SOLAR ENERGY CONVERSION MODULE RESEARCH

Marius Mickevicius, Egidijus Zvicevicius, Kestutis Ziura, Inga Adamonyte
Vytautas Magnus University, Lithuania
marius.mickevicius@vdu.lt, egidijus.zvicevicius@asu.lt,
kestutis.ziura@gmail.com, inga.adamonyte@vdu.lt

Abstract. Due to climate change, decreasing and rising costs of fossil resources, and geopolitical factors, renewable energy sources are becoming increasingly important. The use of solar energy may be one of the solutions. The rapid development of this energy sector encourages the search for ways to increase the efficiency of these modules. One of the simplest methods would be to collect the heat reflected by the module and use it in other processes, while simultaneously reducing the surface temperature of the photovoltaic module and optimizing its operating conditions. On sunny summer days, the overheating of photovoltaic modules can significantly affect the total amount of electricity generated by a solar power plant. This article analyzes the characteristics of three different hybrid solar energy conversion module designs. The research was conducted in 2024 in Kaunas district (Lithuania) under solar irradiance of 800-1000 $W \cdot m^{-2}$. The symbiosis of the photovoltaic solar energy module with an air solar collector allowed the efficiency of the solar energy conversion process to be increased to 62.6 ± 1.2%. In parallel with the electrical energy flow, an additional heat flux of 481 ± 10 $W \cdot m^{-2}$ was generated, which can successfully be used in drying or heating technologies. The hybrid solar energy conversion module design also created conditions for cooling the photovoltaic module and providing more favorable operating conditions: the surface temperature of the photovoltaic module decreased from 55.58 ± 0.81 °C to 39.31 ± 0.73 °C.

Keywords: solar energy, hybrid solar collector, photovoltaic thermal (PVT), conversion efficiency.

Introduction

Sufficient energy resources are one of the essential conditions for the development of technology and economy of a country. However, the amount of energy in the universe is a constant quantity. It cannot be increased or decreased [1]. Using special technologies, only its form can be changed. Solar energy is a clean, abundant, environmentally friendly, and freely available energy resource. In 2024, solar power plants generated 11% (1.273 TWh) of all electricity consumed in Lithuania [2].

The development of solar energy also promotes the improvement of the technologies used: the creation of more efficient photovoltaic and heat-absorbing modules. The efficiency of photovoltaic solar modules is still relatively low, ranging from 13% to 22%, and the average power density generated per unit area is only about 150 $W \cdot m^{-2}$ [3]. Of all the sunlight that reaches the photovoltaic solar module, only about 20% is converted into electricity, while the remaining 80% is converted into heat and radiated into the environment [4]. The efficiency of photovoltaic modules is influenced by factors such as environmental conditions, module design, and material properties. An increase in the surface temperature of the photovoltaic module can negatively affect its efficiency: studies show that the efficiency decreases by about 0.05% for every degree Celsius above STC (Standard Test Conditions) [5]. This confirms the importance of temperature control in photovoltaic systems and suggests that innovative cooling solutions could play a decisive role in maintaining optimal operating conditions. Furthermore, hybrid systems that combine photovoltaic and thermal technologies (PVT), compared to separate photovoltaic or solar thermal collectors, typically generate more energy per unit area. There are studies indicating that hybrid photovoltaic-thermal collectors can achieve an overall (thermal plus electrical) efficiency coefficient ranging from 25% to 85%. In contrast, the conversion efficiency of a simple photovoltaic module made of Si can be only around 15-20% [6]. Therefore, by combining these systems, one can achieve comprehensive benefits: excess heat, which is usually lost in conventional photovoltaic systems, can be used for water heating, drying plant products in dryers, or space heating [7; 8].

The application areas of photovoltaic-thermal technologies are intensively being developed. By testing their synergy with various technologies, such as heat pumps, hybrid systems are being created. Zohri et al. discuss the benefits of such hybrid configurations for solar-powered heat pumps, which improve energy efficiency in various fields [9]. These integrations encourage the trend of using multifunctional energy systems, where the strengths of multiple renewable energy technologies are utilized simultaneously.

Various liquid-fluid-based systems for collecting and transferring thermal energy are integrated into hybrid photovoltaic-thermal technologies. Bandaru et al. state that in such hybrid systems, air, water, or nanosolutions can be used as the coolant or heat transfer fluid. Researchers analyze the design solutions of hybrid systems that affect their thermal and electrical efficiency. The overall efficiency of such systems, which can reach 81%, depends on specific conditions and design characteristics [10].

In conclusion, it can be stated that these photovoltaic-thermal systems provide an excellent opportunity to increase the efficiency of solar energy usage. Their ability to effectively convert solar energy into both electrical and thermal energy, along with ongoing scientific research and technological advancements, makes PVT technologies an important component of sustainable energy production. It is essential to continue conducting research aimed at improving the design solutions of hybrid systems and enhancing their efficiency.

Materials and methods

Research on hybrid solar energy conversion modules was conducted in August – September 2024, in Akademija, Kaunas district (Lithuania), under 800-1000 $W \cdot m^{-2}$ irradiance. The test stand (Fig. 1) was mounted on a platform with the ability to change the direction and tilt angle. The effective area of the hybrid solar energy conversion module is 1.998 m^2.

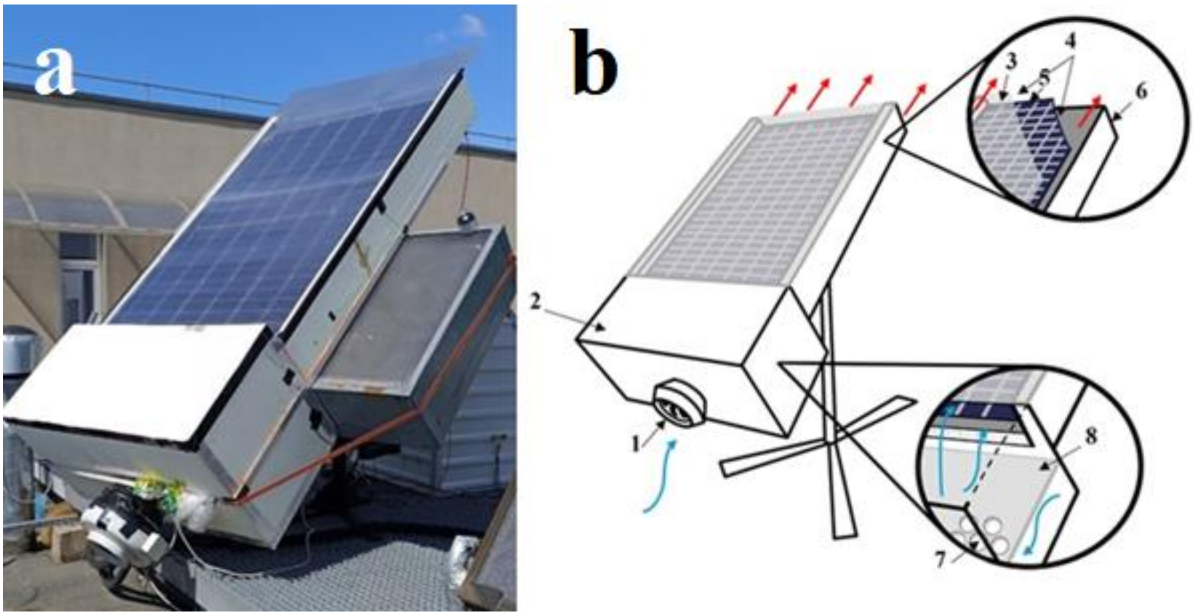

Fig.1 **Real experimental (a) and cross-sectional view of hybrid PV/T setup (b):** 1 – fan; 2 – air preparation chamber; 3 – polycarbonate cover; 4 – ducts; 5 – photovoltaic module; 6 – insulating layer; 7 – air supply openings; 8 – partition

The test stand frame was made using extruded polystyrene foam: 50 mm thick Finnfoam FL - 300XX, with a thermal conductivity coefficient $\lambda_D = 0.033$ $W \cdot (m \cdot K)^{-1}$. The inner side of the frame is additionally reinforced with a 30 mm thick polyurethane foam core with a foil-covered Finnfoam FF - PIR Sauna plate, with a thermal conductivity $\lambda_D = 0.022$ $W \cdot (m \cdot K)^{-1}$. The transparent cover was made from clear, 8 mm thick channel polycarbonate: thermal conductivity $\lambda_D = 0.21$ $W \cdot (m \cdot K)^{-1}$, light transmittance 82%.

The operating principle of the hybrid solar energy conversion module is shown in Figure 1b. A duct fan Salda VKA 200 LD was used to supply the heat transfer fluid to the air preparation chamber: maximum power 162 W, maximum capacity 960 $m^3 \cdot h^{-1}$. To balance and distribute the airflow, an air preparation chamber with a partition was installed, in which twelve 80 mm diameter holes were drilled. The fan supplied the heat transfer fluid (ambient air) to the lower part of the air preparation chamber, and through the air supply openings it entered the upper part of the air preparation chamber, from where the heat transfer fluid entered the collector ducts. Depending on the design of the hybrid solar conversion module, one or two ducts could be formed to wash the absorber. The duct above the absorber has a width of 1007 mm and a height of 30 mm. The duct below the absorber has a width of 1007 mm and a height of 100 mm. The absorber used was the Trina TSM - 420DE09R.08 photovoltaic module (Table 1).

Table 1

Technical data of the PV module

Electrical data (STC*)		**Mechanical data**	
Maximum Power – P_{max}, W	420.0	Solar Cells	Monocrystalline Si
Maximum Power Voltage – V_{MPP}, V	42.00	Number of Cells	144 cells
Maximum Power Current – I_{MPP}, A	10.01	Module Dimensions	1762×1134×30 mm
Open Circuit Voltage – V_{OC}, V	50.01	Weight	21.8 kg
Short Circuit Current – I_{SC}, A	10.58	Encapsulant Material	EVA/POE
Module Efficiency – η_m, %	21.00	Glass	3.2 mm, AR Coated, Heat Strengthened Glass

*STC: Irradiance 1000 W·m^{-2}, Cell Temperature 25 ºC, Air Mass AM 1.5 spectra

During the study, the operation of the hybrid solar energy conversion module was evaluated by recording solar irradiance, the amount of electricity generated, and measuring the airflows in the collector. Temperature and relative humidity sensors Ahlborn FHAD462 were installed for monitoring ambient air parameters. Similar sensors were installed in the upper part of the air preparation chamber and in the collector ducts near the heat transfer fluid outlet holes. Thermocouples were attached to both the inner and outer sides of the photovoltaic element to record the surface temperatures of the photovoltaic module. To measure solar irradiance, a light meter was installed next to the hybrid solar collector. Data was recorded at one-minute intervals in the Almemo 2890 data logger. The photovoltaic module was connected to the hybrid inverter GreenCell INVSOL01. To record the generated electrical power, the inverter's software was used. The inverter charged a LiFePO4 100 Ah battery and ensured a stable power supply to the collector fan and data recording equipment. The air speed was measured in the ducts of the hybrid solar energy conversion module along the air outlet holes. Measurements were carried out using a vane anemometer Ahlborn FVAD15HMK20 connected to the Almemo 2590 data logger.

Based on the obtained measurement results, the airflow passing through the collector is calculated:

$$Q_{air} = \tilde{v}\,\Sigma A_{or}, \tag{1}$$

where Q_{air} – air flow, m^3·s^{-1};
$\tilde{v}$ – air speed average, m·s^{-1};
ΣA_{or} – total area of the collector duct openings, m^2.

The actual thermal power of the hybrid solar energy conversion module [11]:

$$P_{th} = \dot{m}c_p(T_o - T_i), \tag{2}$$

where P_{th} – thermal power of the hybrid solar collector, W;
$\dot{m}$ – mass flow rate of the heat transfer fluid, kg·s^{-1};
c_p – specific heat capacity of the heat transfer fluid, J·(kg·K)$^{-1}$;
T_o – temperature of the outgoing heat transfer fluid, °C;
T_i – temperature of the incoming heat transfer fluid, °C.

The thermal efficiency of the hybrid solar energy conversion module [12]:

$$\eta_{th} = \frac{P_{th}}{GA_{kol}}, \tag{3}$$

where η_{th} – thermal efficiency of the hybrid solar energy conversion module;
G – irradiance intensity, W·m^{-2};
A_{kol} – collector surface area, m^2.

Electrical power generated by the photovoltaic module:

$$P_{el} = I \cdot V, \tag{4}$$

where P_{el} – electrical power generated by the photovoltaic module, W;

I – electrical current, A;
V – electrical voltage, V.

The electrical efficiency of the hybrid solar energy conversion module [12]:

$$\eta_{el} = \frac{P_{el}}{GA_{kol}}, \tag{5}$$

where η_{el} – electrical generation efficiency of the hybrid solar energy conversion module;
G – irradiance intensity, W·m^{-2};
A_{kol} – collector surface area, m^2.

Based on the analysis of energy flows, the overall efficiency of the hybrid solar energy conversion module consists of the thermal and electrical energy generation efficiencies and can be expressed by equation [13]:

$$\eta_k = \eta_{th} + \eta_{el}. \tag{6}$$

Results and discussion

The dependence of the surface temperature of the photovoltaic module of solar collectors with different designs on the irradiance intensity is shown in Figure 2.

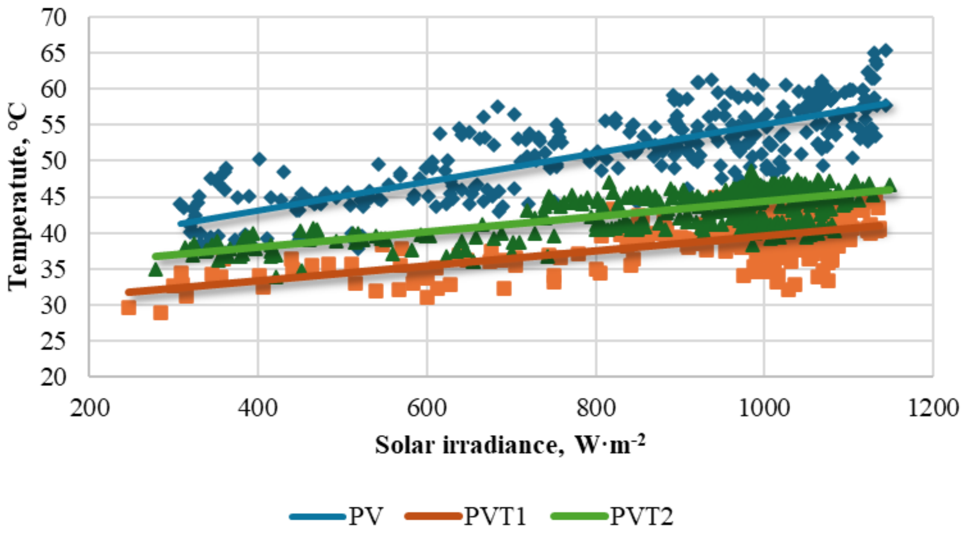

Fig. 2. **Temperature dependence of the PV module surface on solar irradiance**

A linear dependence of the surface temperature of the photovoltaic module on irradiance was established. During all experiments, the lowest surface temperature of the photovoltaic module was observed when the hybrid solar conversion module (PV/T) had a single duct below the photovoltaic module (orange markers). Under average irradiance of 950 ± 8.5 W·m^{-2}, the average surface temperature of the photovoltaic module, mounted and operating under normal conditions, was 55.58 ± 0.81 °C. In the hybrid solar collector with a single duct below the photovoltaic module, the temperature was 39.31 ± 0.73 °C, while with two ducts installed on both sides of the photovoltaic collector, the temperature was 44.32 ± 0.2 °C.

The temperature of the photovoltaic collector is directly proportional to the irradiance temperature. However, as the irradiance increases, the collector ability to convert solar energy into electrical energy decreases (Fig. 3).

With an increase in irradiance from 345 W·m^{-2} to 1140 W·m^{-2}, the temperature of the photovoltaic module increased from 42.2 °C to 59.9 °C (orange markers). Meanwhile, its efficiency decreased from 0.17 to 0.16 (blue markers).

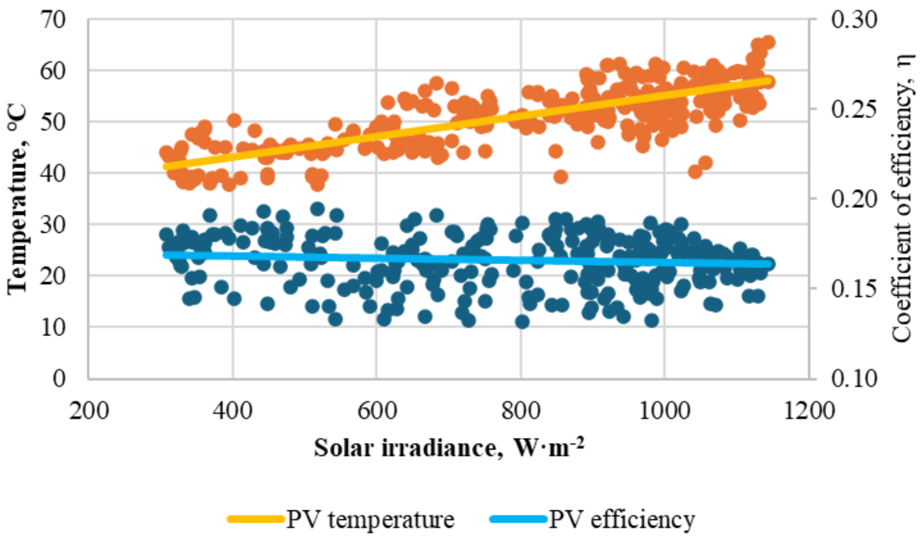

Fig. 3. **Dependance of the PV module surface temperature and efficiency on solar irradiance**

The hybrid solar energy conversion module, both with one and two ducts in parallel to electrical energy flow, generated a heat flux (Fig. 4). The heat flux generated in the collector with one duct was lower, ranging from 200.95 W·m^{-2} to 310.84 W·m^{-2}. Part of the heat was dissipated and radiated back into the environment due to the unglazed upper surface and direct contact of the photovoltaic module with the surrounding air. However, the operating conditions of the photovoltaic module were better (Fig. 2): the temperature of the photovoltaic module with one duct from the bottom was on average 5.01 ± 0.45 °C lower compared to the module where ducts were installed both from the bottom and the top of the photovoltaic module.

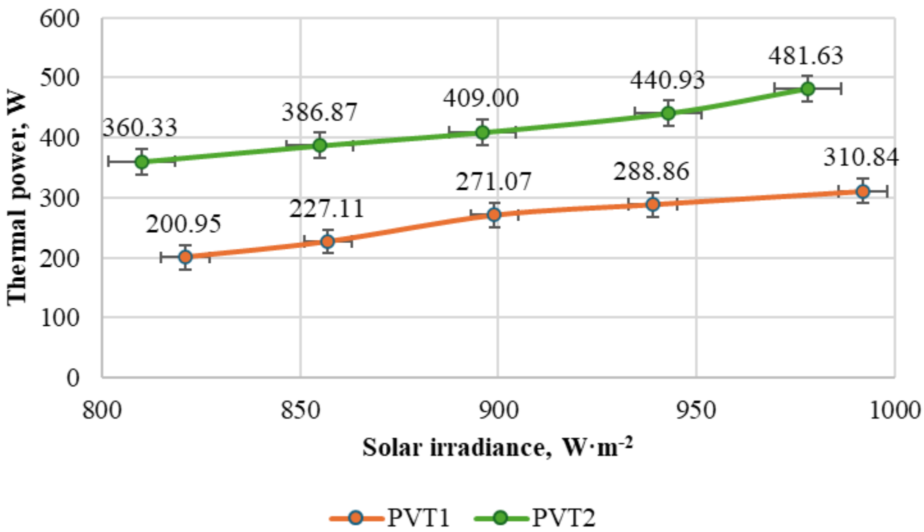

Fig. 4. **Dependence of the generated thermal power on solar irradiance**

The maximum heat flux power, 481.63 ± 8.5 W·m^{-2}, was generated by the hybrid solar energy conversion module with two ducts (PVT2) under 978 ± 5.85 W·m^{-2} of solar irradiance. However, such irradiance is a rare occurrence, and under an average irradiance of 810 ± 7.6 W·m^{-2}, the average heat power generated by this collector was 360.33 ± 7.5 W·m^{-2}.

By determining the electrical energy and heat fluxes generated in solar energy conversion modules with different designs, their useful performance coefficients and solar energy conversion efficiencies were calculated (Fig. 5).

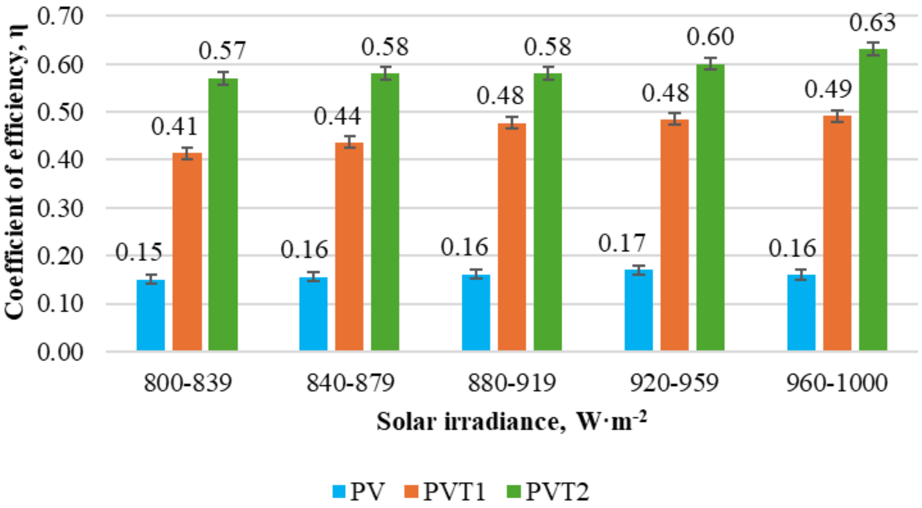

Fig. 5. **Dependence of the efficiency of solar collectors on solar irradiance**

Hybrid-type solar energy conversion modules are characterized by the highest useful performance coefficient. The highest conversion efficiency was achieved with solar irradiance ranging from 960 $W \cdot m^{-2}$ to 1000 $W \cdot m^{-2}$: as the irradiance increased, the surface temperature of the photovoltaic collector also increased, resulting in more thermal energy being obtained. The efficiency coefficient of the hybrid module with two ducts was the highest, 0.63 ± 0.012, but the efficiency of solar energy conversion into electrical energy was the lowest, 0.13 ± 0.01 (Fig. 6).

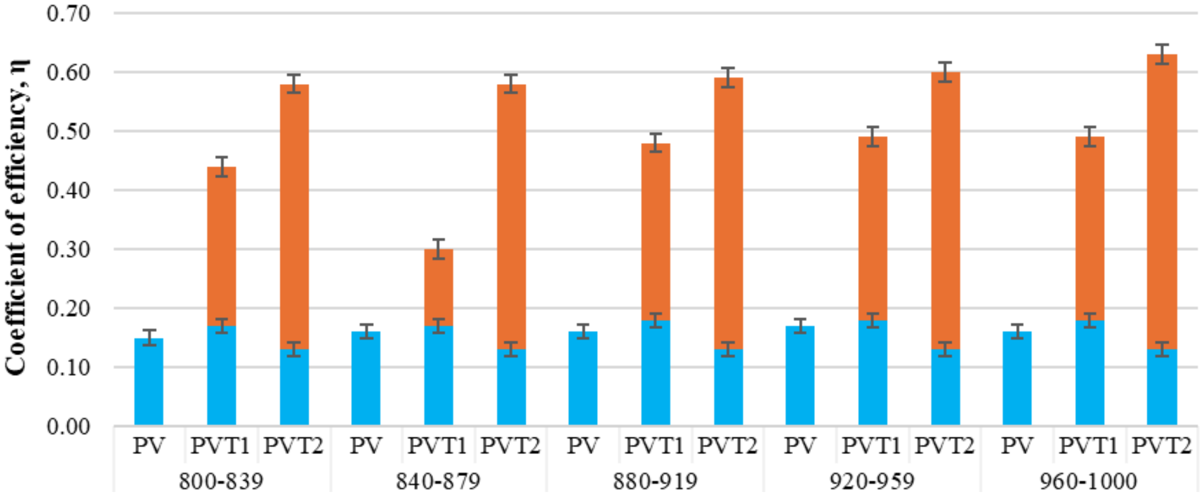

Fig. 6. **Variation of thermal and electrical efficiencies with solar irradiation**

The results obtained in the study are close to those of other researchers. The electrical energy generation efficiency of the collectors they determined ranged from 9% to 12%, while the thermal energy efficiency ranged from 14% to 70% [14-16].

Conclusions

1. The temperature of the photovoltaic module has a significant impact on its efficiency. Therefore, to achieve higher efficiency of photovoltaic modules, it is crucial to control their temperature.
2. The highest average heat flux generated by the hybrid-type solar collector, 481.63 ± 8.5 $W \cdot m^{-2}$, was obtained under an average irradiance of 978 ± 5.85 $W \cdot m^{-2}$. The heat flux generated in the duct above the absorber was 190.3 ± 3.25 $W \cdot m^{-2}$, while the heat flux in the duct below the absorber was 291.33 ± 5.25 $W \cdot m^{-2}$.

3. In the hybrid collector with one duct, under irradiance of 960-1000 W·m^{-2}, the average surface temperature of the photovoltaic module was 38.6 ± 0.73 °C, while in the photovoltaic collector it was 57.2 ± 0.81 °C, which is 32% higher.

Author contributions

Conceptualization, M.M.; methodology, E.Z. and K.Z.; formal analysis, M.M. and E.Z; investigation, M.M. and K.Z.; data curation, M.M. and E.Z.; writing – original draft preparation, M.M.; writing – review and editing, E.Z., K.Z. and I.A.; project administration, I.A.; funding acquisition, I.A. All authors have read and agreed to the published version of the manuscript.

References

[1] Tiwari G. N., Tiwari A., Shyam. Handbook of Solar Energy: Theory, Analysis and Applications (1st ed.). Springer Singapore Pte. Limited, 2016. DOI: 10.1007/978-981-10-0807-8
[2] Elektros suvartojimo ir gamybos duomenys „Pernai fiksuota rekordinė elektros gamyba – daugiau nei du trečdaliai Lietuvoje pagamintos elektros energijos iš atsinaujinančių išteklių" (Electricity consumption and production data: "Last year, a record electricity generation was recorded – more than two-thirds of the electricity produced in Lithuania came from renewable sources") "Ministry of Energy of the Republic of Lithuania" (In Lithuania) [online] [11.03.2025]. Available at: https://enmin.lrv.lt/lt/naujienos/pernai-fiksuota-rekordine-elektros-gamyba-daugiau-nei-du-trecdaliai-lietuvoje-pagamintos-elektros-energijos-is-atsinaujinanciu-istekliu/
[3] Wirth H., Weiß K.A., Wiesmeier C. Photovoltaic Modules: Technology and Reliability (1st ed.). De Gruyter, 2016, pp 8-24. DOI: 10.1515/9783110348286
[4] Rahman M. M., Hasanuzzaman M., Rahim N. A. Effects of operational conditions on the energy efficiency of photovoltaic modules operating in Malaysia. Journal of Cleaner Production, vol. 143, 2017, pp 912-924. DOI: 10.1016/j.jclepro.2016.12.029.
[5] Hasan K., Yousuf S. B., Tushar M. S. H. K., Das B. K., Das P., Islam Md. S. Effects of different environmental and operational factors on the PV performance: A comprehensive review. Energy Science & Engineering, vol. 10(2), 2022, pp 656-675. DOI: 10.1002/ese3.1043.
[6] Herrando M., Wang K., Huang G., Otanicar T., Mousa O. B., Agathokleous R. A., Ding Y., Kalogirou S., Ekins-Daukes N., Taylor R. A., Markides C. N. A review of solar hybrid photovoltaic-thermal (PV-T) collectors and systems. Progress in Energy and Combustion Science, vol. 97, 2023, article 101072. DOI: 10.1016/j.pecs.2023.101072
[7] Sapei L., Tarigan E., Sugiarto D. N., Gianluca D. Drying of celery leaves (Apium graveolens L.) using a PV/T solar dryer. IOP Conference Series. Materials Science and Engineering, vol. 703(1), 2019, article 12042. DOI: 10.1088/1757-899X/703/1/012042
[8] Cen J., du Feu R., Diveky M. E., McGill C., Andraos O., Janssen W. Experimental study on a direct water heating PV-T technology. Solar Energy, vol. 176, 2018, pp 604-614. DOI: 10.1016/j.solener.2018.10.062
[9] Zohri M., Prabowo, Suwarno, Fudholi A., Suyono T., Priandana E. R., Utomo Y. S. Performance Review of Solar-Assisted Heat Pump Systems Using Solar Collectors, PV, and PVT Technologies. Heat and Technology, vol. 41(3), 2023, pp 657-665. DOI: 10.18280/ijht.410318
[10] Bandaru S. H., Becerra V., Khanna S., Radulovic J., Hutchinson D., Khusainov R. A review of photovoltaic thermal (PVT) technology for residential applications: Performance indicators, progress, and opportunities. Energies (Basel), vol. 14(13), 2021, article 3853. DOI: 10.3390/en14133853
[11] Azad A. K., Parvin S. Photovoltaic thermal (PV/T) performance analysis for different flow regimes: A comparative numerical study. International Journal of Thermofluids, vol. 18, 2023, article 100319. DOI: 10.1016/j.ijft.2023.100319
[12] Alshibil A. M. A., Farkas I., Vig P. Multi-aspect approach of electrical and thermal performance evaluation for hybrid photovoltaic/thermal solar collector using TRNSYS tool. International Journal of Thermofluids, vol. 16, 2022, article 100222. DOI: 10.1016/j.ijft.2022.100222
[13] Fudholi A., Farhana Mohd Razali N., Ridwan A., Yendra R., Hartono H., Pani Desvina A., Khan Bin Majahar Ali M., Sopian K. Overview of photovoltaic thermal (PVT) water collector.

International Journal of Power Electronics and Drive Systems, vol. 9(4), 2018, pp 1891-1898. DOI: 10.11591/ijpeds.v9.i4.pp1891-1898
[14] Amori K. E., Abd-AlRaheem M. A. Field study of various air based photovoltaic/thermal hybrid solar collectors. Renewable Energy, vol. 63, 2014, pp 402-414. DOI: 10.1016/j.renene.2013.09.047
[15] Kim S.-M., Kim J.-H., Kim J.-T. Experimental study on the thermal and electrical characteristics of an air-based photovoltaic thermal collector. Energies (Basel), vol. 12(14), 2019, article 2661. DOI: 10.3390/en12142661
[16] Joshi S. S., Dhoble A. S. Photovoltaic -Thermal systems (PVT): Technology review and future trends. Renewable and Sustainable Energy Reviews, vol 92, 2018, pp 848-882. DOI: 10.1016/j.rser.2018.04.067