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The Integration of a Photovoltaic/Thermal System into a District Heating System

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Abstract. District heating systems are increasingly transitioning toward low-carbon and renewable energy sources in response to climate and energy policy objectives. Among emerging technologies, photovoltaic/thermal systems represent a promising solution by enabling the simultaneous production of electrical and thermal energy. This paper investigates the performance and economic feasibility of a photovoltaic/thermal system integrated with a heat pump as a renewable heat source for low-temperature district heating applications. Two system configurations are analysed: a photovoltaic/thermal system coupled with a water-to-water heat pump and a conventional photovoltaic system coupled with an air-to-water heat pump. The systems are evaluated based on electrical energy production, heat pump performance, energy self-sufficiency, and investment profitability. The economic assessment is based on a monthly electricity billing scheme that accounts for the balance between produced and consumed electrical energy, as well as revenues from surplus electrical energy fed into the grid. In addition, both configurations incorporate a battery storage system to enhance operational stability and ensure a reliable electrical energy supply to the heat pump. The results demonstrate the technical and economic potential of photovoltaic/thermal systems for improving the efficiency, flexibility, and sustainability of low-temperature district heating networks.

Key words. photovoltaic/thermal system, electrical energy, thermal energy, district heating

1. Introduction

District heating systems in Slovenia are undergoing a gradual transition from conventional fossil fuels to sustainable, renewable alternatives. A wide range of technologies is currently under consideration, including woody biomass, geothermal energy, solar energy for electrical and thermal energy production, and hydrogen-based solutions. To ensure a reliable and efficient energy supply, future district heating systems increasingly rely on hybrid configurations that combine multiple energy sources to achieve stable and decentralized heat and electrical energy production.

One promising approach for utilizing solar energy in district heating applications is the deployment of photovoltaic (PV) systems for electrical energy production, primarily to supply low-temperature heat pumps (HP). The thermal energy produced by HP can then be integrated with heat from other renewable sources and distributed through district heating networks. In this context, photovoltaic/thermal (PV/T) systems have attracted growing attention, as they enable the simultaneous production of electrical and thermal energy within a single module. A key advantage of PV/T systems is the recovery of excess heat from PV/T modules, which can be used for low-temperature heating applications. At the same time, active heat extraction reduces the operating temperature of PV cells, thereby improving their electrical conversion efficiency. Compared to conventional PV systems, PV/T modules can therefore provide higher electrical energy yields while simultaneously delivering usable thermal energy for HP operation [1].

These characteristics make PV/T systems particularly suitable for integration into low-temperature district heating networks. In recent years, research has increasingly focused on the coupling of PV/T systems with HP to enhance overall system efficiency. The authors in [2, 3] investigated the performance of PV/T-assisted HP systems and reported improved electrical, thermal, and overall efficiencies under various operating conditions. Similarly, the research presented in [4, 5] demonstrated that different PV/T–HP configurations can significantly reduce electrical energy consumption and carbon emissions while improving the sustainability of building heating systems. Several recent papers have further confirmed the suitability of PV/T-assisted HP systems for low-temperature district heating applications. The authors in [6, 7] reported that integrating PV/T modules with HP results in more stable heat-source temperatures, improved seasonal performance factors, and reduced electrical energy consumption compared to conventional air-source systems. Their results also highlighted the importance of thermal energy storage (TES) and appropriate system sizing for reliable district heating operation. Similarly, the research in [8, 9] showed that efficient thermal coupling between PV cells and the heat exchanger significantly enhances both electrical and thermal performance, leading to higher electrical energy production and increased availability of low-grade heat for district heating supply. Furthermore, the authors in [10, 11] emphasized the techno-economic potential of PV/T-based heating systems, reporting reduced primary energy consumption and improved economic viability under favourable operating conditions. Despite these promising findings, comprehensive comparative analyses of PV/T and conventional PV systems under identical boundary conditions remain limited, particularly in industrial environments with stable thermal energy demand. Moreover, the specific role of PV/T-based HP systems as renewable heat sources within low-temperature district heating networks has not yet been sufficiently quantified from both technical and economic perspectives.

The aim of this paper is to present the production capacity of a PV/T system for simultaneous electrical and thermal energy production and to evaluate its applicability in low-temperature district heating systems. For this purpose, a comparative analysis of electrical energy production and investment costs between PV/T and PV systems at a selected location will be conducted.

2. Methodology

This section describes the methodology used to evaluate and compare two system configurations, namely (i) a PV/T system coupled with a water-to-water HP and (ii) a PV system coupled with an air-to-water HP. The assessment focuses on the HP performance and the electrical power production of PV and PV/T systems, which are key drivers of annual electrical energy demand and investment performance. The results presented are based on a dynamic simulation model developed for PV/T and PV systems. The heat pump performance is determined using a variable COP calculated as a function of the instantaneous heat source temperature and required outlet temperature. The electrical performance of the PV and PV/T systems is calculated using a single-diode model, in which the module efficiency depends on the instantaneous solar irradiance and the semiconductor layer temperature. The thermal behavior of the PV/T module is described using a transient multi-layer heat transfer model, which accounts for conductive, convective, and radiative heat transfer mechanisms. The model parameters, including heat transfer coefficients and material properties, were adopted and validated based on the experimental investigation reported in [12].

The HP performance is evaluated using the coefficient of performance (COP), defined as the ratio between the useful thermal energy output and the electrical input power of the HP, described by (1):

$$\boldsymbol{COP} = \frac{\dot{\boldsymbol{m}}\boldsymbol{c}_{\mathbf{p}}(\boldsymbol{T}_{\mathbf{out}} - \boldsymbol{T}_{\mathbf{in}})}{\boldsymbol{P}_{\mathbf{el,HP}}} \qquad (1)$$

where $\dot{m}$ denotes the mass flow rate of the working medium within the HP, c_p is the specific heat capacity of the working medium, $P_\mathrm{el,HP}$ represents the electrical input power of the HP, T_out is the outlet temperature, and T_in is the inlet temperature of the working medium. In the case of the water-to-water HP, the working medium is water, whereas for the air-to-water HP, it corresponds to ambient air. The electrical power output P_el of both the PV and PV/T systems is calculated using the electrical equivalent circuit single-diode model of the solar cell and is expressed as (2):

$$\boldsymbol{I} = \boldsymbol{I}_{\mathbf{ph}} - \boldsymbol{I}_{\mathbf{0}}\left[\boldsymbol{exp}\left(\frac{\boldsymbol{V} + \boldsymbol{IR}_{\mathbf{s}}}{\boldsymbol{nV}_{\mathbf{T}}}\right) - \mathbf{1}\right] - \frac{\boldsymbol{V} + \boldsymbol{IR}_{\mathbf{s}}}{\boldsymbol{R}_{\mathbf{sh}}} \qquad (2)$$

where I_ph is the photocurrent, I_0 is the diode reverse saturation current, R_s is the series resistance, R_sh is the shunt resistance, n is the diode ideality factor, V is voltage, and V_T is the thermal voltage. Since the single-diode model depends on solar radiation and solar cell temperature, the cell temperature for both PV and PV/T systems is determined using a model that accounts for optical and thermal losses, as described in detail in [12].

The outlet temperature of the PV/T working fluid, which represents the inlet temperature of the water-to-water HP, is calculated using a transient heat transfer model based on energy balance equations across the PV/T module layers, from the glass cover to the working fluid. The model accounts for solar gains, conductive heat transfer between adjacent layers, convective heat transfer to the ambient air, radiative exchange with the sky and the ground, and heat extraction by the working fluid. The complete formulation of the model is provided in [12]. For each layer i of the PV/T module, the transient energy balance is expressed as (3):

$$\left(\boldsymbol{\rho dAc}_{\mathbf{p}}\right)_{\boldsymbol{i}}\frac{\boldsymbol{dT}_{\boldsymbol{i}}}{\boldsymbol{dt}} = \dot{\boldsymbol{Q}}_{\mathbf{in},\boldsymbol{i}} - \dot{\boldsymbol{Q}}_{\mathbf{out},\boldsymbol{i}} \qquad (3)$$

where T_i represents the temperature of the i-th layer, $\dot{Q}_{\mathrm{in},i}$, and $\dot{Q}_{\mathrm{out},i}$ represent the incoming and outgoing heat fluxes, including absorbed solar radiation $\dot{Q}_\mathrm{abs}$, conduction $\dot{Q}_\mathrm{cond}$, convection $\dot{Q}_\mathrm{conv}$, radiation $\dot{Q}_\mathrm{rad}$, and heat generation. The absorbed heat flux $\dot{Q}_\mathrm{abs}$ representing the absorbed solar radiation by the PV/T module and is given by (4):

$$\dot{\boldsymbol{Q}}_{\mathbf{abs}} = \boldsymbol{\alpha}_{\mathbf{abs}}\boldsymbol{GA} \qquad (4)$$

where α_abs is the effective optical absorptance of the PV/T module, G is the solar radiation and A is the active surface area. The optical absorptance accounts for transmittance, reflectance, and multiple internal reflections within the glass–cell structure. The conductive heat transfer between two adjacent layers i and i+1 is given by (5):

$$\dot{Q}_{\mathrm{cond}} = \frac{T_i - T_{i+1}}{\frac{d_i}{k_i A} + \frac{d_{i+1}}{k_{i+1} A}} \quad (5)$$

where d and k denote the thickness and thermal conductivity of the corresponding layers. Convective heat transfer at the external surfaces is given by (6):

$$\dot{Q}_{\mathrm{conv}} = hA(T_s - T_{\mathrm{air}}) \quad (6)$$

Radiative heat exchange with the sky is given by (7):

$$\dot{Q}_{\mathrm{rad}} = \varepsilon\sigma A\left(T_{\mathrm{s}}^4 - T_{\mathrm{sky}}^4\right) \quad (7)$$

where h is the convective heat transfer coefficient, ε is the surface emissivity, σ is the Stefan–Boltzmann constant, T_{s} is the surface temperature and T_{sky} is the temperature of the sky. The thermal behavior of the PV/T cell layer is given by (8):

$$\left(\rho d A c_{\mathrm{p}}\right)_{\mathrm{PV/T}} \frac{dT_{\mathrm{PV/T}}}{dt} = \dot{Q}_{\mathrm{abs}} - \dot{Q}_{\mathrm{cond,up}} - \dot{Q}_{\mathrm{cond,down}} - P_{\mathrm{el}} \quad (8)$$

where $T_{\mathrm{PV/T}}$ represents the temperature of the PV/T module, $\dot{Q}_{\mathrm{abs}}$ is the absorbed solar radiation, $\dot{Q}_{\mathrm{cond,up}}$ and $\dot{Q}_{\mathrm{cond,down}}$ denote conductive heat fluxes to the adjacent layers, and P_{el} is the electrical power output of the PV/T module. The temperature of the working fluid inside the heat exchanger is given by (9):

$$\left(\rho c_{\mathrm{p}} V\right)_{\mathrm{f}} \frac{dT_{\mathrm{f}}}{dt} = h_{\mathrm{f}} A_{\mathrm{tube,in}}(T_{\mathrm{tube}} - T_{\mathrm{f}}) - \dot{m}_{\mathrm{f}} c_{\mathrm{p,f}}\left(T_{\mathrm{f,out}} - T_{\mathrm{f,in}}\right) \quad (9)$$

where T_{f} is the working medium temperature in the heat exchanger of the PV/T module, ρ_{f} is the working medium density, $c_{\mathrm{p,f}}$ is the specific heat capacity of the working medium, and V_{f} is the internal fluid volume of the tube. Furthermore, h_{f} denotes the convective heat transfer coefficient between the tube inner wall and the working medium, $A_{\mathrm{tube,in}}$ is the inner heat transfer area of the tube, and T_{tube} is the tube wall temperature. The term $\dot{m}_{\mathrm{f}}$ represents the mass flow rate of the working medium, while $T_{\mathrm{f,in}}$ and $T_{\mathrm{f,out}}$ are the inlet and outlet temperatures of the working medium, respectively. Under steady-state operating conditions, the outlet temperature of the working medium is given by (10):

$$T_{\mathrm{f,out}} = T_{\mathrm{f,in}} + \frac{\dot{Q}_{\mathrm{f}}}{\dot{m}_{\mathrm{f}} c_{\mathrm{p,f}}} \quad (10)$$

where $\dot{Q}_{\mathrm{f}}$ is the thermal power transferred to the working medium.

A. Description of the photovoltaic/thermal system

A PV/T system consists of PV/T modules, a DC/AC inverter, and a set of auxiliary components forming the thermal subsystem, which are essential for ensuring stable, efficient, and reliable operation. One key element is the TES unit, typically implemented as a buffer tank, that enables temporary storage of surplus thermal energy extracted from the PV/T modules. The TES unit plays a crucial role in decoupling energy production from consumption, thereby improving system flexibility and operational stability. Circulation pumps are another important component of the PV/T system, enabling active control of heat transfer within the thermal circuit. By adjusting the mass flow rate on the module side, the operating temperature of the PV/T modules can be reduced, thereby improving electrical efficiency and limiting thermal degradation. Conversely, increasing the mass flow rate on the TES side enhances heat transfer to the buffer tank and increases the usable thermal output. Such flow control strategies allow the system to adapt dynamically to changing operating conditions and load profiles. By appropriately regulating mass flow rates and storage operations, the PV/T system can be configured to prioritize electrical energy production, thermal energy production, or their combined utilization, depending on the consumption profile and system requirements [7]. This operational flexibility is particularly important in applications involving HP and low-temperature heating networks.

Additional system components include plate or shell-and-tube heat exchangers, three-way and ball valves, expansion vessels, control units, sensors, and safety devices, which collectively ensure hydraulic balance, pressure stability, and safe system operation. These elements also facilitate system integration with external heating networks and auxiliary heat sources. Compared to conventional PV installations, PV/T systems require a more complex hydraulic, thermal, and control infrastructure due to the integration of the thermal subsystem. In particular, the inclusion of TES, circulation pumps, heat exchangers, hydraulic fittings, and control equipment, which are not required in standard PV systems, significantly increases the initial investment cost. This additional equipment also increases installation and maintenance requirements. As a result, the higher system complexity and the need for supplementary components directly influence the overall economic performance and payback period of PV/T systems [12]. Although the combined production of electrical and thermal energy can partially offset these additional costs, the increased investment remains a major barrier to the wider commercial deployment of PV/T technology.

B. Configuration of the photovoltaic/thermal and photovoltaic system

The selected site for installing the PV/T and PV systems is an industrial facility with an average annual thermal energy consumption of 102.82 MWh. The thermal energy demand remains relatively constant throughout the year, as it is directly tied to the industrial production process. Due to the transition toward renewable energy technologies and the high prices of thermal energy from the district heating system, which average 89.13 EUR/MWh, two scenarios are considered for the end user. In the first scenario, a PV/T system with TES will be installed on the roof of the facility. The installed electrical capacity of the PV/T system is 34.2 kW, providing an annual electrical energy production of 36.95 MWh. Based on the thermal energy production of the PV/T system, the TES was sized at 5,000 liters. Thermal energy from the TES is supplied to a low-temperature water-to-water HP, which must ensure an outlet temperature of 65 °C. In the second scenario, a PV system with an installed capacity of 43.2 kW will be installed on the roof of the facility, producing 40.99 MWh of electrical energy annually. In this case, the heat source for the low-temperature air-to-water HP is the ambient air, whose temperature varies seasonally. For both scenarios, a techno-economic analysis of the investment to replace the heating source will be presented in the following sections.

3. Results

Based on the presented PV/T and PV system configurations, Figure 1a shows the temporal variation of the heat source temperature for the low-temperature HP. In the PV/T system, this corresponds to the water temperature at the output of the PV/T modules or at the inlet to the TES, whereas in the PV system, it represents the ambient air temperature. Figure 1b shows the temporal variation of the coefficient of performance (COP) of the low-temperature water-to-water HP in the PV/T system and the air-to-water HP in the PV system.

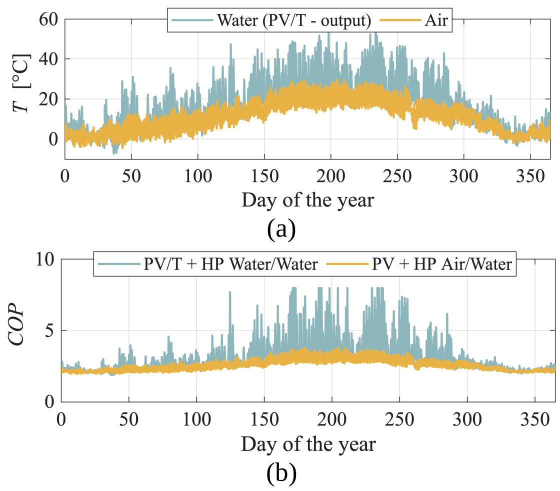


Fig. 1. (a) Heat source temperature of the HP in combination with the PV/T or PV system and (b) COP of the HP in combination with the PV/T or PV system.

Figure 1a shows that the TES temperature, which serves as the heat source for the water-to-water HP in combination with the PV/T system, ranges from −7.23 °C to 57.10 °C. At the same time, the ambient air temperature, which serves as the heat source for the air-to-water HP in combination with the PV system, ranges from −4.49 °C to 29.75 °C. A higher heat source temperature contributes to a higher COP, as less electrical energy is required to achieve the desired outlet temperature. Figure 1b shows that the water-to-water HP has an average COP of 3.02, whereas the air-to-water HP has an average COP of 2.55. The increase in COP for the water-to-water HP is more pronounced during the summer months, when the PV/T system enables the storage of excess thermal energy in the buffer tank, thereby improving HP efficiency. Based on the calculated COP values for both HP, the electrical energy consumption required to maintain a constant water outlet temperature of 65 °C was determined, as shown in Figure 2a. To cover this electrical energy demand, two electrical energy production scenarios based on the PV/T and PV systems were considered, as presented in Section 2 and shown in Figure 2b.

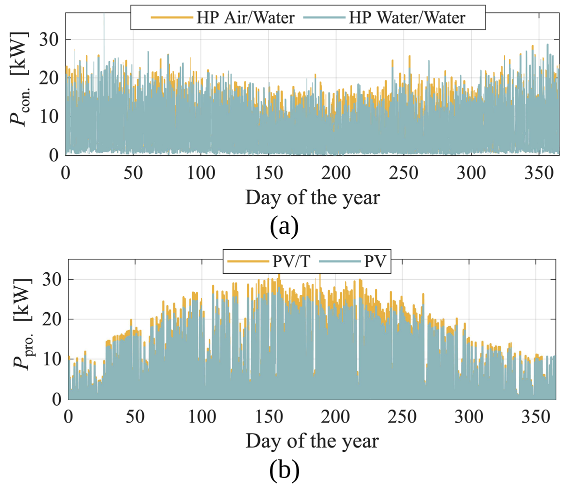


Fig. 2. (a) Electricity consumption of the air-to-water and water-to-water HP in combination with the PV/T and PV system, and (b) electricity production from the PV/T and PV system.

The annual electrical energy consumption of the water-to-water HP amounted to 36.92 MWh, whereas that of the air-to-water HP was 40.82 MWh. The lower electrical energy consumption of the water-to-water HP results from its higher COP and reduced auxiliary heating demand, enabled by the higher heat source temperature provided by the PV/T system. In addition to the lower electricity consumption of the water-to-water HP, the advantages of the PV/T system are also evident in electrical energy production. Compared to the PV system, the PV/T system produces 12.69% more electrical energy at the same installed capacity, with an annual production of 32.79 MWh for the PV system and 36.95 MWh for the PV/T system. Due to lower PV system electrical energy production and the resulting higher air-to-water HP demand, it was necessary to increase the PV system's installed capacity from 34.2 kW to 43.2 kW to achieve self-sufficiency and fully cover the thermal energy demand.

It is also important to note that both the PV/T and PV systems included a battery storage system (BSS), which enables storage of excess electrical energy and contributes to more stable, uniform thermal energy production by the HP. Figure 3 shows the exported and imported grid power P_{grid}, charging and discharging power of the BSS $P_{bat.}$, and the BSS state of charge (SOC).

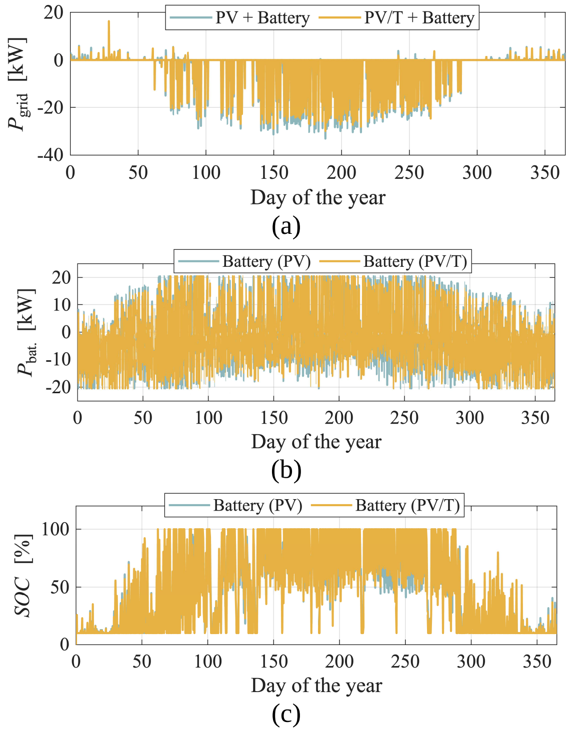
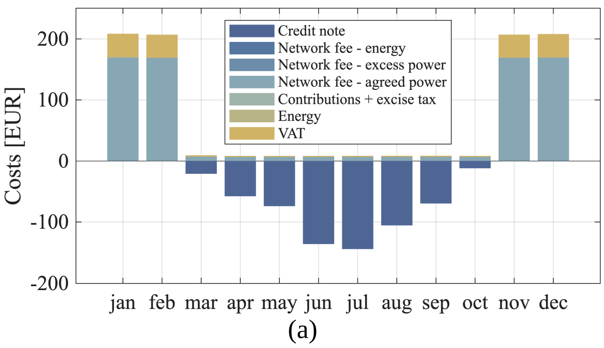


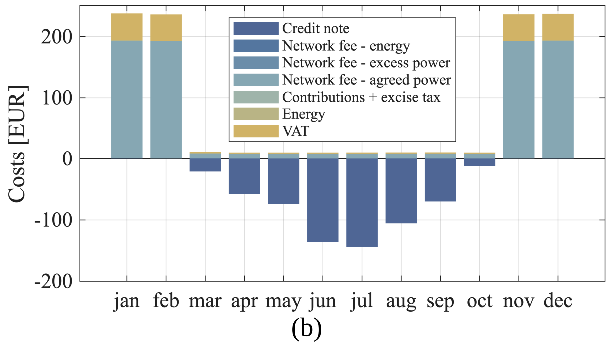
Fig. 3. (a) Exported and imported grid power P_{grid}, (b) charging and discharging power of the BSS $P_{bat.}$, and (c) SOC of the BSS for PV and PV/T systems.

Figure 3 shows that the deviations between electrical energy consumption and production in the PV/T and PV systems are negligible, as the installed capacity of the PV system was appropriately adjusted to compensate for its lower efficiency. With BSS, the PV/T system exports 12.37 MWh to the grid annually, while grid imports are limited to 33.48 kWh. For the PV system, comparable values are observed, with annual grid exports amounting to 12.42 MWh and grid imports to 43.09 kWh.

Based on the ratio of electrical energy production from the PV/T and PV systems to the electricity consumption of the water-to-water and air-to-water HP, an economic analysis of the investment in the PV/T and PV systems was subsequently performed. Figure 4 presents the analysis of electrical energy costs required for HP operation in combination with the PV/T or PV system.



(a)



(b)

Fig. 4. (a) Structure of electrical energy costs for water-to-water HP operation in combination with the PV/T system and (b) structure of electrical energy costs for air-to-water HP operation in combination with the PV system.

In the calculation of electrical energy costs, the network tariff system and the sale of surplus electrical energy under the credit scheme at 0.05 EUR/kWh were considered. Figure 4 shows that electrical energy costs for the air-to-water HP combined with the PV system are higher than those for the water-to-water HP combined with the PV/T system, due to lower contracted capacity charges resulting from lower peak electrical energy demand in the PV/T system. Although the ratio between electrical energy production in the PV and PV/T systems and electrical energy consumption in the air-to-water and water-to-water HP is comparable, the annual electrical energy costs for the PV/T system with a water-to-water HP amount to 283.74 EUR, whereas for the PV system with an air-to-water HP, they are higher by 123.80 EUR, reaching 407.54 EUR. For a comprehensive economic analysis, investment costs and savings are crucial, as they directly affect the payback period. In calculating the investment payback period, the costs of the HP and BSS were deliberately excluded to clearly highlight the difference in payback periods between the PV/T and PV systems. Figure 5 presents the payback periods of the investments in PV and PV/T systems.

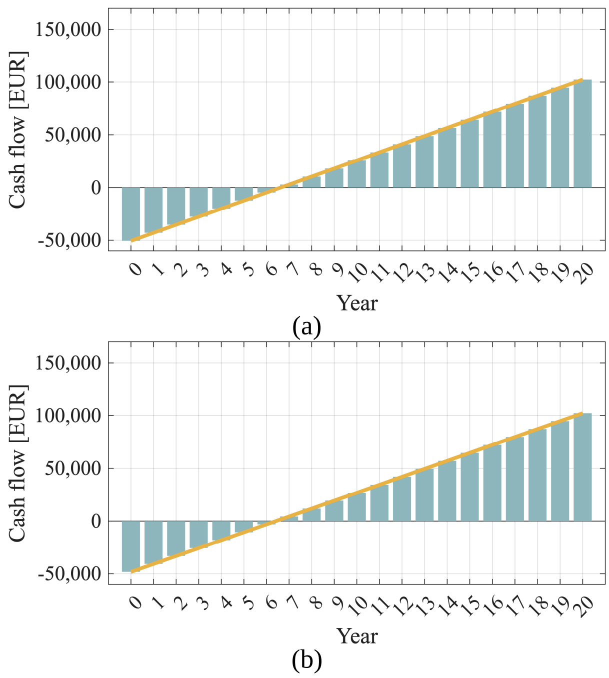


Fig. 5. (a) Payback period of the investment in the PV system and (b) payback period of the investment in the PV/T system.

The investment cost of the PV system with an installed capacity of 43.2 kW was 48,200 EUR, whereas the PV/T system with an installed capacity of 34.2 kW cost 50,555 EUR. Based on the annual savings, which include the reference cost of thermal energy without the HP and PV or PV/T system (9,163.94 EUR per year) and the considered annual electrical energy costs, the investment payback period was calculated. It amounts to 6.4 years for the PV system and 6.6 years for the PV/T system.

Despite the lower electrical energy consumption of the water-to-water HP and higher electrical energy production in the PV/T system, the payback period of the PV/T investment remains slightly longer than that of the PV system. Although the difference is minimal, the high investment costs of PV/T systems still represent a key barrier to their competitiveness compared to commercial PV systems.

4. Conclusion

The paper evaluates the performance and economic feasibility of a PV/T system for simultaneous electrical and thermal energy production, compared with a conventional PV system, in low-temperature district heating applications. The results confirm that the PV/T system achieves superior overall performance, producing 12.69% more electrical energy at the same installed capacity while additionally supplying useful thermal energy. This leads to improved operating conditions of the water-to-water HP, reflected in a higher COP and consequently lower electrical energy demand compared to the air-to-water HP.

From a system perspective, the results demonstrate that integrating PV/T technology enhances both energy efficiency and operational synergy in low-temperature heating networks. The simultaneous generation of electricity and heat reduces the system's dependence on external energy sources and improves overall system flexibility. From an economic standpoint, the PV/T system has a slightly longer payback period (6.6 years) than the PV system (6.4 years), primarily because of higher initial investment costs. However, the difference remains marginal, indicating that PV/T systems are already close to economic competitiveness under current conditions.

A simplified sensitivity analysis shows that the payback period is particularly influenced by electricity prices, investment costs, and heat utilization levels. An increase in electricity prices or a reduction in system investment costs by approximately 10 % can reduce the PV/T payback period below that of the conventional PV system. Similarly, higher utilization of the recovered thermal energy further improves economic performance.

Overall, the results indicate that PV/T systems offer a promising solution to improve the efficiency and sustainability of district heating systems. Further research should focus on cost optimization, improved integration strategies, and long-term operational validation to strengthen their economic viability.

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References

[1] C. Kutlu, A. Dik, M. T. Erdinc, Y. Su, and S. Riffat, “Comparative Analysis of Solar Photovoltaic/Thermal Assisted Heat Pump Systems Coupled with PCM Storage and EV Charging with Reference to the UK's National Carbon Intensity,” *Energies,* vol. 18, no. 4, Feb, 2025.

[2] P. Mi, J. Zhang, and Y. Han, “Operation study of the photovoltaic thermal heat pump integrated energy system under trigeneration condition and harsh conditions,” *Energy,* vol. 312, Dec 15, 2024.

[3] C. Zhou, A. Riaz, J. Wang, J. Zhang, and L. Xu, “Photovoltaic Thermal Heat Pump Assessment for Power and Domestic Hot Water Generation,” *Energies,* vol. 16, no. 19, Oct, 2023.

[4] I. Pakere, D. Lauka, and D. Blumberga, “Solar power and heat production via photovoltaic thermal panels for district heating and industrial plant,” *Energy,* vol. 154, pp. 424–432, Jul 1, 2018.

[5] H. Namdar, E. R. di Schio, G. Semprini, and P. Valdiserri, “Photovoltaic-thermal solar-assisted heat pump systems for building applications: A technical review on direct expansion systems,” *Energy and Buildings,* vol. 334, May 1, 2025.

[6] A. G. N. Sofiah, A. K. Pandey, R. K. Rajamony, M. Samykano, J. Pasupuleti, N. F. Sulaiman, and R. Saidur, “Energetic, exergetic, and entropy generation prediction and optimization of photovoltaic thermal system integrated hexagonal boron nitride-water nanofluid,” *Applied Thermal Engineering,* vol. 263, Mar 15, 2025.

[7] K. Sredensek, S. Seme, B. Stumberger, M. Hadziselimovic, A. Chowdhury, and Z. Praunseis, “Experimental Validation of a Dynamic Photovoltaic/Thermal Collector Model in Combination with a Thermal Energy Storage Tank,” *Energies,* vol. 14, no. 23, Dec, 2021.

[8] A. Al-Sayyab, J. Navarro-Esbrí, A. Barragán-Cervera, and A. Mota-Babiloni, “Techno-economic analysis of a PV/T waste heat-driven compound ejector-heat pump for simultaneous data centre cooling and district heating using low global warming potential refrigerants,” *Mitigation and Adaptation Strategies for Global Change,* vol. 27, no. 7, Oct, 2022.

[9] A. Al-Sayyab, J. Navarro-Esbrí, and A. Mota-Babiloni, “Energy, exergy, and environmental (3E) analysis of a compound ejector-heat pump with low GWP refrigerants for simultaneous data center cooling and district heating,” *International Journal of Refrigeration,* vol. 133, pp. 61–72, Jan, 2022.

[10] Y. Chen, H. Hua, J. Wang, and P. Lund, “Thermodynamic performance analysis and modified

thermo-ecological cost optimization of a hybrid district heating system considering energy levels," *Energy*, vol. 224, Jun 1, 2021.

[11] H. Jouhara, M. Szulgowska-Zgrzywa, M. Sayegh, J. Milko, J. Danielewicz, T. Nannou, and S. Lester, "The performance of a heat pipe based solar PV/T roof collector and its potential contribution in district heating applications," *Energy*, vol. 136, pp. 117–125, Oct 1, 2017.

[12] K. Sredensek, E. Simonic, K. Dezelak, M. Bizjak, N. Lukac, and S. Seme, "Dynamic Modeling and Experimental Validation of the Photovoltaic/Thermal System," *Applied Sciences-Basel*, vol. 15, no. 19, Sep 28, 2025.