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OPTIMIZATION OF BUILDING AIR CONDITIONING USING A HYBRID COGENERATION SYSTEM WITH PHOTOVOLTAIC ENERGY*

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Abstract. Photovoltaic (PV) systems are a promising alternative for electricity production as they harness solar energy, a clean and renewable source, reducing reliance on fossil fuels and minimizing environmental impact. However, the overall efficiency of conventional PV systems remains limited since a significant portion of the incident solar energy is converted into heat, which is typically wasted (Zhou et al. 2025). To address this issue, in this paper we are developing a cogeneration system (PV/T) that not only generates electricity but also captures and utilizes the excess thermal energy for space heating (Wei et al. 2025). This system integrates a heat storage solution to enhance energy availability and optimize thermal management, ensuring improved overall efficiency and better utilization of solar resources. To achieve this, we will use Matlab/Simulink to design and simulate a Photovoltaic Thermal (PV/T) Hybrid Solar Panel system, allowing us to analyze its performance and optimize its operation for residential heating applications. As results, we will obtain key parameters such as module temperature, electrical power output, and the required storage tank volume. Additionally, we will test different PV technologies, comparing their performance to identify the most suitable option for the climatic conditions of Lithuania. Furthermore, we will observe solar variables variations and pump flow rates to assess their impact on system efficiency and optimize energy distribution. These results highlight the potential of PV/T technology for optimizing solar energy utilization in residential heating. Further experimental validation is needed to refine the model and optimize system performance for different climatic conditions.

Keywords: Photovoltaic Thermal (PV/T) Hybrid Solar Panel; solar variables variations; pump flow

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1. Introduction

As climate concerns grow and energy prices rise, solar energy has become a vital alternative for residential energy systems (Castillo-Díaz et al., 2024; Pizzuti et al., 2024; Firoozi et al., 2025; Spellmeier et al., 2025).

Photovoltaic (PV) technology, in particular, allows clean electricity generation directly from sunlight. However, traditional PV panels typically convert only 15–20% of solar radiation into electricity, with the rest lost as heat, reducing efficiency and increasing cell temperature, which can further degrade performance (Kalogirou, 2004; Kuang & Wang, 2006). This thermal waste not only reduces electrical performance but misses an opportunity to recover energy that could otherwise support domestic heating needs especially in countries with cold climates.

To address this, hybrid photovoltaic/thermal (PV/T) systems have been developed, which integrate solar cells and thermal collectors in a single unit to simultaneously generate electricity and useful heat (Chow, 2010; Obalanlege et al., 2020). These systems have demonstrated high efficiency and flexibility, making them attractive for residential cogeneration applications. For example, a study conducted in northwestern China investigated the performance of a micro heat pipe PV/T system inside a greenhouse and showed total efficiencies of 53.6%, 52.0%, and 42.9% on sunny, partly cloudy, and overcast days respectively. These results represented 14.7% to 21.3% performance gains over identical systems installed outdoors, confirming the importance of environmental control and tilt optimization (Zhou et al., 2025).

Cost-effective PV/T designs have been proposed to reduce material use and manufacturing complexity, such as plateless absorbers and polymer-based exchangers (Zondag et al. 2002). Wei et al. (2025) proposed a low-cost absorber-plateless PV/T design using plastic capillary mats as heat exchangers. Despite the absence of a traditional metal absorber plate, the system achieved thermal efficiencies ranging from 26.4% to 33.4%, and overall efficiencies above 50%. Furthermore, the levelized cost of heat was reduced significantly, falling between 0.010 and 0.013 USD/kWh much lower than that of conventional PV/T systems with metal components. These innovations suggest that PV/T technology can be scaled to building applications without prohibitive cost.

Material and structural innovations have also contributed to performance gains. A flat-plate PV/T system using CdTe thin-film solar cells showed higher electrical performance under elevated temperatures than polycrystalline silicon modules, thanks to the lower temperature sensitivity of CdTe cells (Li et al., 2021). The sandwich structure of the panel also helped resist environmental degradation. In their experimental and numerical study, Wang et al. found that increasing the cell coverage ratio improved overall system performance, and reducing the air gap thickness between layers enhanced heat transfer. These findings underscore the value of component-level optimization in adapting PV/T systems to specific climates.

Further advancement came from low-concentration PV/T designs. Zhang et al. (2019) compared a low-concentration PV/T system (LCPV/T) with a flat-plate PV/T module. They found that the LCPV/T system produced three times more electrical power and nearly double the thermal output, albeit with some trade-offs in heat transfer stability. While more complex to build, these systems point to the potential of enhancing solar capture without significantly expanding panel surface area an important consideration in urban settings.

In addition to physical configuration, operational strategies are increasingly recognized as key factors in improving PV/T system performance within building energy networks. Recent studies have evaluated strategies such as maximum self-consumption (MSC), time-of-use (TOU), and optimization-based control (OPT), finding that each approach offers different trade-offs in efficiency, cost, and grid interaction. For instance, the OPT strategy offered the greatest flexibility and lowest operational cost, though with reduced energy utilization efficiency and a greater impact on the grid. In contrast, the MSC strategy showed low sensitivity to battery charge states and exhibited more stable performance. Battery and thermal storage sizing were also affected, with optimal

capacities for different strategies ranging from 2.5 to 4.5 kWh and 100 to 200 L (Wang et al., 2024). These insights are especially important in designing PV/T systems for seasonal climates, where thermal demand and solar availability vary widely across the year.

This operational perspective is particularly relevant for Lithuania, where cold winters dominate the energy demand profile, and residential heating is one of the most significant energy uses. Despite moderate annual solar irradiance, Lithuania's seasonal thermal needs align well with the dual-output capacity of PV/T systems, particularly when integrated with intelligent storage and control strategies. However, there remains a lack of tailored system modelling that accounts for Lithuanian climate specifics and residential consumption behaviour.

This study addresses that gap by developing and simulating a PV/T hybrid cogeneration system for space heating in Lithuanian homes. Using MATLAB/Simulink, we will analyse key parameters such as electrical and thermal output, module temperature, storage sizing, and system responsiveness to solar variation. We will also compare different PV technologies to determine which offers optimal performance under local conditions. Ultimately, this work aims to support the design of smarter, more efficient solar energy systems that are both technically and economically viable in northern European climates

2. Systeme description

2.1. Mathematic model

The hybrid photovoltaic/thermal (PV/T) system modeled in this study is a flat-plate solar collector designed to simultaneously produce electricity and low-temperature thermal energy.(El Ouakili et al. 2024) It comprises multiple thermally and optically interactive layers: a transparent glass cover, a photovoltaic (PV) cell layer, an absorber plate with thermal contact to embedded fluid-carrying tubes, and a water circulation loop for heat extraction. The modeling approach follows the methodology of (da Silva & Fernandes 2010) and other PV/T modeling efforts using dynamic simulation and energy balance techniques (Hegazy, 2000; Sami, 2019), where each physical layer is described by a transient one-dimensional energy balance, ensuring spatial and temporal resolution of heat accumulation and transfer phenomena across the collector components.

The optical behavior of the system is governed by the combined transmittance and absorptance properties of the glass and PV surface. Solar irradiance G_{GG} enters the collector and is partially reflected and absorbed. (Farkad et al. 2024)The effective solar input G_{eff} reaching the PV cell is modeled using:

$$G_{eff} = G \cdot \tau \cdot \alpha \quad (1)$$

where τ is the transmittance of the glass and α the effective absorptance of the PV surface.

This energy is split between electrical and thermal pathways. The electrical conversion efficiency η_e of the PV cell is temperature-dependent and follows:

$$\eta_e = \eta_{ref} [1 - \beta(T_{pv} - T_{ref})] \quad (1)$$

where β is the thermal degradation coefficient, and T_{pv} is the temperature of the PV cell. The electrical power output is thus:

$$P_{elec} = \eta_e \cdot G_{eff} \cdot A \quad (1)$$

The residual portion of the solar energy not converted into electricity is dissipated as heat and distributed across the layers of the system. Each solid component in the system is modeled as a lumped thermal mass, governed by a first-order energy balance equation. The glass cover, denoted as layer 1, obeys:

$$m_1 C_{p1} \frac{dT_1}{dt} = h_{conv,1}(T_{amb} - T_1) + \sigma \varepsilon_1 A (T_{sky}^4 - T_1^4) + h_{cond,1}(T_2 - T_1) \quad (1)$$

where T_1 is the glass temperature, $h_{conv,1}$ is the convective heat transfer coefficient with ambient air, and the radiative loss is modeled with the Stefan–Boltzmann law.

The PV layer (layer 2) receives optical input and dissipates waste heat:

$$m_2 C_{p2} \frac{dT_2}{dt} = G_{eff} A (1 - \eta_e) + h_{conv,1}(T_1 - T_2) + h_{cond,2}(T_2 - T_3) \quad (1)$$

The absorber plate (layer 3), thermally connected to the fluid tube, satisfies:

$$m_3 C_{p3} \frac{dT_3}{dt} = h_{conv,2}(T_2 - T_3) + h_{cond,fluid}(T_3 - T_4) \quad (1)$$

The fluid–tube interface (layer 4) is described by:

$$m_4 C_{p4} \frac{dT_4}{dt} = h_{cond,fluid}(T_3 - T_4) - \dot{m} C_p (T_4 - T_{fluid}) \quad (1)$$

Lastly, the working fluid itself, modeled at the average temperature T_{fluid} , exchanges energy with the absorber and flows into a storage tank:

$$m_5 C_{p5} \frac{dT_5}{dt} = \dot{m} C_p (T_4 - T_5) - UA(T_5 - T_{amb}) \quad (1)$$

These coupled equations describe the unsteady heat transfer and energy transformation throughout the collector. Each component's temperature is influenced by solar flux, convective and radiative losses, and thermal interactions with neighboring layers (Aqachmar et al., 2022). The fluid loop completes the cogeneration cycle by recovering heat for domestic hot water or space heating applications.

The described model is highly suitable for simulation in environments like MATLAB/Simulink, where each energy balance equation can be translated into physical blocks representing thermal masses and heat fluxes. It also offers a solid foundation for coupling with electrical and control subsystems, enabling detailed performance evaluation of hybrid PV/T collectors under various climatic conditions, including those representatives of northern Europe such as Lithuania.

2.2. Simulation

The simulation of the hybrid photovoltaic/thermal (PV/T) system was developed in MATLAB/Simulink as in prior numerical simulations of PV/T systems (Villalva, Gazoli & Filho, 2009), using the Hybrid Solar Panel model from MathWorks, built within the Simscape Fluids environment (Figure 2). The model couples electrical, thermal, and hydraulic subsystems to simulate the real-time interaction between solar energy input and the physical structure of a PV/T collector (Ji et al., 2008).

The system consists of a photovoltaic layer with temperature-dependent electrical behavior, a metallic absorber plate in thermal contact with circulating fluid, a transparent cover for optical transmission and thermal insulation, a dynamic water loop with a controlled pump, and a thermal storage tank. In this study, we implemented a glazed,

flat-plate, water-based PV/T collector (Figure 1), which represents the most common configuration for building-integrated applications as supported in the classification of PV/T system architectures (Chow, 2003). This choice is supported by the review of (Cuenca, Ortiz, and Boza 2010), who classify PV/T systems into multiple types: air-based vs. liquid-based collectors, glazed vs. unglazed surfaces, and concentrating vs. non-concentrating designs. While air-based systems offer simpler construction, they suffer from low heat transfer rates and limited thermal efficiency (Jouhara et al. 2016; Yerdesh et al. 2020). Concentrating PV/T collectors can achieve higher temperatures, but require direct solar tracking and are more suitable for large-scale or industrial installations. In contrast, flat-plate water-based collectors, especially with a glazed cover, provide an excellent balance of electrical and thermal performance, compactness, and ease of integration into residential buildings. The use of water as a working fluid enables efficient heat extraction due to its superior thermal properties compared to air, while the glazed cover reduces convective heat losses from the absorber surface, particularly in cold climates.

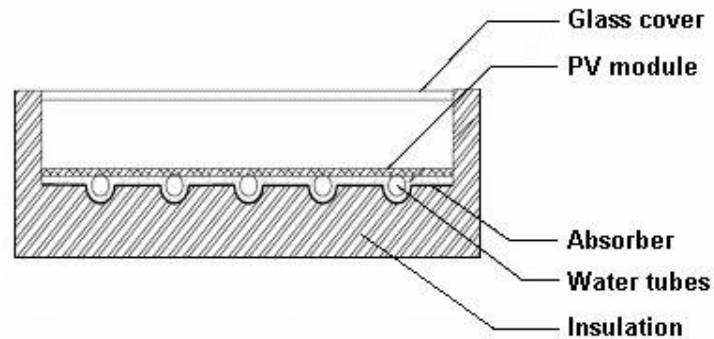


Figure 1. Flat plate PV/T collector
Source: (Ramos, Cardoso & Alcaso 2010)

To simulate the system under realistic conditions, we adapted the model for the local climate of Vilnius, Lithuania, using hourly solar radiation and temperature data from the PVGIS (Photovoltaic Geographical Information System) platform. These meteorological variables were dynamically applied in the simulation as time-dependent inputs. The solar irradiance signal was corrected by cosine projection to represent the effective area seen by the sun, allowing precise calculation of both thermal and electrical outputs. The simulation was carried out over a representative sunny day, selected to analyze system performance under high solar availability. This configuration and approach allow the assessment of the PV/T system's potential for residential energy cogeneration in northern European climates, where both electricity and low-temperature heat are in high demand during the heating season.

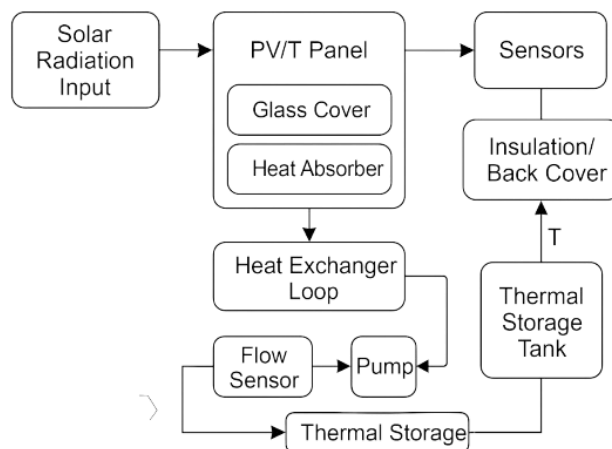


Figure 2. schematic representation of the hybrid PV/T system

To evaluate the impact of photovoltaic technology on the overall performance of the hybrid PV/T system, two different types of solar modules were considered in the simulation: monocrystalline silicon and polycrystalline silicon. These technologies were selected due to their widespread use in commercial applications and their distinct electrical and thermal characteristics. Monocrystalline panels are generally known for their higher efficiency and better performance under low irradiance conditions, whereas polycrystalline panels are more cost-effective and exhibit slightly lower efficiency, particularly at higher temperatures. By simulating both technologies under identical operating conditions, including identical irradiance profiles, ambient temperature, and system configuration, the study aims to highlight how the choice of PV material influences thermal output, electrical production, and overall system efficiency.

The detailed input parameters including nominal power, efficiency at standard test conditions, and surface area, are presented in Table 1.

Table 1. The detail parameter of the PV/T used

Parameters	Values
Pannel	- Canadian Solar CS 3W-453MS (Monocrystalline)
Pipe	- Canadian Solar CS 3W-420P (Polycrystalline)
Length	5 m
Section	0.0007 m ²
Hydraulic diameter	0.03 m
Internal roughness	15e-6 m
Tank	
Volume	0.25 m ³
Cross section	0.3 m ²
Pompe	
Internal circuit mass flow	0.02 g/s

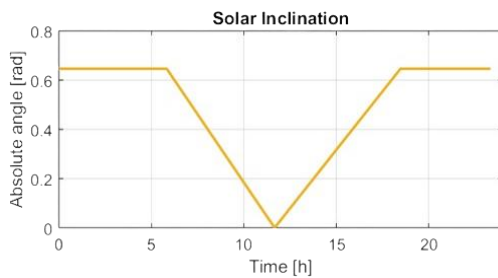
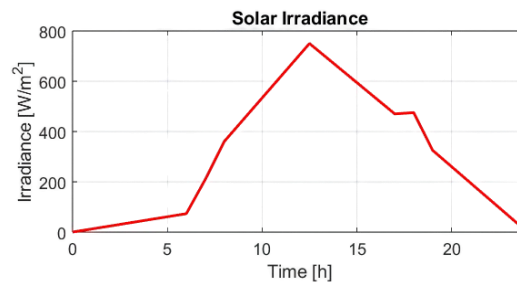


Figure 3. a) optimal inclination for Vilnius



b) radiation for one day in Vilnius

Figure 3 above represent the optimal inclination for Vilnius and the radiation during day in summer.

3. Results and discussion

The simulation results in Figure 4 below offer a clear comparative insight into the performance of a hybrid PV/T system using monocrystalline and polycrystalline photovoltaic technologies. The temperature profiles for both configurations show similar thermal behavior in the glass cover, solar cells, heat exchanger, and storage tank, reflecting that the thermal subsystem's operation is not significantly affected by the PV cell material. However, the **useful electrical power output** consistently shows higher peaks for the monocrystalline panel, with average

electrical energy supplied per day reaching **2.56 kWh/day**, compared to **2.34 kWh/day** for the polycrystalline panel, performance gap between mono- and polycrystalline panels is well documented in the literature (V and M 2018). This higher electrical yield results directly from the intrinsic material properties of monocrystalline silicon, which has fewer grain boundaries, higher carrier mobility, and thus greater conversion efficiency under the same solar irradiation.

The calculated **electrical efficiency** reinforces this difference: **20.5 %** for monocrystalline versus **18.8 %** for polycrystalline. This confirms that monocrystalline panels are more effective at converting solar energy into electricity. Interestingly, the **thermal efficiency** remains almost unchanged between the two technologies, with both systems achieving around **19 %**. This stability arises because the heat extraction process depends mainly on the collector design and heat exchanger effectiveness, rather than the type of PV cell. This is consistent with findings on how absorber structure, glazing, and flow rates dominate thermal behavior (Royne, Dey, and Mills 2005)

The **total system efficiency** combines both contributions and slightly favors the monocrystalline panel (**39.8 %**) compared to the polycrystalline (**37.8 %**). While the difference is modest, it demonstrates the cumulative advantage of higher electrical efficiency over time. The water volume dynamics in the tank also follow similar cycles for both cases, indicating that the thermal energy demand and supply are balanced similarly, independent of the PV module type.

From a practical perspective, these results underline the trade-off between performance and cost. This reflects common challenges in PV/T selection, where monocrystalline panels offer better efficiency, but at higher upfront investment (Hossain et al. 2021). Monocrystalline panels are known for their higher cost per watt due to more complex manufacturing, but they deliver better electrical performance, which can be critical for applications with limited roof area or higher electricity demand. Polycrystalline panels, on the other hand, remain competitive where lower upfront costs are prioritized, and the thermal fraction of the system provides substantial energy savings.

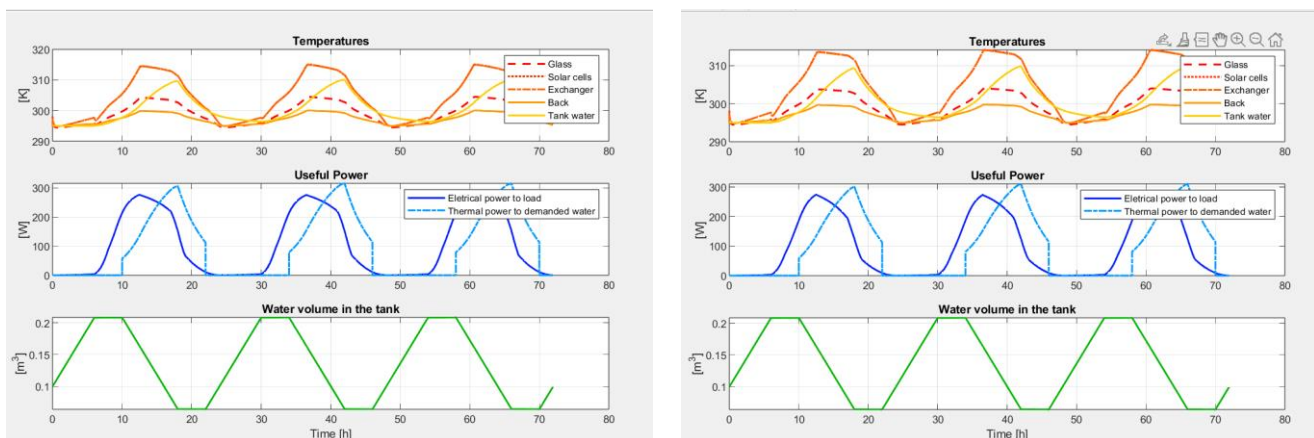


Figure 4. a) The outputs of the model Monocrystalline

b) The outputs of the model Polycrystalline

In summary, the comparative simulation suggests that while both PV/T configurations efficiently combine electrical and thermal production, the **monocrystalline system offers slightly superior overall performance**, especially for electricity-focused applications. However, the small margin in total efficiency should be balanced

with economic factors and local climate conditions when selecting the optimal PV technology for integrated PV/T systems.

Conclusions

This study demonstrated the potential of a flat-plate hybrid PV/T cogeneration system for residential space heating in a cold climate, using detailed MATLAB/Simulink modeling under realistic meteorological conditions for Vilnius, Lithuania. By integrating thermal and electrical outputs, the system effectively recovers a larger portion of incident solar energy than conventional PV modules alone (Tonui & Tripanagnostopoulos 2007). The comparison between monocrystalline and polycrystalline PV panels under identical conditions confirmed that monocrystalline technology achieves slightly higher electrical efficiency (20.5 % vs. 18.8 %) and thus a higher total system efficiency (39.8 % vs. 37.8 %)(Carr and Pryor 2004). However, the thermal efficiency remained practically unchanged for both technologies (~19 %), highlighting that the heat recovery performance depends mainly on the collector design rather than the PV cell type.

These results emphasize that while monocrystalline PV/T systems offer marginally better overall energy yield, polycrystalline systems remain a viable and cost-effective alternative, especially when capital cost constraints are critical (Breyer et al., 2017). For climates like Lithuania's, where heating demand is significant during winter, PV/T technology shows strong potential to reduce reliance on conventional heating sources by utilizing otherwise wasted thermal energy(Sommerfeldt and Madani 2019).

Integrating PV/T systems with seasonal thermal energy storage and novel power-to-X solutions can support year-round renewable heating, with promising techno-economic potential specially in Lithuania because of the cold climates (Baeuerle, Arpagaus & Haller 2025).

Future work should include experimental validation of the model (Bachseitz et al., 2024) (Cao et al., 2025), economic analysis of the lifecycle costs for each PV technology, and an assessment of advanced control strategies to optimize energy management and storage under variable operating conditions.

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