Bulletin of Electrical Engineering and Informatics
Vol. 13, No. 3, June 2024, pp. 1475~1482
ISSN: 2302-9285, DOI: 10.11591/eei.v13i3.6823

Experimental investigation of a hybrid photovoltaic-thermal energy system for hot air production

Ayong Hiendro[1], Fitriah Husin[2], Muhammad Taufiqurrahman[1], Abqori Aula[2]
[1]Department of Mechanical Engineering, Faculty of Engineering, Tanjungpura University, Pontianak, Indonesia
[2]Department of Electrical Engineering, Tanjungpura University, Pontianak, Indonesia

Article Info

Article history:

Received May 29, 2023
Revised Jul 24, 2023
Accepted Sep 28, 2023

Keywords:

Hybrid energy system
Photovoltaic-thermal
Real-time monitoring
Solar air heater
Solar collector

ABSTRACT

Solar energy as a non-fossil alternative energy source has become the best choice to overcome the problem of energy demand in most countries in the world. There are two different techniques to convert solar energy: photovoltaic (PV) panels to produce electricity and thermal collectors to generate heat. The two technologies can be combined to provide electrical and thermal energy either simultaneously or separately. In order to optimize the performance of a hybrid photovoltaic-thermal (PVT) solar air heater, it is necessary to collect experimental data on solar irradiation and temperature. This paper emphasized the development of a PVT energy system for hot air production in a temperature range of 50-55 °C. Additionally, experiments were constructed to monitor the information acquired from the proposed PVT solar air heater and the environment, such as hot air temperature, ambient temperature, and solar irradiation. The real-time monitoring system was set for five sample days. A microcontroller unit was used to control the hot air temperature and save the measurement data into memory. The experimental results showed that the proposed PVT solar air heater is capable of maintaining a certain level of hot air temperature throughout the day and night.

Corresponding Author:

Ayong Hiendro
Department of Mechanical Engineering, Faculty of Engineering, Tanjungpura University
Jalan Prof. Dr. H. Hadari Nawawi, Pontianak 78124, West Kalimantan, Indonesia
Email: ayong.hiendro@ee.untan.ac.id

1. INTRODUCTION

Environmental issues related to the consumption of non-renewable energy resources have attracted more and more attention. On the other hand, increasing global interest in sustainable energy production is inevitable. For this reason, various renewable energy resources are explored and exploited as a substitute for fossil energy [1], [2]. Solar energy is a clean, accessible, limitless, and sustainable energy source that can be utilized to provide electrical and thermal energy [3]. Solar photovoltaic (PV) industries have expanded rapidly to reduce energy costs and increase the mass production of solar PV panels to cut prices. Subsequently, crystalline silicon PV cells become mature technologies, and PV industries are starting to modify PV cells into half-cut cells to improve the efficiency of PV panels. The PV panels can be installed as rooftop, ground-mounted, or floating structures [4] to generate electricity. Solar collectors or solar thermal panels are another way to use solar energy. The collectors absorb heat from solar radiation to heat up water or air. A solar thermal collector (STC) is commonly used for heating water applications for homes, hotels, hospitals, swimming pools, and dairy plants. Besides, the STC is also used to produce hot air for building space heating [5], [6] and process applications such as drying food, fruits, and agricultural products [7].

Combining solar PV and STC as an integrated system will optimize the benefits of solar energy [8]-[10]. Solar PV energy conversion efficiency is about 10% to 20% [11], and most of the solar energy is released into the environment as heat [12]. Various studies [13]-[18] have reported that the efficiency of converting solar energy to thermal is higher than photovoltaic energy conversion. Thus, solar energy utilization is maximized when the solar PV is hybridized with an STC into a hybrid photovoltaic-thermal system (PVT). Consequently, the PVT increases the overall efficiency by converting solar energy into electricity [19], heat, or both electricity and heat [20].

Solar PV can create electricity and heat using an efficient electric heater. The advantage of solar PV is that it generates electricity during the day and stores electricity in batteries. The STC has limitations in that it only works during the day and does not store heat for later use. Moreover, the STC does not function well on cloudy, rainy, or foggy days. Therefore, the hybridization of solar PV and STC can continuously produce electrical energy and heat during the day and night [21], [22].

Many investigations have been carried out on developing PVT systems for air heating and their application as dryers. Solar PV and STC integration can be designed simultaneously or separately to generate hot air. Hussain *et al.* [23] developed a PVT system combined with a hexagonal honeycomb heat exchanger to enhance thermal efficiency. Çiftçi *et al.* [24] designed a vertical structure and fins over the absorber plate for a PVT dryer to increase the thermal efficiency value. In another study, Gürbüz *et al.* [25] utilized natural dolomite powder for thermal energy storage to improve the thermal and electrical efficiencies of a PVT system. Hadisaputra *et al.* [26] analyzed the effect of channel dimensions of a PVT with ∇-groove collector on thermal and electrical efficiencies. Lamrani *et al.* [27], [28] investigated a PVT hot air collector system applied to the wood drying industry to reduce drying time [27] and energy consumption [28] in summer and winter. Ceylan *et al.* [29] developed a PVT system for generating hot air to provide high energy efficiency during cold winter climates. In different study, Tuncer *et al.* [30], [31] developed a foldable PVT collector [30] and used a grooved absorber, spherical turbulators, and planar baffles to modify a PVT solar dryer [31]. Experimental results showed that the thermal efficiencies of the PVT collector and the drying chamber increased significantly. Another experimental investigation of a PVT system for indoor and outdoor operations to evaluate the exergy and exergy efficiency was reported by Bahtiar *et al.* [32].

It is obvious that most of the investigations reported are about energy and exergy efficiencies of PVT systems. Even though the air temperature is a vital parameter in PVT solar air heaters, very few experimental investigations have reported about hybrid PVT solar air heating systems operating day and night with specifically controlled temperatures. The hot air temperature must be kept reliably and constant during the day and night for air heating applications. Moreover, a well-designed PVT energy system is essential to reduce the incidence of unexpected failures in the hybrid PVT solar air heater and therefore reduce operating and maintenance costs. This study aimed to propose a novel PVT energy system for hot air production that could operate continuously during both day and night hours. The proposed PVT energy system consisted of a solar thermal collector and a photovoltaic panel, which run separately but synergized with each other to produce hot air continuously. In addition, a hot air temperature controlling mechanism was introduced in the configuration to maintain the temperature level. Finally, experimental investigations were conducted to monitor the information obtained from the hybrid PVT solar air heater and the environment to ensure the proposed configuration worked as expected.

2. METHOD

This study employed a hybrid PVT system to preheat the fresh air required for drying in a hot air chamber. An operating and monitoring mechanism was built to ensure the PVT air heater system worked appropriately to produce hot air within the temperature of 50-55 °C. Ambient temperature, solar irradiation, and air temperature in the hot air chamber were recorded and analyzed for five sample days of operation.

2.1. Photovoltaic-thermal solar air heater

The proposed PVT solar air heater combines two different technologies. One technology provides electricity, and the other operates to generate heat. Both are designed to heat fresh air and deliver hot air to the hot air chamber, as seen in Figure 1. A PV panel is used to directly generate electricity and produce hot air by means of an electric hot air heater/blower. The PV system includes an inverter/controller to manage the charge and discharge process and a battery to store electrical energy for later use. Charging and storing electrical energy to the battery lasts throughout the day as long as the PV panels are capable of producing electrical energy.

Batteries play a significant role in serving the PVT solar air heater system when electrical and heat energy production decreases in cloudy weather or at night hours. In this study, a 470 Wp monocrystalline half-cut PV panel was used to generate electricity, while a 200 Ah battery was utilized to store electricity and discharge the electricity whenever needed. The half-cut PV panel has the advantages of having high shade tolerance, minimizing hot spot temperatures, increasing power efficiency, and having good performance in low light conditions. The specifications of PV panel and battery are provided in Tables 1 and 2, respectively.

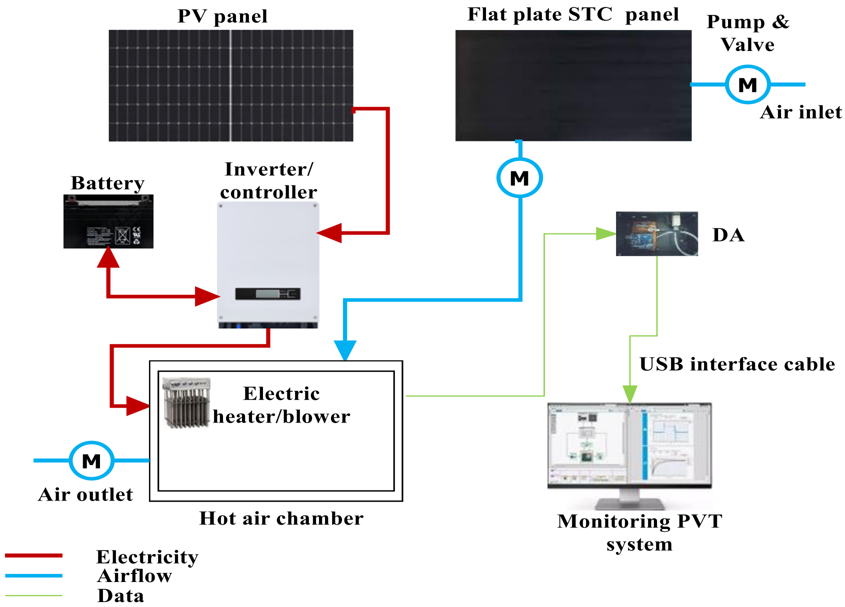

Figure 1. PVT solar air heater system

Table 1. Specifications of PV panel

Specification	Value
Maximum power	470 W
Maximum power voltage	34.51 V
Maximum power current	13.64 A
Open-circuit voltage	41.58 V
Short-circuit current	14.37 A

Table 2. Specifications of battery

Specification	Value
Nominal voltage	12 V
Nominal capacity	200 Ah
Max discharge current	2400 A

According to Farahat *et al*. [33], flat plate solar collectors are suitable for use in low and medium temperature (<100 °C) PVT applications. In this study, a flat-plate STC used as a solar thermal device consists of: i) transparent glass cover, ii) solar radiation absorber, iii) solar radiation reflector, iv) glass wool thermal insulation, v) frame, vi) fresh air inlet valve, vii) fresh air inlet pump, viii) air temperature sensor, ix) air pressure sensor, x) air temperature sensor cable, xi) air pressure sensor cable, xii) clamps, xiii) air circulating space, xiv) fresh air input, xv) hot air output, xvi) hot air outlet valve, and xvii) hot air outlet pump, as shown in Figure 2. The flat-plate STC and hot air chamber were manufactured in this work to generate hot air.

The flat-plate STC together with the electric hot air heater/blower powered by electricity from the PV system, are designed to generate hot air for a hot air chamber. The air temperature in the hot air chamber is maintained in the range of 50-55 °C. The flat-plate STC operates to heat the fresh air on sunny days, while the electric heater/blower generates hot air on cloudy days and at night hours. Combining these two elements can be used to produce hot air for 24 hours every day. In the hybrid PVT solar air heater, the battery supports hot air generation at night. The electricity from the PV panel is stored in the battery during the day and is ready for use after sunset. Thermal energy to increase air temperature in the PVT system is absorbed from solar radiation, electric heater, or both. The thermal energy produced by the flat-plate STC is dependent on the energy absorbed from solar radiation (E_{sun}). A certain amount of energy will become the heat loss (E_{loss}) due to the conductive, convective, and radiative heat transfer losses. The thermal energy generated from the STC can be expressed by:

$$E_T = E_{sun} - E_{loss} \quad (1)$$

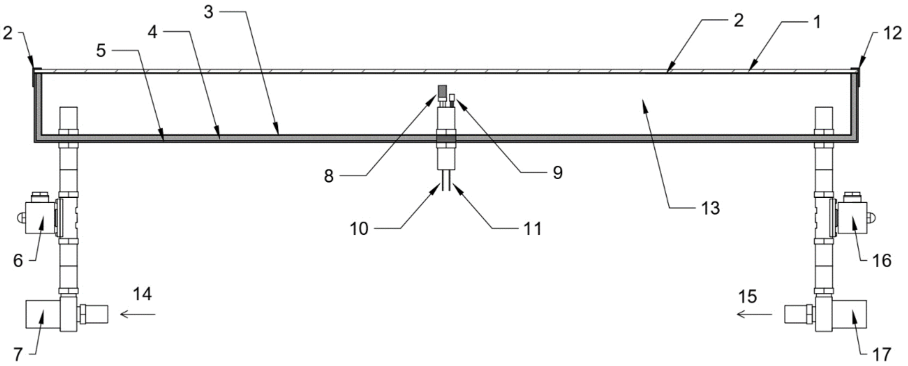

Figure 2. A flat-plate solar thermal collector

Energy from solar radiation are the multiplication of global solar irradiation (G), transmissivity (τ), and absorptivity (α), as (2):

$$E_{sun} = G.\tau.\alpha \quad (2)$$

Separately, electrical energy obtained from the PV panel is used to power the electric heater. The electrical energy generated by the PV panels is:

$$E_E = V_{oc}.I_{sc}.FF \quad (3)$$

where V_{oc}, I_{sc}, and FF are the open-circuit voltage, the short-circuit current, and the fill factor of the PV panel, respectively.
Finally, the overall thermal energy absorbed by hot air in the PVT system is specified as (4) [34]:

$$E_{PVT} = m.C_{p,air}.\Delta T_{air} \quad (4)$$

where m, $C_{p,\,air}$, and ΔT_{air} are the mass flow rate of air in the PVT system, the specific heat capacity of the air, and the hot air temperature difference, respectively.

2.2. Experimental setup

The experiment was carried out in July 2022 in Pontianak City of Indonesia. The best tilt angle to place a PVT collector must be adequately set to get maximum solar radiation. Benkaddour *et al.* [35] found the best tilt angle in the daytime when the PVT collector was set at 35° for the site of Tetouan (Morocco). For solar energy technologies deployed in Pontianak, the PVT air heating system orientation angle is set to 1.69° facing due north to maximize its exposure to the sun [36]. A microcontroller is placed close to the STC panel, and the information acquired is stored on a secure digital (SD) card. A monitoring system is designed to provide information through a data acquisition (DA) module. The DA module gives information on the ambient temperature (T_A), solar irradiation (G), and air temperature in a hot air chamber (T_C). The flow of hot air temperature is controlled by pumps and valves. A pyranometer is installed to monitor solar irradiation. The data acquisition system consists of a microcontroller, a battery, a SD card module, a real-time clock (RTC), and sensors. Figure 3 shows a block diagram of the DA module. The SD card module is used to store T_A, G, and T_C data acquired from sensors, while the RTC device performs real-time monitoring. The microcontroller unit detects the timer every second and records the measurement data in memory. The microcontroller also regulates an electronic switch to operate pumps and valves. The inlet pump and valve control fresh air flow from the environment into the STC panel. The heated air is then delivered to the hot air chamber utilizing the outlet pump and valve. In order to maintain the hot air temperature (T_C), the operation of the electric heater/blower is controlled by the DA module. The heater/blower is operated when the T_C is less than 50 °C and will be turned off when the T_C is more than 55 °C.

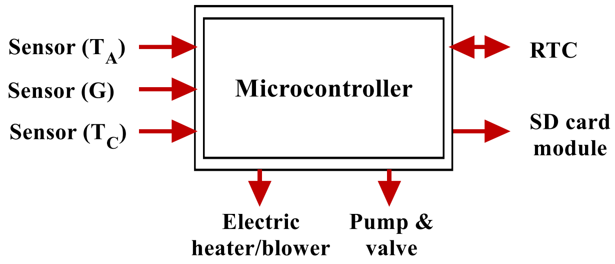

Figure 3. Configuration of the DA module

3. RESULTS AND DISCUSSION

The experiment is conducted to acquire information and any system errors during operations. In this section, all measurements are used to determine the performance of the PVT system in generating hot air. Figure 4 presents the solar irradiation during five sample days. The daylight is about 12 hours from 05.30 to 17.30. The average peak solar irradiation is 1.028 kW/m^2, and the STC panel achieves less solar irradiation at near sunset time. Figure 5 shows the ambient temperature for five days of PVT operations. The ambient temperatures vary from 25.4-33.1 °C. Evaluation of measurement data showed that the temperature pattern followed the pattern of solar irradiation, and this was similar to the study performed by Obi *et al.* [37].

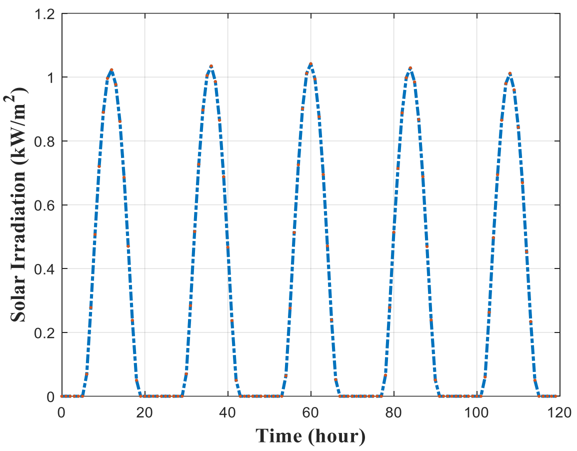

Figure 4. Hourly average solar irradiation

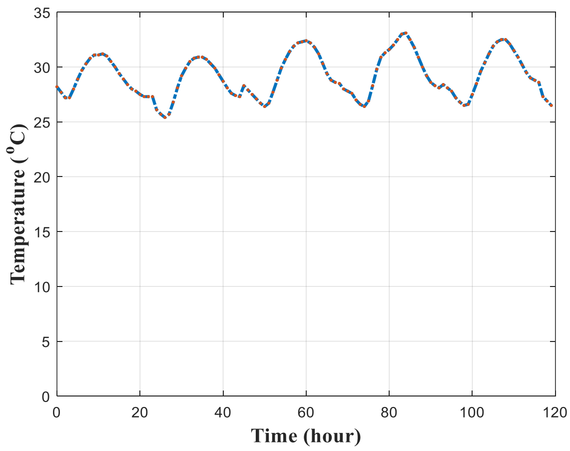

Figure 5. Hourly average ambient temperature

The heat energy produced by the STC panel depends on the environmental conditions. Variations in environmental conditions change the temperature value of hot air in the PVT solar air heater system. Solar thermal energy increases the temperature of the air flowing from the STC panels into the hot air chamber. The measured hot air temperature achieved 54.5 °C at 11.00. However, the hot air temperature could exceed the ambient temperature by 30 °C or more in full-sun conditions. Further investigation found that at the full-sun, when the ambient temperature was 38.7 °C, the temperature of the air flowing in the hot air chamber was 66.5 °C. Conversely, the air temperature dropped to the ambient temperature after sunset and at night. Regarding performance, the proposed PVT configuration is competitive with PVT air heaters developed in other study by Tuncer *et al.* [34] and Aste *et al.* [38]. In their study, Tuncer *et al.* [34] found that the PVT air heater had the capability to generate 40 °C hot air at the full-sun with an ambient temperature of 33.8 °C in the Muğla Province of Turkey weather conditions, while Aste *et al.* [38] found that the hot air produced by the PVT air heater reached more than 40 °C in the warm season at the Politecnico di Milano.

This study aimed to maintain the hot air temperature values ranging from 50-55 °C. The microcontroller in DA module operates to control pumps and valves if the hot air temperature exceeds 55 °C at full-sun conditions. Meanwhile, the microcontroller module must turn on the electric heater/blower to produce heat and raise the air temperature to 50 °C after sunset. The mechanism for producing hot air temperature in the proposed PVT solar air heater works as follows: i) heat is transferred from the STC panel into the hot air generator; when the hot air temperature is in the range of 50-55 °C, then the synergy between the STC panel and the hot air generator goes well, ii) if the air temperature exceeds 55 °C then the hot air valve from the STC panel is stopped until the air temperature decreases within a predetermined range (50-55 °C), iii) if the hot air temperature drops below 50 °C and the STC panel is unable to provide enough heat, the electric heater element is switched on to raise the air temperature to the specified range (50-55 °C), and iv) the electric heater element is stopped when the hot air temperature reaches ≥50 °C. As results, this mechanism successfully maintains the hot air temperature between 50-55 °C, as shown in Figure 6.

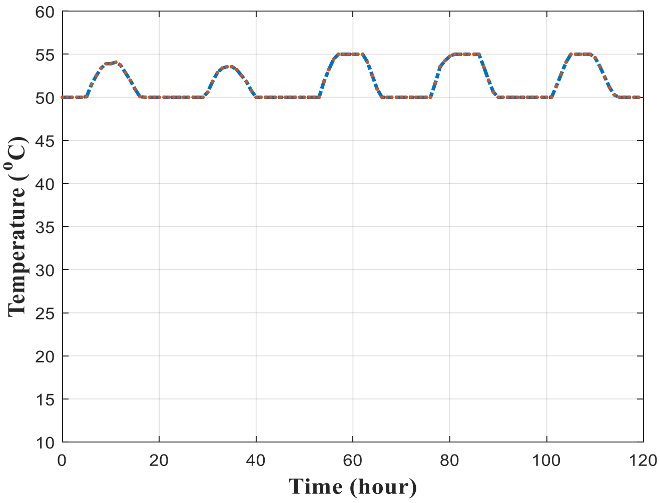

Figure 6. Hourly average hot air temperature

4. CONCLUSION

A hybrid PVT system has been developed using two leading technologies to produce heat separately. In this configuration, solar thermal collectors and photovoltaic panels can operate simultaneously and synergize to generate hot air at a specific temperature range if the hybrid PVT system is managed with an appropriate mechanism. The proposed PVT system was designed, manufactured, and tested under real environmental conditions. Experimental investigations were carried out to provide overall knowledge about PVT operations in producing hot air, including the control equipment, to ensure plant safety and proper operation. Information on hot air temperature, ambient temperature, and solar irradiation was acquired by utilizing sensors to provide real-time data. Hence, the users were able to analyze the hot air production. Experimental results showed that the proposed PVT solar air heater system was capable of producing hot air up to 66.5 °C at full-sun conditions. The hot air temperatures were less than 30 °C at night hours. The study demonstrated that with proper operations with the aid of sensors, electronic switches, pumps/valves, and electric heaters/blowers, the PVT system could be maintained to generate hot air within the range of 50 °C to 55 °C continuously. The advantage of the proposed hybrid PVT configuration is that it is able to create hot air for 24 hours throughout the day and night. Therefore, future studies can apply the proposed PVT air heater system to feed the agricultural product drying machine and evaluate the drying performance.

ACKNOWLEDGEMENTS

We gratefully acknowledge the funding from the Ministry of Education, Culture, Research, and Technology Indonesia through the National Competitive Research under research grant no. 147/E5 /PG.02.00.PT/2022 and no. 064/E5 /PG.02.00.PL/2023.

REFERENCES

[1] A. A. Ananno, M. H. Masud, P. Dabnichki, and A. Ahmed, “Design and numerical analysis of a hybrid geothermal PCM flat plate solar collector dryer for developing countries,” *Sol. Energy*, vol. 196, pp. 270-286, 2020, doi: 10.1016/j.solener.2019.11.069.
[2] Z. Dong, L. Bingyang, Z. Qintong, and L. Jinping, “Thermal performance and energy characteristic analysis of multiple renewable energy complementary heat pump system,” *Sol. Energy*, vol. 196, pp. 287-294, 2020, doi: 10.1016/j.solener.2019.12.030.
[3] M. J. Molaei, “The optical properties and solar energy conversion applications of carbon quantum dots: A review,” *Sol. Energy*, vol. 196, pp. 549-566, 2020, doi: 10.1016/j.solener.2019.12.036.
[4] K. Saadaoui, K. S. Rhazi, Y. Mejdoub, and A. Aboudou, “An analysis of the prospects and efficiency of floating and overland

photovoltaic systems," *Int. J. Appl. Power Eng.*, vol. 12, no. 2, pp. 144-152, 2023, doi: 10.11591/ijape.v12.i2.pp144-152.
[5] A. Fudholi, M. Zohri, I. Taslim, M. A. Indrianti, and I. N. Manyoe, "Theoretical approach model of building integrated photovoltaic thermal air collector," *Int. J. Power Electron. Drive Syst.*, vol. 11, no. 2, pp. 1002-1010, 2020, doi: 10.11591/ijpeds.v11.i2.pp1002-1010.
[6] X. Bu, K. Jiang, and Z. Guo, "Storing high temperature solar thermal energy in shallow depth artificial reservoir for space heating," *Sci. Rep.*, vol. 12, p. 19549, 2022, doi: 10.1038/s41598-022-24003-0.
[7] L. Kumar, J. Ahmed, M. El H. Assad, and M. Hasanuzzaman, "Prospects and challenges of solar thermal for process heating: A comprehensive review," *Energies*, vol. 15, no. 22, p. 8501, 2022, doi: 10.3390/en15228501.
[8] Y. Jia, G. Alva, and G. Fang, "Development and applications of photovoltaic-thermal systems: A review," *Renew. Sustain. Energy Rev.*, vol. 102, pp. 249-265, 2019, doi: 10.1016/jrser.2028.12.030.
[9] J. Wang, H. Chen, H. Deng, and F. Dong, "A combined power and steam system integrated with solar photovoltaic/thermal collector: Thermodynamic characteristics and cost-benefit analyses," *Case Stud. Therm. Eng.*, vol. 39, p. 102477, 2022, doi: 10.1016/j.csite.2022.102477.
[10] G. Guerrero and A. Ramos, "Techno-economic assessment of solar technologies to meet hospitals energy needs," *Int. J. Appl. Power Eng.*, vol. 12, no. 2, pp. 162-178, 2023, doi: 10.11591/ijape.v12.i2.pp162-178.
[11] B. Durakovic, G. Yıldız, and M. E. Yahia, "Comparative performance evaluation of conventional and renewable thermal insulation materials used in building envelops," *Tech. Gaz.*, vol. 27, pp. 283-289, 2020, doi: 10.17559/TV-20171228212943.
[12] A. Hereza, H. E. Hage, T. Lemenand, M. Ramadan, and M. Khaled, "Review on photovoltaic/thermal hybrid solar collectors: Classifications, applications and new systems," *Sol. Energy*, vol. 207, pp. 1321-1347, 2020, doi: 10.1016/j.solener,2020.07.062.
[13] S. C. Solanki, S. Dubey, and A. Tiwari, "Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors," *Appl. Energy*, vol. 86, pp. 2421-2428, 2009, doi: 10.1016/j.apenergy.2009.03.013.
[14] S. M. Bambrook and A. B. Sproul, "Maximising the energy output of a PVT air system," *Sol. Energy*, vol. 86, pp. 1857-1871, 2012, doi: 10.1016/j.solener.2012.02.038.
[15] A. Kazemian, M. Hosseinzadeh, and M. Sardarabadi, "Effect of glass cover and working fluid on the performance of photovoltaic thermal (PVT) system: An experimental study," *Sol. Energy*, vol. 173, pp. 1002-1010, 2018, doi: 10.1016/j.solener.2018.07.051.
[16] W. Fan, G. Kokogiannakis, and Z. Ma, "A multi-objective design optimisation strategy for hybrid photovoltaic thermal collector (PVT)-solar air heater (SAH) systems with fins," *Sol. Energy*, vol. 163, pp. 315-328, 2018, doi: 10.1016/j.solener.2018.02.014.
[17] T. Maatallah, R. Zachariah, and F. G. Al-Amri, "Exergo-economic analysis of a serpentine flow type water based photovoltaic thermal system with phase change material (PVT-PCM/water)," *Sol. Energy*, vol. 193, pp. 195–204, 2019, doi: 10.1016/j.solener.2019.09.063.
[18] S. Senthilraja, R. Gangadevi, R. Marimuthu, and M. Baskaran, "Performance evaluation of water and air based PVT solar collector for hydrogen production application," *Int. J. Hydrogen Energy*, vol. 45, pp. 7498-7507, 2020, doi: 10.1016/j.ijhydene.2019.02.223.
[19] I. Etier, S. Nijmeh, M. Shdiefat, and O. Al-Obaidy, "Experimentally evaluating electrical outputs of a PV-T system in Jordan," *Int. J. Power Electron. Drive Syst.*, vol. 12, no. 1, pp. 421-430, 2021, doi: 10.11591/ijpeds.v12.i1.pp421-430.
[20] M. Fuentes, M. Vivar, J. de la Casa, and J. Aguilera, "An experimental comparison between commercial hybrid PV-T and simple PV systems intended for BIPV," *Renew. Sust. Energ. Rev.*, vol. 93, pp. 110-120, 2018, doi: 10.1016/j.rser.2018.05.021.
[21] S. Tiwari and G. N. Tiwari, "Exergoeconomic analysis of photovoltaic-thermal (PVT) mixed mode greenhouse solar dryer," *Energy*, vol. 114, pp. 155–164, 2016, doi: 10.1016/j.energy.2016.07.132.
[22] Rashmi, A. Tiwari, G. N. Tiwari, and T. S. Bhatti, "Performance evaluation of a semitransparent photovoltaic thermal (SPVT) inverted absorber flat plate collector (IAFPC) for constant collection temperature (CCT) mode," *Sol. Energy*, vol. 186, pp. 382–391, 2019, doi: 10.1016/j.solener.2019.05.022.
[23] F. Hussain *et al.*, "An improved design of photovoltaic/thermal solar collector," *Sol. Energy*, vol. 122, pp. 885-891, 2015, doi: 10.1016/j.solener.2015.10.008.
[24] E. Çiftçi, A. Khanlari, A. Sözen, İ. Aytaç, and A. D. Tuncer, "Energy and exergy analysis of a photovoltaic thermal (PVT) system used in solar dryer: A numerical and experimental investigation," *Renew. Energy*, vol. 180, pp. 410-423, 2021, doi: 10.1016/j.renene.2021.08.081.
[25] E. Y. Gürbüz, B. Kusun, A. D. Tuncer, and T. Ural, "Experimental investigation of a double-flow photovoltaic/thermal air collector with natural dolomite powder-embedded thermal energy storage unit," *J. Energy Storage*, vol. 64, p. 107220, 2023, doi: 10.1016/j.est.2023.107220.
[26] S. Hadisaputra1, M. Zohri, Bahtiar, and A. Fudholi, "Effect analysis of the different channel length and depth of photovoltaic thermal system with ∇-groove collector," *International Journal of Electrical and Computer Engineering*, vol. 10, no. 2, pp. 1200-1207, 2020, doi: 10.11591/ijece.v10i2.pp1200-1207.
[27] B. Lamrani, A. Draoui, and F. Kuznik, "Thermal performance and environmental assessment of a hybrid solar-electrical wood dryer integrated with photovoltaic/thermal air collector and heat recovery system," *Sol. Energy*, vol. 221, pp. 60-74, 2021, doi: 10.1016/j.solener.2021.04.035.
[28] B. Lamrani, F. Kuznik, A. Ajbar, and M. Boumaza, "Energy analysis and economic feasibility of wood dryers integrated with heat recovery unit and solar air heaters in cold and hot climates," *Energy*, vol. 228, p. 120598, 2021, doi: 10.1016/j.energy.2021.120598.
[29] I. Ceylan, A. E. Gürel, A. Ergün, I. G. H. Ali, U. Ağbulut, and G. Yıldız, "A detailed analysis of CPV/T solar air heater system with thermal energy storage: A novel winter season application," *J. Build. Eng.*, vol. 42, p.103097, 2021, doi: 10.1016/j.jobe.2021.103097.
[30] A. D. Tuncer, A. Khanlari, and A. Sözen, "Seasonal energy-exergy analysis of a new foldable photovoltaic-thermal air collector: An experimental and numerical study," *Heat Transf. Res.*, vol. 53, no. 14, pp. 25-53, 2022, doi: 10.1615/HeatTransRes.2022042394.
[31] A. D. Tuncer *et al.*, "Experimental and numerical analysis of a grooved hybrid photovoltaic-thermal solar drying system," *Appl. Therm. Eng.*, vol. 218, p. 119288, 2023, doi: 10.1016/j.applthermaleng.2022.119288.
[32] Bahtiar, M. Zohri, and A. Fudholi, "Experimental investigation of photovoltaic thermal solar air collector with exergy performance comparison," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 19, no. 2, pp. 652-658, 2020, doi: 10.11591/ijeecs.v19.i2.pp652-658.
[33] S. Farahat, F. Sarhaddi, and H. Ajam, "Exergetic optimization of flat plate solar collectors," *Renew. Energy*, vol. 34, no. 4, pp. 1169-1174, 2009, doi: 10.1016/j.renene.2008.06.014.
[34] A. D. Tuncer, E. Y. Gürbüz, A. Keçebaş, and A. G. Georgiev, "Experimental evaluation of a photovoltaic/thermal air heater with metal mesh-integrated thermal energy storage system," *Energies*, vol. 16, no. 8, p. 3449, 2023, doi: 10.3390/en16083449.
[35] A. Benkaddour, H. Boulaich, and E. Aroudam, "Solar photovoltaic/thermal air collector with mirrors for optimal tilts,"

International Journal of Electrical and Computer Engineering, vol. 12, no. 3, pp. 2273-2284, 2022, doi: 10.11591/ijece.v12i3.pp2273-2284.
[36] R. Kurnianto, A. Hiendro, and M. I. Yusuf, "Optimum orientation angles for photovoltaic arrays to maximize energy gain at near equator location in Indonesia," *Int. Rev. Autom. Control*, vol. 10, no. 1, pp. 86-91, 2017, doi: 10.15866/ireaco.v10i1.11017.
[37] A. Obi, O. Iloeje, C. Anyaoha, and O. Ojike, "Development of a twenty-two-point multichannel temperature data logger specially customized and coupled to a 160Wpeak hybrid photovoltaic/thermal (PV/T) flat plate solar air heater," *Eng. Proc.*, vol. 2, no. 1, p. 48, 2020, doi: 10.3390/ecsa-7-08276.
[38] N. Aste, G. Chiesa, and F. Verri, "Design, development and performance monitoring of a photovoltaic-thermal (PVT) air collector," *Renew. Energy*, vol. 33, no. 8, pp. 914-927, 2008, doi: 10.1016/j.renene.2007.06.022.

BIOGRAPHIES OF AUTHORS

Ayong Hiendro is currently an associate professor at the Department of Electrical Engineering and served as the head of the Department of Mechanical Engineering, Tanjungpura University. He received his M.Eng. degree in electric power engineering from Bandung Institute of Technology, Indonesia, in 2000. He is a member of the Institution of Engineers Indonesia (PII) and the Indonesian Electrical Power Society (MKI). His research interests include renewable energy, power quality, power electronics, and metaheuristic optimization algorithm. He can be contacted at email: ayong.hiendro@ee.untan.ac.id.

Fitriah Husin received the B.Eng. and M.Eng. degrees in electrical engineering from Tanjungpura University, Pontianak, Indonesia, in 2009 and 2011, respectively. She is a lecturer at the Department of Electrical Engineering, Tanjungpura University, Indonesia. Her research interests involve renewable energy, computation, and energy management and planning. She can be contacted at email: fitriah@ee.untan.ac.id.

Muhammad Taufiqurrahman received his B.Eng. degree in electrical engineering from Tanjungpura University, Pontianak, Indonesia, in 2005 and his M.Eng. degree in mechanical engineering from Universitas Brawijaya, Indonesia, in 2011. He is a lecturer at the Department of Mechanical Engineering, Tanjungpura University. His research interests include mechatronics, materials testing, and energy. He can be contacted at email: m.taufiqurrahman@untan.ac.id.

Abqori Aula received his B.Eng. degree in electrical engineering from Universitas Al-Azhar Indonesia in 2007 and his M.Eng. degree in mechatronic engineering from International Islamic University, Malaysia, in 2015. He is a lecturer at the Department of Electrical Engineering, Tanjungpura University. His research interests include linear and nonlinear control theory, innovative and applied electronics, and mechatronics system. He can be contacted at email: abqoriaula@ee.untan.ac.id.