Experimental performance study of water PVT collectors for integration with seasonal storage

Summary

Photovoltaic (PV) systems have grown rapidly, though solar thermal technologies still offer higher efficiencies. Hybrid PVT systems combine both approaches, providing improved overall energy performance. However, challenges remain in performance and system integration. This work presents three novel PVT prototypes using TOPCon N-type silicon technology where different heat exchanger geometries are evaluated to assess thermal behavior. The system targets low-temperature applications with seasonal thermal storage integration, and the selected PVT panels are planned to be installed in a demo site in the Netherland. A dedicated test bench has been built, enabling the performance analysis of the prototypes under real environmental conditions. Preliminary results highlight strong performance, with thermal-to-electrical ratios up to 1.4:1 for sunny calm days and sensitivity to wind conditions.

Keywords: Water PVT; experimental; energy performance; solar energy; seasonal storage

Field of application for the findings: PVT solar technology (photovoltaic-thermal)

Addressed audience: Energy Researchers; Engineers, Solar planners, Public Administrations

1. Introduction

Photovoltaic (PV) systems have considerably grown in residential and industrial markets due to their cost decrease and ease of installation (Bórawski et al., 2023). However, solar thermal technologies still achieve higher energy conversion efficiencies in comparison with photovoltaic technologies. In this context, hybrid photovoltaic-thermal systems (PVT), which combine solar thermal and photovoltaic technologies on the same panel, emerges as a promising solution.

As highlighted by the IEA Solar Heating and Cooling Programme through the Task 73 (IEA SHC, 2025), the PVT technology shows considerable potential. However, experts also indicate some barriers for market adoption: insufficient operational performance (Nahar et al., 2017), complexity on the installation or integration with other technologies (Miglioli et al., 2023). Recent advances include modifications related to the internal design of these PVT collectors, such as optimized geometries (Das et al., 2021), new components (Joshi and Dhoble, 2018), advances in PV cell technologies (Al-Ali et al., 2025) and new integration strategies, including coupling with heat pumps (Coca-Ortegón et al., 2023a) or seasonal storage (Chen et al., 2025).

This work presents the operational performance of three novel PVT prototypes incorporating cutting-edge PV technologies. These prototypes have been specifically designed for low-temperature operation and for their integration with a seasonal thermal energy storage, demonstrating their integration potential for high-efficiency renewable energy systems.

2. Material & Methods

2.1. Description of the PVT components

This work aimed to developed a water-based PVT prototype which integrates some of the latest PV cell and module technologies. In this particular case, tunnel oxide passivated contact (TOPCon), N-type silicon has been included, which involves the benefits of reducing recombination losses, achieving higher conversion efficiencies, and improving thermal and operational stability compared with other conventional silicon cells such as Passivated Emitter and Rear Cell (PERC). Each panel has a peak electrical power of 600W, with an aperture area of 2.7 m^2, considerably bigger than other commercial PVT collectors.

Since the main focus of this PVT prototype collector was enhancing electrical efficiencies and electricity generation through the integration of new PV technologies, thermal integration has been achieved using conventional heat exchanger configurations and materials: harp and meander geometry in copper and aluminum. A third heat exchanger design combining the two previous types (harp and meander) has also been explored. Overall, three PVT prototypes have been proposed for experimental evaluation.

2.2. Description of the testing installation and operational procedure

The testing bench has capacity for three panels and has been designed so that the performance of each panel can be assessed simultaneously, under identical environmental and operating conditions. For this purpose, PVT panels are hydraulically connected in parallel, and work against a thermal storage tank.

This test bench is equipped with a comprehensive set of measurement instruments, including eleven temperature sensors, three flow meters and a weather station (anemometer, pyranometer, and environmental temperature). All the measurements are registered in a PLC Modicon 241 (Schneider) and transferred through Modbus TCP language protocol, with one-minute frequencies, enabling a detailed analysis of the prototypes' performance under real environmental conditions. Electrical parameters (current, voltage and power generated) are registered directly through the inverter commercial platform. Fig. 1 shows the test bench with the three prototypes under testing and evaluation.

Fig. 1: Frontal side of the test bench, with the three prototypes installed.

2.3. Demo site description

The development of this prototype is part of a European research project and involves its installation in a greenhouse use case in the Netherlands. The project plans the integration of PVT systems with Aquifer Thermal Energy Storage (ATES) and groundwater heat pumps (GWHPs) to support decarbonization and increase the share of renewable and waste heat utilization. In this context, a solar field of 126 PVT panels (75.6 kW of peak electrical power) is planned to be installed by the end of September 2026 on the south-facing side of the building, where the technical equipment is located.

3. Preliminary Results

The prototypes have been operating under real Mediterranean winter environmental conditions with an average flow rate of 150 L/h per collector.

The following presents the energy production data for three typical days, representing the conditions of sunny and calm (day 1), sunny with wind (day 2) and cloudy (day 3). The environmental conditions for the three days are shown in Fig. 2, while the energy production and solar radiation are presented in Fig. 3. In these figures, only two prototypes are shown, since the third one is still under investigation.

It can be observed that during cool winter days without wind (wind speed < 1.5 m/s), the prototypes are capable of generating thermal and electrical power at a 1.4:1 ratio, operating with an average collector temperature 12 °C above the ambient temperature. Under similar solar radiation conditions but on a windy day (wind speed > 3.5 m/s), a significant reduction in collector temperature is observed, leading to a decrease in thermal generation and lowering the ratio to 1:1.

No significant differences were observed between the absorber models, although the meander geometry proved to be slightly more thermically efficient. However, it also presents certain limitations in terms of pressure drop, which should be taken into account. The complete analysis of the prototypes, as well as the evaluation of the third geometry, is currently ongoing and is expected to be completed in the coming months.

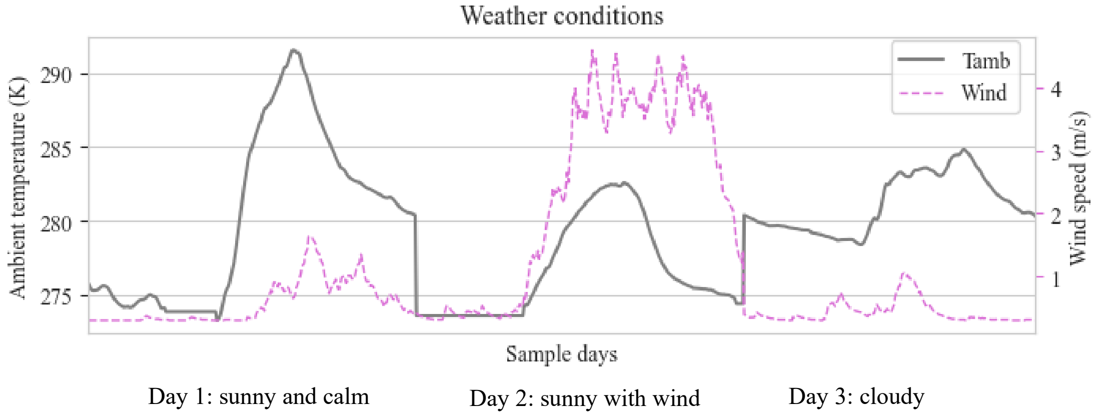

Fig. 2: Environmental conditions for two prototypes for three days of different weather conditions.

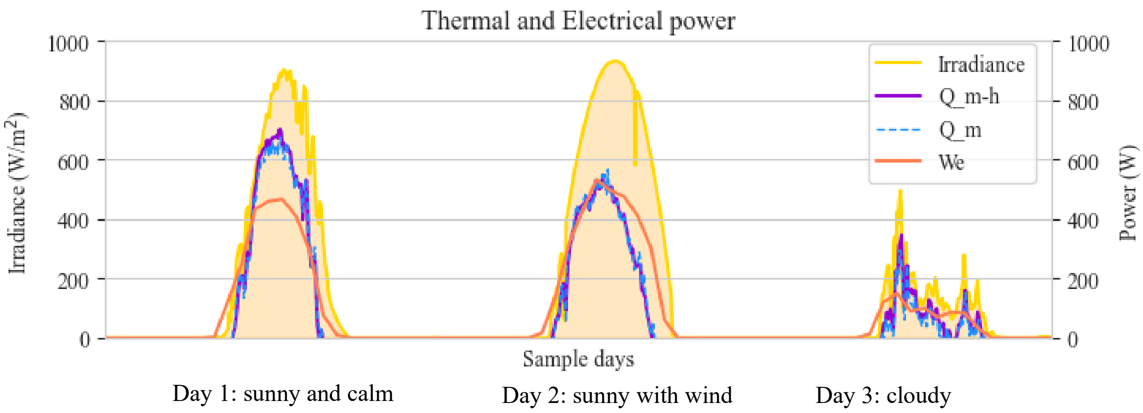

Fig. 3: Solar irradiance (left axis) and thermal and electrical power productions (right axis) for two prototypes (m: meander; m-h: harp and meander) for three days of different weather conditions.

4. References

Al-Ali, S., Olabi, A.G., Mahmoud, M., 2025. A review of solar photovoltaic technologies: developments, challenges, and future perspectives. Energy Conversion and Management: X.

Bórawski, P., Holden, L., Bełdycka-Bórawska, A., 2023. Perspectives of photovoltaic energy market development in the european union. Energy 270, 126804.

Chen, J., Chen, K., Zhao, B., Yu, J., Hu, M., Pei, G., 2025. Numerical analysis of spectrally selective photovoltaic-thermal collectors coupled with pit thermal energy storage in solar district heating systems. Appl. Therm. Eng. 262, 125239.

Coca-Ortegón, A., Simón-Allué, R., Guedea, I., Brun, G., Villén, R., 2023. Operational performance of trigeneration PVT-assisted HP system. Energy Build. 296.

Das, D., Bordoloi, U., Kamble, A.D., Muigai, H.H., Pai, R.K., Kalita, P., 2021. Performance investigation of a rectangular spiral flow PV/T collector with a novel form-stable composite material. Appl. Therm. Eng. 182, 116035.

IEA SHC, 2025. Task 73 - PVT Heating Systems. URL https://task73.iea-shc.org/ (accessed 3.13.26).

Joshi, S.S., Dhoble, A.S., 2018. Photovoltaic -Thermal systems (PVT): Technology review and future trends. Renewable and Sustainable Energy Reviews.

Miglioli, A., Aste, N., Del Pero, C., Leonforte, F., 2023. Photovoltaic-thermal solar-assisted heat pump systems for building applications: Integration and design methods. Energy and Built Environment.

Nahar, A., Hasanuzzaman, M., Rahim, N.A., 2017. Numerical and experimental investigation on the performance of a photovoltaic thermal collector with parallel plate flow channel under different operating conditions in Malaysia. Solar Energy 144, 517–528.