photovoltaic-thermal*) híbrido combinado com uma bomba de calor para aquecimento de motores em usinas termelétricas. Utilizando o *software* Ansys Fluent para simulações de dinâmica de fluidos computacional, a pesquisa examinou o desempenho térmico e a eficiência do sistema PVT sob condições reais de operação. As simulações confirmaram que o sistema PVT pode alcançar alta eficiência térmica, especialmente durante períodos de máxima radiação solar. O modelo de malha utilizado nas simulações foi composto por 6.589.347 elementos, refinado para capturar os detalhes do fluxo de fluido e transferência de calor. Os resultados indicaram que a temperatura máxima da água na saída atingiu 315 K, enquanto os testes experimentais mostraram uma temperatura máxima de 328,15 K. A eficiência térmica máxima observada foi de 73% ao meio-dia. O estudo também demonstrou a viabilidade de ampliar o sistema de um protótipo em escala de bancada para aplicações industriais. Ao empregar a aproximação de Boussinesq e manter os números adimensionais de Reynolds, Nusselt, Prandtl, Grashof e Rayleigh, as simulações em escala reduzida mostraram-se confiáveis e comparáveis a sistemas em escala real. A integração do sistema PVT com uma bomba de calor demonstrou ser eficaz na redução do consumo de combustíveis fósseis, permitindo a geração simultânea de eletricidade e calor, melhorando a eficiência energética e reduzindo os custos operacionais em ambientes industriais. O sistema PVT enfrenta limitações climáticas, altos custos e desafios de integração industrial. O presente estudo reconhece os desafios para a adoção generalizada de sistemas PVT e sugere pesquisas futuras para otimizar esses sistemas em diversos contextos climáticos e geográficos.

Palavras-chave: protótipo em escala de bancada; dinâmica de fluidos computacional; eficiência térmica; ampliação de escala; energia solar; aplicações industriais.

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Introduction

The growing demand for energy, combined with the urgent need to mitigate environmental impacts, has driven the search for more sustainable and efficient energy sources (Hasan et al., 2023). Among emerging solutions, photovoltaic-thermal (PVT) systems stand out for their ability to simultaneously generate electricity and heat from solar radiation (Alghamdi et al., 2024). This integrated approach optimizes energy conversion, maximizing productivity in industrial applications and positioning itself as a promising alternative in the global energy transition (Ghamari and Sundaram, 2024). However, the implementation of PVT systems in industrial environments still faces significant technical and economic challenges.

One of the main obstacles is the efficient integration of PVT systems with existing industrial processes, which may require complex adaptations (Ghanim and Farhan, 2022). Additionally, the variability in thermal and electrical efficiency, influenced by climatic conditions and solar radiation, presents a relevant operational challenge (Yan et al., 2022). The high initial cost, along with the need for specialized maintenance, also limits large-scale adoption, especially in industries that require high reliability (Sornek et al., 2022). The joint application of PVT systems with heat pumps demands careful analysis to ensure that the thermal energy generated is effectively utilized, optimizing energy efficiency and reducing dependence on fossil fuels.

This study aimed to address these gaps through the experimental and computational validation of a hybrid PVT system with a heat pump, designed to operate in thermal power plants (Gaur et al., 2022). Using computational fluid dynamics (CFD) simulations and experiments with a bench-scale prototype, we investigated the system's performance under controlled and simulated conditions (Rosli et al., 2021). The Boussinesq approximation was adopted to ensure thermal modeling accuracy, assessing the impact of solar radiation and fluid circulation on the system's energy responses (Mayeli and Sheard, 2021).

The results presented in this study contribute to the optimization and scalability of PVT systems, promoting greater energy efficiency and a more sustainable energy matrix. Additionally, this study provides insights for future research aimed at adapting PVT systems to different climatic and industrial contexts, emphasizing the importance of investigating new materials and integration methodologies (Lorenzo and Narvarte, 2019; Dahham et al., 2022).

Materials and Methods

Energy demand for the needs of standby plant engines

Currently, at the thermal power plant of Petrolina Energy Company (CEP, Companhia Energética de Petrolina), in Pernambuco, Brazil, the engines are kept heated in standby condition using a heat exchanger. The steam from a steam boiler heats the water, which in turn provides heat to the engines. Figure 1 illustrates the current scheme for heating an engine at the plant.

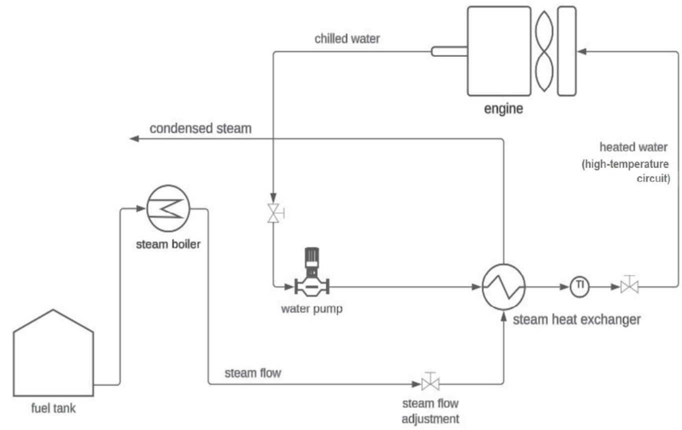


Figure 1 – Engine standby heating scheme with steam boiler at the thermal power plant of Petrolina Energy Company.

The flow rate of the engine heating water circuit is constant. Plant operation is controlled manually via a valve that regulates the steam heating the water, thereby controlling the temperature of the engine inlet.

Knowing the thermal energy demand of the standby engine at the power plant is crucial for sizing the solar heating system. The thermal energy demand is calculated by Equation 1:

$$\dot{Q}_{engine} = \dot{m}.C_p.(T_{in} - T_{out}) \quad (1)$$

Where:

$\dot{Q}_{engine}$ = thermal power consumed by the engine [W];

$\dot{m}$ = mass flow rate of water [kg/s];

Cp = specific heat of water [J/kg/°C]; and

T_{in} and T_{out} = inlet and outlet temperatures of the water in the engine, respectively.

Photovoltaic-thermal collector

Traditional photovoltaic panels convert sunlight into electricity but heat up significantly, which can reduce their efficiency. PVT collectors address this issue by adding a thermal absorption layer that captures the heat and uses it to heat water or another fluid, generating electricity and useful heat for various applications (Starowicz et al., 2023). To reach their full potential, it is essential to develop advanced modeling and control techniques, including CFD simulations to improve performance under different operational and environmental conditions, and to invest in new materials that ensure the durability of the systems (Saurabh et al., 2022). The industrial application of PVT collectors faces significant challenges, and it is crucial to address these issues through research, development, and incentive policies to optimize their efficiency and promote widespread adoption, contributing to a more sustainable and efficient energy matrix (Dahham et al., 2022).

Proposed solution for water heating using photovoltaic-thermal systems and a heat pump

Figure 2 illustrates the arrangement of the engine heating system to be implemented at the CEP thermal power plant (Pernambuco, Brazil). It consists of a solar heating system with a heat pump connected in series with the current system, which includes an industrial steam boiler. The concept is to provide the maximum energy required for engine heating using the energy from the solar generation system with a heat pump (Lorenzo and Narvarte, 2019).

Considering the following values as nominal design conditions:

$$\dot{m} = 3.89\,\frac{kg}{s} \rightarrow 14\,\frac{m^3}{h}$$

$$C_p = 4,180\,\frac{J}{kg.^\circ C}$$

$$T_{in} = 66\,^\circ C \rightarrow 339.15\ K$$

$$T_{out} = 65\,^\circ C \rightarrow 338.15\ K$$

The following value is obtained for the thermal demand of the engine:

$$\dot{Q}_{engine} = 16.26\ kW$$

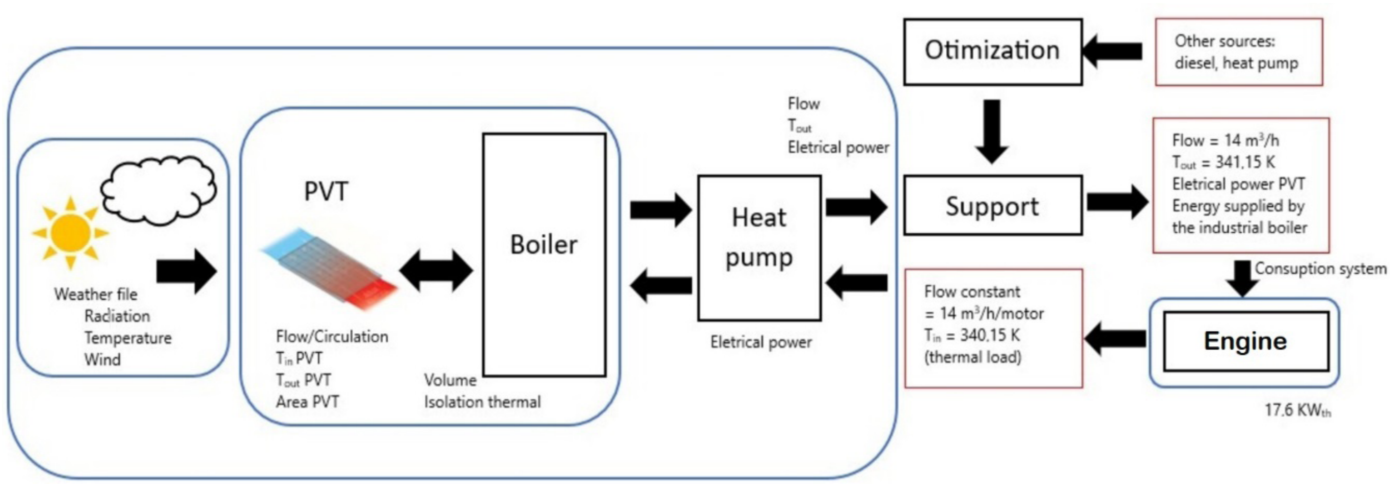
The value found of 16.26 kW, with heat supply at 338.15 K, represents the engine's thermal energy demand and is considered the nominal design value for sizing the solar heating system.

Bench-scale prototype

A bench-scale prototype (Figure 3) was developed based on a detailed analysis of system requirements and expected operational conditions. The conceptual design aimed to simulate the heating operation of a motor in a thermal power plant in standby mode, utilizing various thermal energy sources, including the PVT system. The primary objective was to develop a solution for the simultaneous generation of electricity and water heating, contributing to the reduction of the heat pump's operating time. The materials used in the construction of the prototype must be selected based on their durability, high-temperature resistance, and compatibility with thermal fluids.

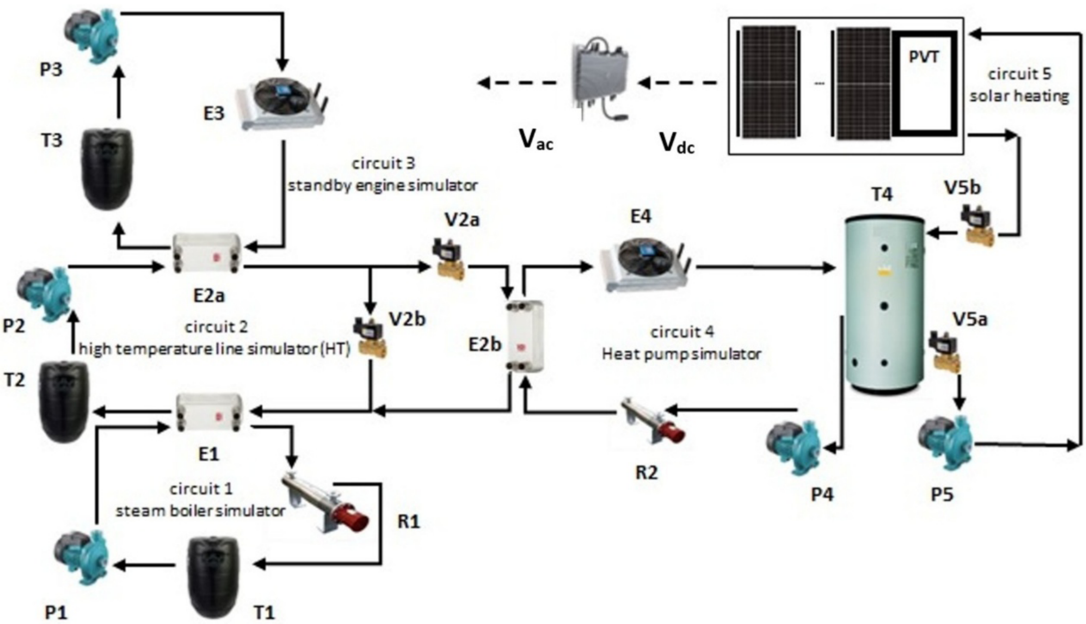
The bench-scale prototype consists of five distinct circuits (Figure 3), each simulating different components and processes of the industrial system. Circuit 1 simulates the operation of a steam boiler and is composed of an electric heater, a water tank, a centrifugal pump, and a plate heat exchanger responsible for transferring heat to Circuit 2, which transports the heat to maintain the motor in standby mode. Circuit 3 represents the motor in standby mode, keeping the water heated above. Circuit 4 simulates a heat pump, receiving heat from Circuit 5, which replicates the set of heat exchangers installed at the bases of the PVT panels. The integration of these circuits allows for precise simulation of the heating and heat exchange processes essential for the efficient operation of hybrid PVT systems in industrial environments. The components of this bench-scale prototype must be carefully installed and connected according to a predetermined design.

In the system depicted in Figure 3, the water heated in the PVT and stored in the thermal reservoir, at temperatures between 308.15–318.15 K, serves as the cold source for the heat pump. The heat pump transfers this thermal energy to the hot source, the engine, at 340.15 K, with electrical energy consumption. The photovoltaic electricity generation in the PVTs should be compared to the electrical energy consumption of the heat pump. The advantage of this configuration is that the heat pump is decoupled from the solar collectors, allowing it to be activated at any time. Another advantage is that the water stored in the thermal reservoir has a lower temperature of 318.15 K than that of the standby engine, which requires 333.15 K to operate, thus reducing thermal losses (Gaur et al., 2022).



PVT: photovoltaic-thermal.

Figure 2 – Integration of the solar heating system (photovoltaic-thermal) with a heat pump designed to help warm up engines on standby at the thermal power station of Petrolina Energy Company.



PVT: photovoltaic thermal; P: pump; T: tank; E: heat exchanger; R: electric heater; V: valve; Vac: alternating voltage; Vdc: direct voltage.

Figure 3 – Schematic diagram of the photovoltaic-thermal bench-scale prototype.

Sizing and installation of a bench-scale solar system

The sizing of a solar heating system for industrial applications, even on a bench scale, involves four essential steps, from determining the thermal energy demand to assessing economic feasibility (Saini et al., 2023). The first step consists of calculating the thermal energy required for the system (Equation 1).

In the second step, the thermal energy consumption profile is identified. For this, data on the daily duration of system operation and the weekly or daily frequency of hot water usage are required. This information helps to understand the energy consumption profile and plan the system operation efficiently (Gil et al., 2021).

In the third step, with the demand data and consumption profile, annual simulations are performed using available meteorological data. Aspects such as information on solar radiation and temperature throughout the year, the area required for installing the PVT panels, the thermal reservoir volume, and the hot water reservoir capacity must be considered (Yüzer and Bozkurt, 2023). The area of the PVTs (A) can be calculated, considering the efficiency of the panels (HPVT) and the average solar radiation (I_{solar}) as shown in Equation 2.

$$A = \frac{Q_{total}}{\eta_{PVT}.I_{solar}.t} \quad (2)$$

Where:

Q_{total} = total thermal energy demand (J);

η_{PVT} = efficiency of the PVT panels;

I_{solar} = average incident solar radiation (W/m²); and

t = daily exposure time to the sun (s).

Computational fluid dynamics modeling and simulations with the photovoltaic-thermal module

For the present study, the software used for modeling and simulations includes SpaceClaim for geometry creation and Ansys Fluent for fluid dynamics simulations. Ansys Fluent is a commercial software well suited for simulating transient systems, including solar power generation systems and other renewable energy sources (Rosli et al., 2021). It is also employed for the energy simulation of residential and commercial buildings.

CFD simulations have emerged as a powerful tool for analyzing and optimizing PVT modules concerning temperature control. PVT modules combine electricity generation through photovoltaic cells with heat production. CFD simulations enhance these modules by enabling precise thermal performance control and optimization. A key application of CFD simulations in PVT modules is investigating the operational temperatures of photovoltaic cells. Accurate monitoring and management of heat are crucial to ensure the longevity and efficiency of these cells during sunlight to electricity conversion (Rosli et al., 2021).

Furthermore, CFD simulations facilitate the modeling of airflow or coolant liquid used to cool the photovoltaic cells. This includes analyses of flow distribution, fluid velocity, and heat dissipation in various module parts. Adjustments to the design of cooling channels and optimization of the cooling flow rate based on environmental conditions help maintain cell temperatures within optimal levels. These simulations also assess the impact of external factors such as climate changes and the orientation of the PVT module, which are critical in regions with pronounced seasonal variations. Effective thermal management provided by CFD simulations enhances these hybrid systems' energy efficiency and durability, making them a promising option for clean and sustainable energy generation (Yan et al., 2022).

In most CFD simulations, the conditions at the inlet boundary of the computational domain must be specified. These conditions include properties such as velocity, pressure, and temperature. Defining appropriate inlet conditions is crucial for accurately modeling flow and heat transfer within the domain. A pressure inlet boundary condition specifies the pressure conditions for the fluid as it enters the computational domain. Depending on the specific simulation, one can set a constant pressure, a variable pressure profile, or other pressure-related parameters (Céspedes et al., 2021).

Mesh

The proper choice of mesh is crucial for the accuracy and efficiency of CFD simulations. The mesh, or discretization grid, divides the problem domain into small elements, allowing the numerical solution of fluid flow equations. A well-structured mesh accurately captures geometric details and gradients of variables such as velocity, pressure, and temperature, which are essential for correctly representing physical phenomena and obtaining reliable results (Céspedes et al., 2021).

The spatial resolution of the mesh must be sufficient to capture critical flow details, especially in regions with high gradients such as leading edges, boundary layers, and recirculation zones. Mesh quality, including orthogonality and aspect ratio, directly impacts the stability and accuracy of the numerical solution. Poor quality meshes can introduce errors and instabilities in the simulation (Einarsrud et al., 2023). Local refinement is necessary in areas with abrupt changes in properties to ensure that gradients are adequately resolved and predictions are accurate. The type of mesh structured, unstructured, hybrid, or adaptive depends on the problem geometry and available computational resources. Structured meshes are more efficient for simple geometries, while unstructured meshes are more flexible for complex geometries. Additionally, computational cost must be considered; finer meshes increase accuracy but require more computational resources.

The selection and refinement of the mesh were guided by a grid independence study, using the average outlet temperature of the PVT module as a parameter, as shown in Figure 4A. The mesh was refined to capture fluid flow details, with a size set at 0.00055 m, resulting in a mesh model with 6,589,347 elements, as shown in Figure 4B, that accurately capture fluid flow and heat transfer details.

The simulation parameters used in this study were defined based on a combination of the plant's specific operating conditions and guidelines established by previous studies (Rosli et al., 2021). The selection of parameters, such as mass flow rate, incident solar radiation, and thermal boundary conditions, was validated using experimental data comparable to the studied scenario, ensuring the representativeness and accuracy of the simulations. Mesh refinement, with 6,589,347 elements, and the use of the Boussinesq approximation allowed for the faithful reproduction of thermal and dynamic phenomena, ensuring consistent results at both reduced and full scales (Mayeli and Sheard, 2021).

The validation of parameters was conducted by comparing the experimental data obtained from the bench-scale prototype with the CFD simulation results, demonstrating good agreement between the numerical models and physical tests (Yan et al., 2022). This approach reinforces the reliability of the proposed model, enabling its replication in different industrial contexts and establishing a solid foundation for future optimizations.

The simulations require the precise definition of boundary conditions to ensure consistent results. Table 1 presents these conditions, including input and output parameters, heat flux, and solar radiation, accurately reflecting the operational scenario analyzed.

Boussinesq approximation

The Boussinesq approximation is a simplification often applied in CFD simulations involving buoyancy-driven flows, especially in natural convection. It assumes that fluid density variations are small, except in the buoyancy term of the governing equations, which simplifies the modeling of flows driven by temperature differences (Mayeli and Sheard, 2021).

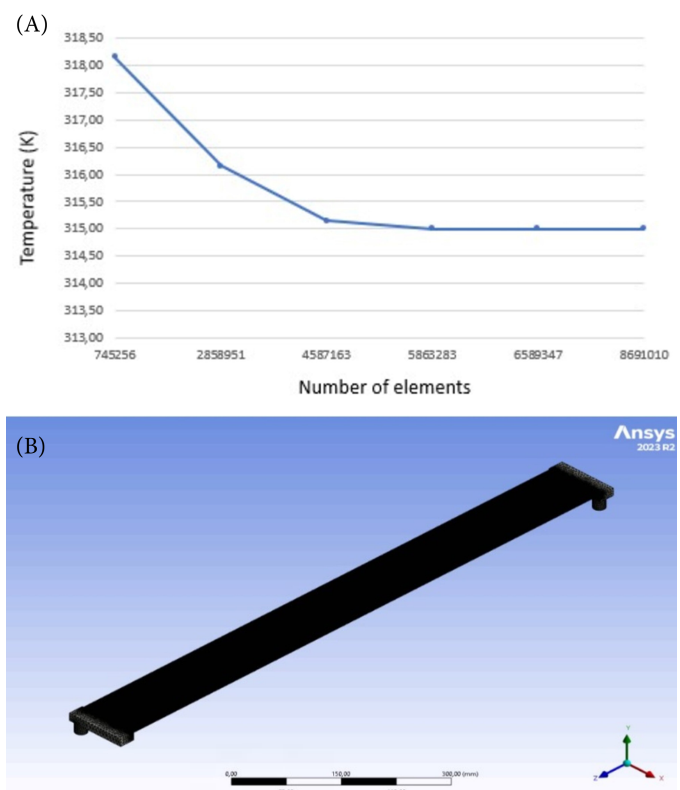


Figure 4 – Mesh configuration: (A) Effect of the number of elements on the water outlet temperature in the photovoltaic-thermal module; (B) Cross section along the flow direction with hexahedral elements adopted for the photovoltaic-thermal module.

In Ansys Fluent, the Boussinesq approximation can be activated in the material properties section, where the fluid's thermal expansion coefficient is specified. This simplification is useful for analyzing complex fluid dynamics and heat transfer phenomena, ensuring representative results of the involved physical phenomena (Krishnani and Basu, 2016).

Applying this approximation allows for maintaining constant dimensionless parameters, such as the Reynolds and the Nusselt numbers, between the scaled model and the real prototype. This reduces computational load and allows the results to be scaled to the larger prototype, as long as these parameters are maintained (Nikitin and Ryzhak, 1981). Experimental validation of the reduced-scale model is considered valid if the flow patterns and heat transfer observed are similar to those expected in the full-scale prototype.

Scale-up adjustments for the physical model

To simulate a PVT system for water heating in CFD using the Boussinesq approximation, it is essential to ensure that key dimensionless numbers are equal between the scaled model and the real structure. These dimensionless numbers help ensure that physical phenomena are consistently represented across different scales. According to Reichl et al. (2022), the main dimensionless numbers to be matched are: Reynolds, Nusselt, Prandtl, Grashof, and Rayleigh. Matching these dimensionless numbers between the scaled model and the real structure ensures that fluid dynamics and heat transfer are consistently represented, allowing the results of the smaller-scale simulation to be reliably scaled up to the real application (Khan et al., 2021).

Table 1 – Boundary conditions used in the simulation of the photovoltaic-thermal model.

Boundary Conditions		
Inlet Conditions		
Velocity inlet	0.89	m/s
Temperature inlet	300.00	K
Outlet Conditions		
Pressure outlet	101,325	Pa
Wall Conditions		
Heat flux	600.00	W/m²
Solar Radiation Simulation		
Solar radiation intensity	1,000.00	W/m²
Mesh Configuration		
Mesh type	Structured hexaedric	-
Element size	0.003	m
Number of elements	6,589,347	-
Mesh refinement	Outlet	K
Turbulence Model		
Model	$k-\varepsilon$ standard model	-
Approach type	Boussinesq approximation	-

Table 2 displays the property panel of Ansys Fluent for modifying the characteristics of the fluid used (water) and applying the Boussinesq approximation regarding density, specific heat, thermal conductivity, viscosity, and coefficient of thermal expansion.

Results and Discussion

Figure 5 depicts PVT modules utilized for testing at the Advanced Institute of Technology and Innovation (IATI) to maximize the contribution to heating the cooling water for simulation in the benchtop prototype. A test was performed with water at 333.15 K to verify the temperature distribution in the system using a thermographic camera (Figure 6) (Guo et al., 2021). The water entered at the bottom and left at the top of the heat exchanger. This water drainage strategy is the most common in solar heaters, allowing the system to be closed by natural convection, and in systems with forced convection; this configuration is used to facilitate the elimination of air in the collectors when they come into operation (Zisopoulos et al., 2021). After preliminary tests, the photovoltaic modules were assembled and installed on the IATI roof. Figure 7 shows the bench-scale prototype built based on the schematic diagram of Figure 3, developed at the facilities of the IATI in Recife, state of Pernambuco, Brazil.

Table 2 – Properties of the fluid used in the simulation of the photovoltaic-thermal physical model.

Fluid: water liquid		
Properties	**Values**	**Units**
Density	998.2	kg/m³
Specific heat (Cp)	4182	J/(kg K)
Thermal conductivity	0.6	W/(m K)
Viscosity	0.001003	kg/(m s)
Thermal expansion coefficient	0.00333	K⁻¹
Temperature	300	K

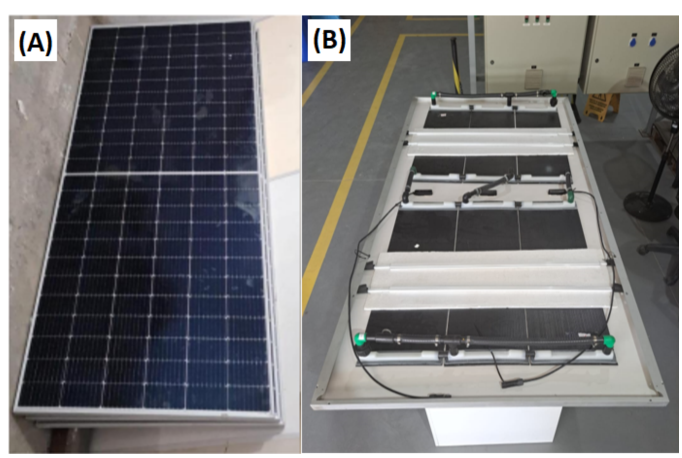


Figure 5 – Images of the thermal-photovoltaic collectors used in the bench prototype. (A) Top view of the set of photovoltaic-thermals; (B) Bottom view of the joint.

This prototype was designed to simulate the integrated operation of the PVT system and the heat pump.

The PVT collectors used in the experiments are at the forefront of solar energy innovation, providing an impressive example of how technology can evolve to meet the growing demands for clean energy and efficiency.

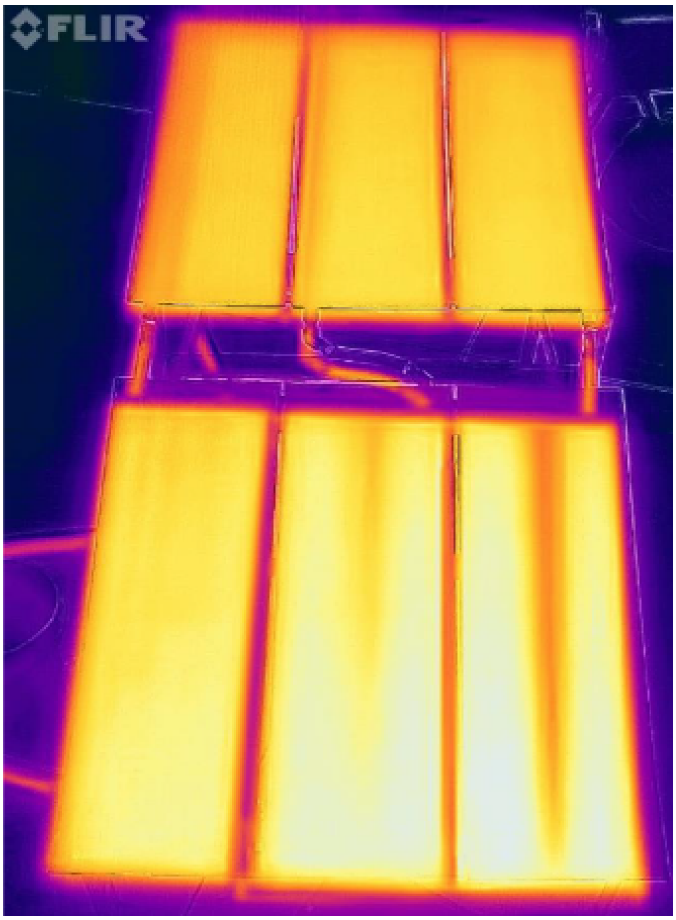


Figure 6 – Image captured by a thermal camera during hot water flow during preliminary tests with the photovoltaic-thermal exchanger set.

Figure 7 – Bench-scale prototype developed by the Advanced Institute of Technology and Innovation research team.

As research and development continue to improve these systems, they may play an even more significant role in the global transition to renewable and sustainable energy sources. Figures 8A, B, and C present information about the model used for simulations of the PVT collector. The material used for the construction of the PVT collector's heat exchanger was polypropylene.

Table 3 presents the structural characteristics of the PVT module used in the simulations and the construction of the bench-scale prototype. These data detail the composition of the module's different layers, including thickness, density, and specific heat capacity, which are essential aspects for thermal modeling and system efficiency.

The bench-scale prototype was equipped with essential components for simulating industrial processes. The key elements include 5 kW and 15 kW electric heaters, 200- and 500-liter water storage tanks, and centrifugal pumps for fluid circulation. The system also incorporates plate heat exchangers to optimize thermal transfer and radiators to simulate engine cooling. PT100 temperature sensors and flow meters were installed for precise monitoring and control of operational conditions. These instruments ensure the collection of necessary data to validate CFD simulations and adjust system performance according to experimental needs.

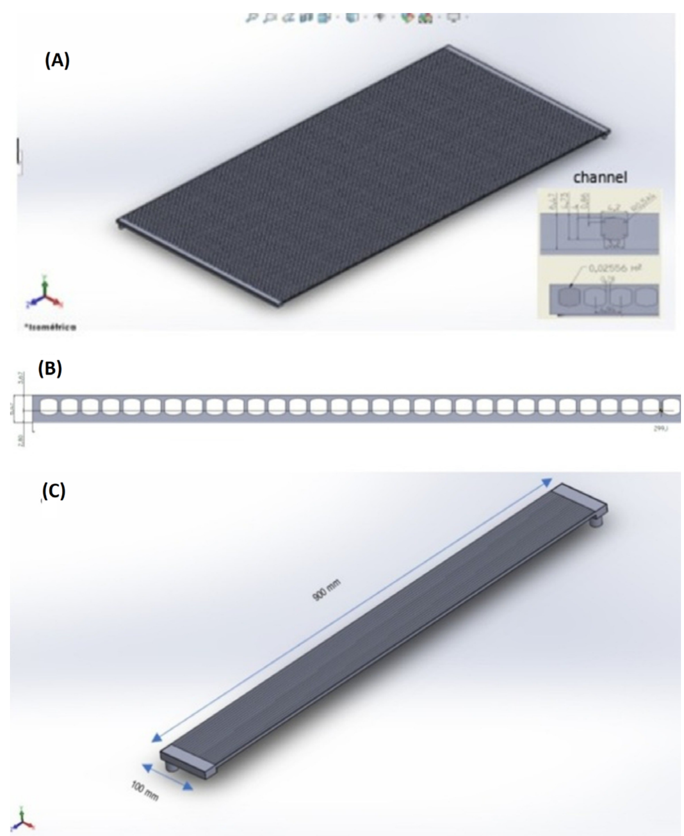


Figure 8 – Photovoltaic-thermal collector used in the construction of the bench prototype of this work: (A) PVT panel model; (B) Cross-section of the photovoltaic-thermal panel exchanger; (C) Reduced scale PVT model.

Figure 9 presents the results of the CFD simulation of the PVT collector using the Boussinesq approximation, at temperature variations from 300–315 K, using water as the fluid. This simulation was essential to validate the heat exchanger's heat exchange area and its thermal efficiency, represented by only one-third of its total size. In addition, Figure 9 shows the temperature variation along the PVT collector, indicating how heat is distributed and transferred through the different layers of the system.

Table 3 – Structural details of the photovoltaic-thermal module used in the simulations.

Layer	Layer name	Thickness (m)	Density (kg/m³)	Specific heat capacity (J/kg.K)
Photovoltaic (PV)				
1	ARC	100 x 10^{-9}	2,400	691
2	Glass	3 x 10^{-3}	3,000	500
3	EVA	500 x 10^{-6}	960	290
4	PV Cells	225 x 10^{-6}	2,330	677
5	Rear contact	10 x 10^{-6}	2,700	900
6	Tedlar® (PVF)	10 x 10^{-5}	1,200	1,250
Thermal (T)				
7	Polypropylene	6.47 x 10^{-5}	1,200	2,000
8	Expanded Polystyrene	2 x 10^{-2}	11	1,450

ARC: anti-reflective coating; EVA: ethylene vinyl acetate; PV: photovoltaic; PVF: polyvinyl fluoride.

The Boussinesq approximation allowed for a detailed assessment of thermal variations, providing a better understanding of the system's efficiency under different operational conditions. The simulation results allowed for precise optimization of the thermal energy demand for the bench prototype engine. Considering the simulated thermal variable, this ensures that the designed system can meet energy needs efficiently.

Figure 10 presents the experimental data obtained from the PVT prototype in the laboratory, including temperatures measured at different points of the system during real operation. The CFD simulation results, which were used to predict the PVT collector's thermal performance, are also compared with these experimental data. A good agreement is observed between the simulated and experimental results, validating the accuracy of the heat transfer models applied.

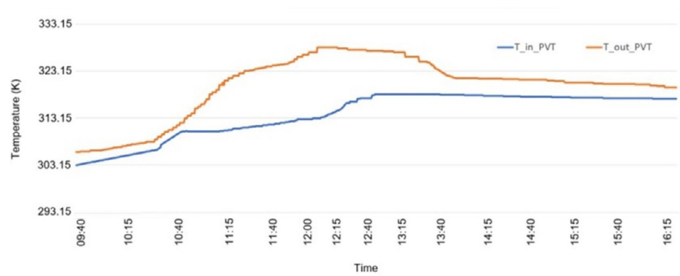


Figure 10 – Performance graph of the photovoltaic-thermal collectors installed in the Advanced Institute of Technology and Innovation laboratory prototype in relation to temperature over a specific time interval.

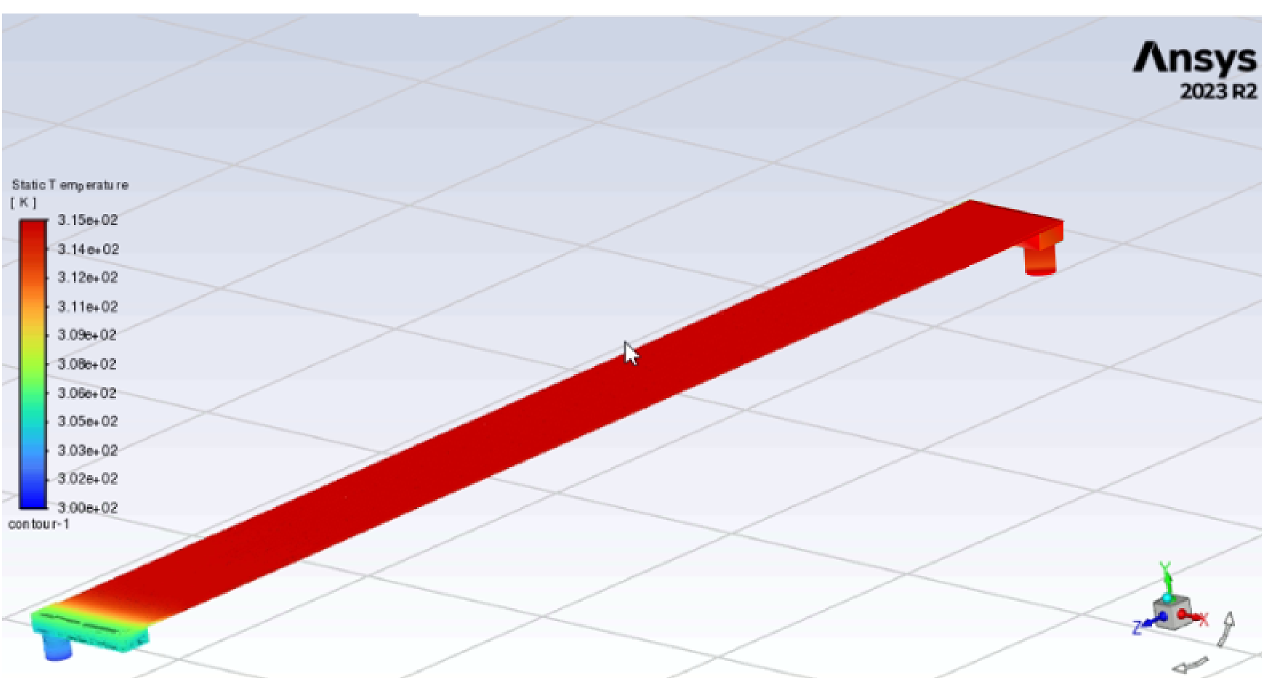


Figure 9 – Outcome of the photovoltaic-thermal collector simulation using the Boussinesq approximation with a temperature variation from 300–315 K, employing water as the fluid.

This figure highlights how the PVT collector can maintain good thermal and electrical efficiency, confirming the effectiveness of the design and the proposed improvements. The comparison between the experimental data and the simulation results provides a solid basis for future optimizations and practical applications, ensuring that the designed system can meet energy needs efficiently.

Salameh et al. (2021) analyzed the thermal efficiency of PVT systems under different mass flow rates and solar irradiance, observing that thermal efficiency increases with the mass flow rate up to a certain point, similar to the results presented in this study. Accordingly, Saurabh et al. (2019) validated the efficiency of PVT systems using CFD simulations and experimental comparisons, corroborating that thermal efficiency varies significantly with the mass flow rate and solar irradiance, as observed in this work. Pauly et al. (2016) also concluded that efficiency tends to increase with the mass flow rate, aligning with the experimental and simulation results presented.

Figure 11 illustrates the thermal efficiency of the PVT panel. The operational data used were obtained at specific time intervals. During the tests, with the mass flow rate kept constant at 0.015 kg/s, thermal efficiency varied according to solar irradiance, reaching a peak at noon due to the higher temperature difference between the inlet and outlet water.

Solar radiation is a crucial factor that directly affects the thermal efficiency of the PVT panel. Higher radiation levels increase the amount of thermal energy captured, improving this efficiency. During the afternoon, the recirculation reservoir accumulates heat, resulting in smaller temperature differences between the inlet and outlet water and, consequently, lower thermal efficiency. This behavior demonstrates the importance of considering the diurnal variation of solar radiation and managing the accumulated heat in the reservoir to optimize the efficiency of PVT systems. In a similar study, Herrando et al. (2014) analyzed the thermal efficiency of a PVT system in a temperate climate. The authors also found a diurnal variation in thermal efficiency, with efficiency peaks at noon and drops during the morning and afternoon, directly reflecting the variation in available solar radiation. The difference in thermal efficiency between morning and afternoon was attributed to the smaller temperature difference between the inlet and outlet water, caused by heat accumulation in the PVT system components, consistent with the results observed in the present study.

Figure 12 illustrates the behavior of heat sources over time. Based on the data, it is observed that the average heat consumption by the simulated engine (Circuit 3), according to the test conducted, was 2.01 kW. The simulated boiler (Circuit 1) provided an average of 0.86 kW, while the simulated heat pump (Circuit 4) and the PVT collectors (Circuit 5) provided 1.15 kW of this thermal energy. Thus, it is noted that implementing the solution composed of PVT collectors and a heat pump enables the reduction of heat consumption in maintaining the engine in standby mode. Considering this system on a larger scale, it becomes feasible to reduce the consumption of energy from fossil fuel sources in this type of application. This is significant because steam boilers generally depend on these sources for energy generation.

Conclusions

This study validated the thermal and electrical efficiency of a hybrid PVT system integrated with a heat pump for industrial applications. The results of the CFD simulations and experimental tests confirmed the system's ability to generate energy efficiently, especially during periods of high solar incidence. The use of the Boussinesq approximation allowed for accurate modeling of the thermal behavior, optimizing the prototype's energy demands.

It is recommended that, for practical application, the system be integrated with industrial processes that require continuous heating and low consumption of fossil fuels, such as in thermoelectric plants and solar water heating installations. To maximize the economic impact, we suggest incentive policies that reduce the initial implementation costs.

Future research should explore the adaptation of the system to different climatic conditions and geographies, in addition to developing new materials and configurations that increase its durability and efficiency. Full-scale investigation and integration with intelligent monitoring systems are also essential to expand applicability and optimize performance.

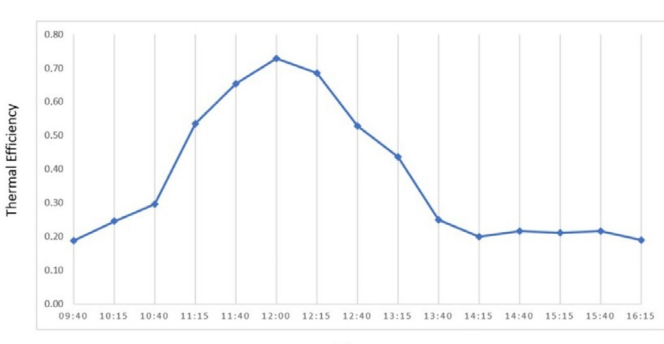


Figure 11 – Thermal efficiency of the photovoltaic-thermal installed at the Advanced Institute of Technology and Innovation estimated with the aid of the operational conditions of these panels during a specific test day.

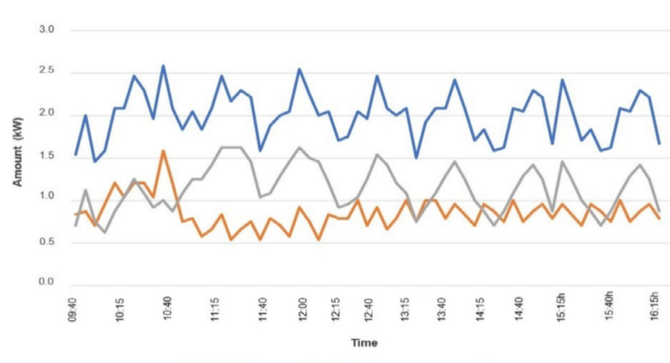


Figure 12 – Behavior of the heat sources that make up the bench-scale prototype over time.

Authors' contributions

Barbosa, L. T.: conceptualization, methodology, investigation, writing — review, visualization, supervision, project administration. **Rocha e Silva**, N. M. P.: project administration, visualization. **Sarubbo,** L. A.: visualization, writing — review and editing. **Silva**, R. C. F. S.: visualization, writing — review & editing. **Santos**, L. B.: conceptualization, methodology, investigation, validation, writing — original draft, writing — review & editing, visualization. **Santos**, V. A.: conceptualization, methodology, validation, writing — original draft preparation, writing — review and editing.

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