Research Article

Performance and economic analysis of a reversed circular flow jet impingement bifacial PVT solar collector

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Abstract. As the world shifts towards a more sustainable future, solar energy has emerged as a preeminent and economically feasible alternative to traditional energy sources, gaining widespread adoption. This study presents a reversed circular flow jet impingement (RCFJI) which aims to improve the performance of a bifacial PVT collector. An indoor experiment using a solar simulator to assess the energy, exergy, and economic efficiency of a RCFJI bifacial PVT collector. The study was carried out using a solar irradiance ranging from 500-900W/m^2 and a mass flow rate between 0.01-0.14 kg/s. Energy performance-wise, the highest photovoltaic efficiency achieved was 11.38% at solar irradiance of 500 W/m^2, while the highest thermal efficiency achieved was 61.4% under 900 W/m^2, both obtained at 0.14 kg/s mass flow rate. Regarding exergy performance, the highest photovoltaic exergy obtained was 47.27 W under 900 W/m^2 at 0.14 kg/s, while the highest thermal exergy was 9.67 W at 900 W/m^2 at 0.01 kg/s. Overall, higher solar irradiance is more desirable for energy and exergy performance. Meanwhile, economic point of view, lower solar irradiance is preferable. Based on the findings, the optimal mass flow rate was 0.06 kg/s.

Keywords: Jet impingement, Photovoltaic thermal (PVT), Heat transfer, Energy analysis, Exergy analysis

1. Introduction

As the world undergoes development and changes, the demand for sustainable and renewable energy continues to surge with each passing day (Esmer, 2022). Solar energy has become a subject of interest owing to its expeditiously advancing technology and robust capacity to satisfy the escalating energy demand of the developing world (Javed, 2022). The demand for sustainable and renewable energy has exhibited a consistent upward trend and is anticipated to sustain its growth trajectory (Alsaqoor *et al.*, 2023; Lee *et al.,* 2023; Wattana *et al.,* 2022). As the IEA reported, solar technologies are projected to experience significant growth over the coming years (Guno *et al.*, 2021). This upsurge is expected to account for over 60% increase globally, leading to a transformation in the production and consumption of electricity (Bisengimana *et al.,* 2023). Solar energy technologies offer an anticipated lifespan of 20 to 30 years (Ibrahim *et al.,* 2011). In the contemporary world, solar energy has established itself as one of the most prominent forms of energy and is an extensively adopted source of renewable energy (Kingsley-amaehule *et al.,* 2022). Being abundant and conveniently accessible, solar energy emerges as an optimal choice for renewable energy, presenting an unprecedented opportunity for sustainable energy generation *(Adu-Kankam et al.,* 2022). In contrast to conventional energy sources, solar energy represents an environmentally friendly and viable form of energy, marking a significant shift towards a cleaner and more sustainable energy future (Faizal *et al.,* 2013). Strategically

integrating clean energy sources, maximizing energy performance, and improving electrical consumption practise can results in a 94% reduction in greenhouse gas emissions (Rahmat *et al.,* 2022).

Solar photovoltaic thermal, commonly referred to as PVT, is a leading-edge technology at the forefront of rapidly growing solar energy technologies. Replacing the absorber plate with a photovoltaic cell, solar PVT operates similarly to thermal collectors (Ahmed *et al.*, 2020; Bassam *et al.,* 2023). By integrating photovoltaic cells and thermal collectors, this innovative technology effectively harnesses the sun's abundant energy, producing electricity and thermal energy (Sopian *et al.,* 2000). The capability to produce both electrical and thermal energy has rendered it a burgeoning technology in the realm of solar applications (Madas *et al.,* 2023; Touti *et al.,* 2023; Vengadesan *et al.,* 2020). Usually, the efficacy of solar energy conversion into thermal energy is significantly greater in comparison to electrical energy (Hussein *et al.,* 2023). Due to its unique dual functionality, PVT technology stands out as a compelling alternative to conventional solar PV and thermal technologies, offering a significant advantage in efficiency, cost-effectiveness, and space utilization (Caruso *et al.,* 2018). In this study, a reversed circular flow jet impingement (RCFJI) was introduced to enhance the efficiency of a bifacial PVT collector. A solar simulator was utilized to assess the energy analysis as well as the exergy and techno-economics analysis. The experiment was conducted with varying solar irradiance between 500-900W/m^2 and a mass flow rate of 0.01-0.14kg/s.

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2. Literature Review

Solar photovoltaic (PVT) can be classified into two distinct categories: solar photovoltaic, which involves the conversion of solar energy into electricity, and solar thermal, which generates thermal energy by absorbing heat from the sun (Dwivedi *et al.,* 2020). The integration of these two systems is referred to as hybrid photovoltaic thermal (Cabral *et al.,* 2018; Mustapha *et al.,* 2020). PVT solar collectors have emerged as a highly efficient and sustainable solution for energy generation (Li *et al.,* 2022). The principal advantage of these systems lies in their ability to decrease dependence on non-renewable energy sources (Zarei *et al.,* 2020). Researchers have directed their attention toward renewable energy sources to generate power owing to the increasing need for energy which led to the exploration of solar technologies such as PVT solar collectors (Cabral, 2022).

There are two distinct classifications of PVT collectors: air-based and water-based. The utilization of air-based is a common practice in PVT solar collectors due to its simplicity and reduced likelihood of leakage-related complications (Yadav *et al.*, 2020). Air-based PVT collectors can be passively or actively cooled. This study uses an air-based bifacial PVT solar collector using active cooling from an air compressor to distribute high-speed air through the PVT collector. In addition, air-based PVT collector operates with minimal commotion and no emissions (Jha *et al.*, 2020). Air-based PVT collectors are often less weight than water-based collectors (Ooshaksaraei, 2015).

In PVT technologies, the photovoltaic module plays a vital role in the electrical performance of the collector. On the other hand, a bifacial module allows the module to harvest the sun from the front and rear sides of the module (Ooshaksaraei *et al.,* 2017). The initial bifacial module was invented in 1980 (Luque *et al.,* 1980; Obraztsova *et al.,* 2022). A highly reflecting material is placed below the modules to redirect the sunlight onto the bifacial module's rear side. As a result, the module could absorb as much sunlight as possible. However, when heat accumulation elevates alongside sunlight absorbed, the bifacial module's electrical performance decreases (Jang *et al.,* 2021). Since both sides of the bifacial module must be subjected to sunlight, cooling alternatives for such modules are limited. Jet impingement, a highly effective cooling approach, is one of the suitable cooling alternatives for bifacial modules (Mohammadpour *et al.,* 2022).

In 1991, the initial jet impingement for PVT solar collectors was invented (Choudhury *et al.,* 1991; Singh *et al.,* 2020). The initial approach of the jet impingement involves the utilization of a jet plate to enhance the efficiency of the PVT solar collector. The findings indicated an efficiency performance enhancement of about 19-26.5%. The heat transfer enhancement of a jet impingement has been the focus of intensive study (Wai *et al.,* 2022). This study presents a reversed circular flow jet impingement (RCFJI) to cool off a bifacial PVT solar collector. The jet impingement technique improves heat transfer in the bifacial PVT solar collector. This technique utilizes arrays of high-velocity jets intended to strike or impinge the bifacial module. Air is dispersed throughout the bifacial PVT solar collector using a jet plate with a spanwise of 0.126m and streamwise 0.113m.

The utilization of solar energy has demonstrated significant potential as a viable technology (Panchal *et al.,* 2020). Numerous research has demonstrated that implementing solar photovoltaic thermal may result in substantial energy reduction (Saini *et al.*, 2023). However, among the obstacles to implementing PVT technologies are the significant initial expenses and associated inadequate cost efficiency *(Adebayo et al.,* 2017; Lin *et al.,* 2019). Consequently, diverse techno-economic analyses have been carried out in prior solar energy research (Ellabban *et al.,* 2019). Techno-economics helps to visualize the feasibility and viability of the PVT collector (Elfeky *et al.,* 2023; Rahimi *et al.,* 2023). The techno-economics analysis comprehensively considers all expenses and benefits arising over the PVT collector's lifespan (Rebitzer *et al.,* 2004; Ren *et al.,* 2020). At the end of this study, a techno-economic analysis is performed to assess the economic viability of the RCFJI bifacial PVT collector. Numerous assessment methodologies have been employed for appraising the economic viability of a solar collector (Naveen *et al.,* 2023). It is recommended to formulate economic growth strategies that facilitate the transition towards renewable and sustainability (Ahmad *et al.,* 2022; Kaci *et al.,* 2023).

3. Experiment Setup

An indoor experiment was conducted at the SERI, Universiti Kebangsaan Malaysia, to analyze the performance of a reversed circular flow jet impingement (RCFJI) bifacial PVT solar collector in terms of energy, exergy, and economic performance. A solar simulator comprised of 32 halide lights with 500-watt capacity was used, as depicted in Fig. 1. 14 K-type thermocouples were tested by submerging the thermocouple probes in boiling water before being placed around the RCFJI bifacial PVT solar collector. The PVT collector's temperature was logged using thermocouples connected to an AT4824 data logger. The experiment procedure was executed according to the previous study cited in the ref (Moshery *et al.,* 2021; Ooshaksaraei *et al.,* 2017).

The RCFJI measured 40mm in diameter and 20mm in depth and was fixed to a jet plate and mounted 25mm below the bifacial module to cool down the bifacial module's temperature. Fig. 2 shows the RCFJI attached to a jet plate. The jet plate has 36 holes, each measuring 3mm in diameter. The spanwise and streamwise of the jet plate holes were 126mm and 113.34mm. A 6mm polyurethane hose was connected to the 3mm RCFJI inlet. Air from the compressor was distributed through the polyurethane hose and entered the 3mm RCFJI inlet. A circular airflow motion will be produced in the RCFJI cup before exiting the 3mm jet plate holes with high velocity causing impinging effects on the bifacial module. The circular flow motion and impinging effects help to cool down the bifacial module by increasing the heat transfer rate within the PVT solar collector.

The RCFJI bifacial PVT solar collector was tested under solar irradiance of 500-900W/m^2 and a mass flow rate from 0.01-0.14 kg/s. The experiment was conducted in force convection mode, using an air compressor to produce high-velocity air. The air velocity from the air compressor is adjusted
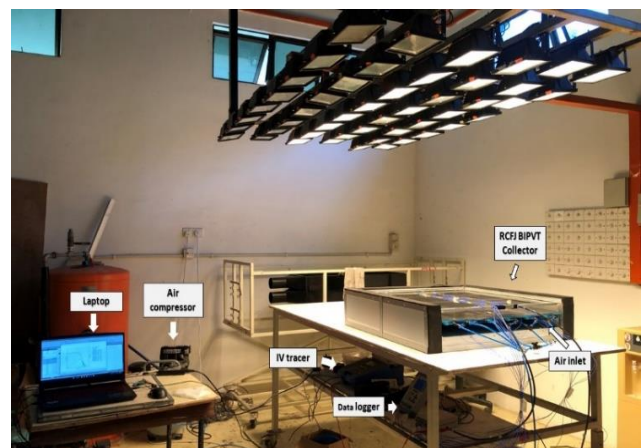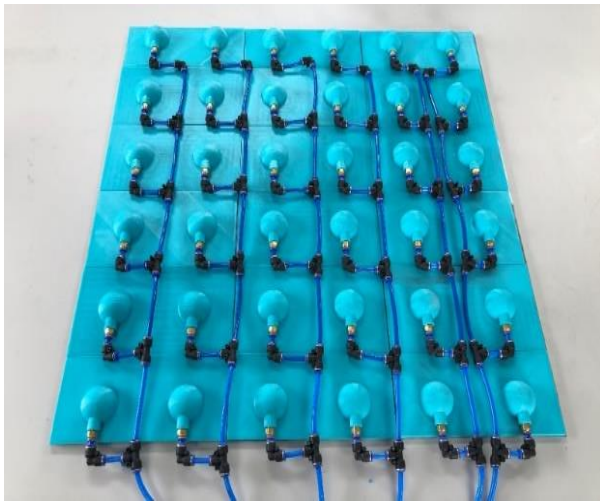

Fig. 1 Indoor experiment setup.

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Fig. 2 RCFJI mounted on a jet plate with a 6mm air hose inlet.

and measured using an anemometer based on the required mass flow rate. Meanwhile, the solar simulator was set and monitored using a pyranometer to achieve the desired solar irradiance. The data logger was set to record the temperature of the RCFJI bifacial PVT solar collector for every 1-second interval for 30 minutes. After approximately 25-30 minutes, the PVT collector reached a steady state condition where no temperature change had been noticed. An I-V tracer was employed to record the current and voltage reading of the PVT collector at the steady state condition. After obtaining the data, the PVT collector was cool down for two hours before taking a new data set with different parameters.

4. Energy Analysis

Energy analysis was performed on the reversed circular flow jet impingement (RCFJI) bifacial PVT solar collector to examine the photovoltaic and thermal efficiency of the bifacial PVT collector. Table 1 presents the parameters and values involved throughout the performance analysis in the study.

4.1. Reynolds Number

Determining airflow within the RCFJI bifacial PVT solar collector involves the utilization of the Reynolds Number, a fundamental parameter used to evaluate the flow characteristic. The Reynolds Number, Re, is expressed as (Fudholi *et al.,* 2019):

$$Reynolds\ number = \frac{\dot{m}Dh}{Wd\mu} \tag{1}$$

While the hydraulic diameter, *Dh,* is given by (Fudholi, Sopian, Othman, *et al.,* 2013):

$$Dh = \frac{4\,Wd}{2\,(W+d)} \tag{2}$$

And the air viscosity, μ, is given by (Fudholi, Sopian, Othman, *et al.,* 2013):

$$\mu = [1.983 + 0.00184\,(T-300)] \times 10^{-5} \tag{3}$$

4.2. Convective Heat Flux

The convective heat flux, *q0,* is expressed as:

$$qO = h.\,(T_{ext} - T_{PV}) \tag{4}$$

4.3. Photovoltaic Efficiency

The photovoltaic efficiency, $\eta_{Photovoltaic}$, is expressed as:

$$\eta_{Photovoltaic} = \frac{Pmax}{(I \times Ac)} \tag{5}$$

Where the peak rate power, *Pmax,* is computed using an I-V tracer and can be given as (Ewe *et al.,* 2022):

$$P_{max} = IA_c\alpha_{PV}P(\eta_{PVfront}) + IA_c\tau_i(1-P)n_r\alpha_{PV}P(\eta_{PVrear}) \tag{6}$$

And the efficiency of the cell is given by (Ewe *et al.,* 2022):

$$\eta_{pvfront} = \eta_{pvrear} = \eta_{ref}[1 - \beta\,(T_{pv} - T_{ref}) \tag{7}$$

4.4. Thermal Efficiency

The thermal efficiency, $\eta_{thermal}$, is expressed as (Ewe *et al.,* 2022):

$$\eta_{thermal} = \frac{Qu}{(I \times Ac)} \tag{8}$$

Where the useful heat gain, *Qu,* is given by:

$$Qu = \dot{m}C_p(T_o - T_i) \tag{9}$$

And the specific heat capacity of air, Cp, is defined as:

$$C_p = 1.0057 + 0.000066\,(T - 300) \tag{10}$$

5. Exergy Analysis

The exergy analysis of the RCFJI bifacial PVT collector was performed to evaluate its photovoltaic and thermal exergy efficiency. Exergy analysis emphasizes the importance of analyzing losses and internal irreversibility to achieve optimal performance.

5.1. Photovoltaic Exergy

The photovoltaic exergy, *ExPhotovoltaic*, is defined as (Ewe *et al.,* 2022):

$$Ex_{photovoltaic} = P_{max}\left[1 - \left(\frac{4}{3}\right)\left(\left(\frac{T_a}{T_s}\right) + \left(\frac{1}{3}\right)\left(\frac{T_a}{T_s}\right)^4\right)\right] \tag{11}$$

The sky temperature, T$_s$, is calculated using (Moshery *et al.,* 2021):

$$T_s = 0.0552\,(T_a^{1.5}) \tag{12}$$

5.2. Thermal Exergy

The thermal exergy, *Exthermal*, is defined as (Ewe *et al.,* 2022):

$$Ex_{thermal} = Qu \times \left(1 - \frac{T_a}{T_{out}}\right) \tag{13}$$

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Table 2
Parameters and values.

Parameter	Value
Mass flow rate, ṁ	0.1 – 0.14 kg/s
Width of collector, W	0684mm
Length of collector, L	705mm
Duct depth, d	25mm
Solar irradiance, I (W/m^2)	500, 600, 700, 800, 900
Area of collector, Ac	0.48m^2
Temperature ambient, Ta	30 °C
Absorptivity of PV cell, α_{pv}	0.91
Packing factor, P	0.66
Heat transfer coefficient, h	9 W/(m^2.K)
External temperature, T_{ext}	30 °C
The transmittance of Lamination, T_1	0.85
The reflectivity of the jet plate, n_R	0.7
Electrical efficiency at reference condition, n_{ref}	0.16
Temperature Coefficient, β	0.0045 K^{-1}
The temperature at reference condition, T_{ref}	303.15 K

6. Economic Analysis

The cost-benefit ratio, CBR, is a widely used profitability indicator in economic analysis. CBR determines the viability of cash flow generated by the reversed circular flow (RCFJI) bifacial PVT solar collector. To achieve high economic feasibility, the RCFJI bifacial PVT solar collector must generate the highest energy and exergy performance at the most cost-effective. Therefore, to calculate the CBR value, the annual cost (AC), annual energy gain (AEG), and annual exergy gain (AEXG) must be determined. The following equations are developed from previous studies (Ewe *et al.,* 2022; Fudholi, Sopian, Ruslan, *et al.,* 2013; Nazri *et al.,* 2018). Table 2 lists the data information involved in the economic analysis. The interest rate, *IR*, and the bifacial module lifespan, n, are assumed to be 5% and 20 years. Meanwhile, the electric cost is based on Tenaga Nasional Berhad, TNB, Malaysia domestic Tariff A, 2023.

6.1. Annual Cost

In order to evaluate the annual cost (AC), it is necessary to consider various parameters that may affect the system's overall economic viability, including the annual collector cost (ACC), maintenance cost (MC), annual pumping cost (APC) and annual salvage value (ASV). The annual cost of the RCFJI bifacial PVT solar collector is expressed as follows:

$$AC = ACC + MC + APC - ASV \tag{14}$$

Where the annual collector cost, *ACC*, is determined using:

$$ACC = CRF \ \times \ CI \tag{15}$$

And the capital recovery factor, *CRF*, is determined using:

Table 1
Relevant data of economic analysis.

Parameters	Estimated value
PVT collector material cost, PVTCM	RM450
Fabrication and labor cost, FLC	RM150
Support and structure cost, SSC	RM200
Electric cost, EC	RM0.21/kWh
Interest Rate, IR	5%
Bifacial module lifespan, n	20 years
Annual operating time, AO (days x hours)	365days x 8hrs

$$CRF = \frac{IR \times (IR+1)^n}{(IR+1)^n - 1} \tag{16}$$

IR denotes the interest rate, while the bifacial module lifespan (years) is denoted by *n*. The capital investment, *CI*, is determined using:

$$CI = PVTCM + FLC + SSC \tag{17}$$

Which PVTCM represents the PVT collector material cost, FLC represents the fabrication and labor cost, and SCC represents the support and structure cost. The RCFJI bifacial PVT solar collector maintenance cost, *MC*, is determined using:

$$MC = 10\% \ of \ ACC = 0.1 \ \times \ ACC \tag{18}$$

The annual pumping cost, *APC*, is determined using:

$$APC = P_m \ \times AO \ \times EC \tag{19}$$

Which P_m denotes the pumping power, annual operation time is denoted by *AO,* and EC denotes the electric cost. The annual salvage value, *ASV*, is determined using:

$$ASV = SFF \times SV \tag{20}$$

While the salvage fund factor, *SFF*, is defined as:

$$SFF = \frac{IR}{(IR+1)^n - 1} \tag{21}$$

And the salvage value, *SV*, is determined using:

$$SV = 10\% \ of \ CI = 0.1 \ \times \ CI \tag{22}$$

6.2. Annual Energy/Exergy gain

The annual energy gain evaluation encompasses the annual electrical energy gain (AEEG) and the annual thermal energy gain (ATEG). The annual energy gain (AEG) is expressed as:

$$AEG = \frac{ATEG + AEEG}{n_{powerplant}} \tag{23}$$

The efficiency of a powerplant, $n_{powerplant}$, is referred to as 0.38 (Ji *et al.,* 2007). While *AEEG* is determined using:

$$AEEG = \frac{(P_{max} \times AO)}{1000} \tag{24}$$

While the annual thermal energy gain, ATEG, is determined using:

$$ATEG = \frac{(Qu \ \times AO)}{1000} \tag{25}$$

6.3. Cost-Benefit Ratio

The cost-benefit ratio, *CBR*, is expressed as:

$$CBR = \frac{AC}{AEG} \tag{26}$$

7. Results and Discussion

7.1. Energy Analysis

Based on Fig. 3, it is evident that higher solar irradiance leads to a decrease in photovoltaic efficiency in the bifacial PVT collector because increased solar irradiance results in higher
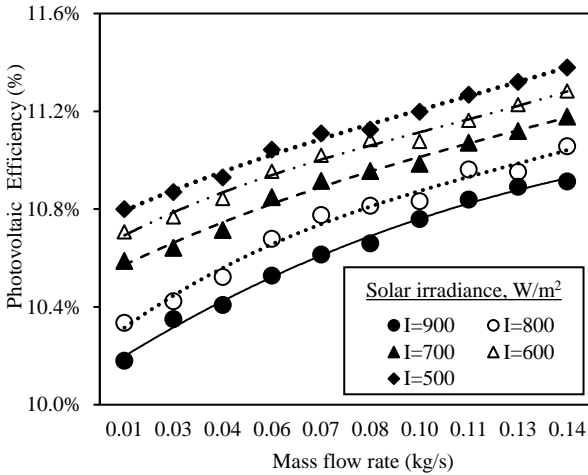
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Fig. 3 RCFJI bifacial PVT solar collector photovoltaic efficiency.

heat gain within the collector, which in turn affects the bifacial module performance. Excess heat can cause temperature rise and reduce photovoltaic conversion efficiency. Conversely, the photovoltaic efficiency improves with a higher mass flow rate in the bifacial PVT collector and is attributed to the cooling effects facilitated by the RCFJI. At the highest solar irradiance of 900 W/m^2, the photovoltaic efficiency ranges from 10.18-10.91%, while at the lowest solar irradiance of 500 W/m^2, the photovoltaic efficiency ranges between 10.80-11.38%. From the results, the highest photovoltaic efficiency recorded was 11.38% at 500 W/m^2 and a mass flow rate of 0.14 kg/s. Meanwhile, when operating at the highest solar irradiance of 900 W/m^2, the maximum photovoltaic efficiency achieved was 10.91% at 0.14 kg/s. When considering thermal efficiency, the data presented in Fig. 4 illustrates a notable improvement as the mass flow rate and solar irradiance increase. This observation implies that an increased mass flow rate significantly augments the airflow within the bifacial PVT collector, thereby leading to better thermal efficiency. Increasing the mass flow rate allows better airflow to pass through the collector, promoting effective heat transfer within the bifacial PVT collector. The maximum thermal efficiency achieved was 61.4% under solar irradiance of 900W/m² and 0.14kg/s mass flow rate. In addition, when tested with the lowest solar irradiance of 500 W/m^2, the maximum thermal efficiency achieved was 54.28% at 0.14 kg/s. Overall
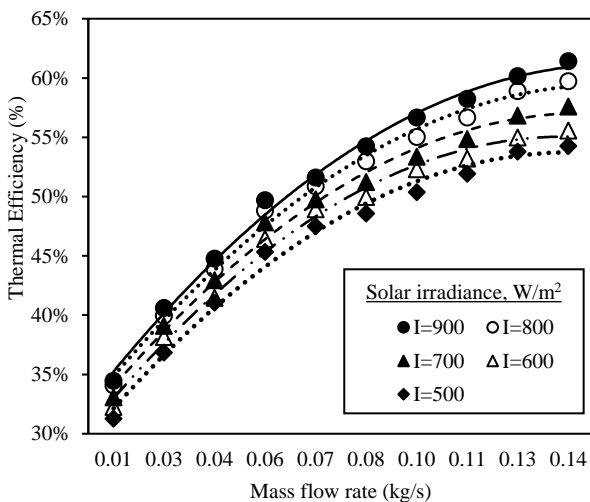
the lowest thermal efficiency obtained was 31.28% under 500W/m² with a 0.01kg/s mass flow rate.

7.2. Exergy Performance

In terms of exergy analysis, the highest photovoltaic exergy obtained was under 900W/m², while the lowest photovoltaic exergy obtained was under 500W/m², as illustrated in Fig. 5. Based on the observation, it is apparent that higher solar irradiance leads to an increase in the photovoltaic exergy in the realm of solar energy conversion. An increase in solar irradiance leads to an enhanced influx of solar irradiance onto the bifacial module, resulting in greater absorption of photons and subsequent conversion into electrical energy. Consequently, this leads to an increased exergy output of the photovoltaic systems. The highest photovoltaic exergy achieved was under 900W/m² and 0.14kg/s with a photovoltaic exergy of 47.27W, while the lowest was 28.10W under 500W/m² solar irradiance and 0.01kg/s mass flow rate. Overall, the photovoltaic exergy ranges from 24.88-27.18W for 500W/m², 29.45-32.34W for 600W/m², 33.89-37.40W for 700W/m², 38.20-42.38W for 800W/m² and 42.39-47.27W for 900W/m² solar irradiance. Notably, the photovoltaic exergy can be influenced by additional variables, such as the efficiency of the bifacial cells and the system's configurations.
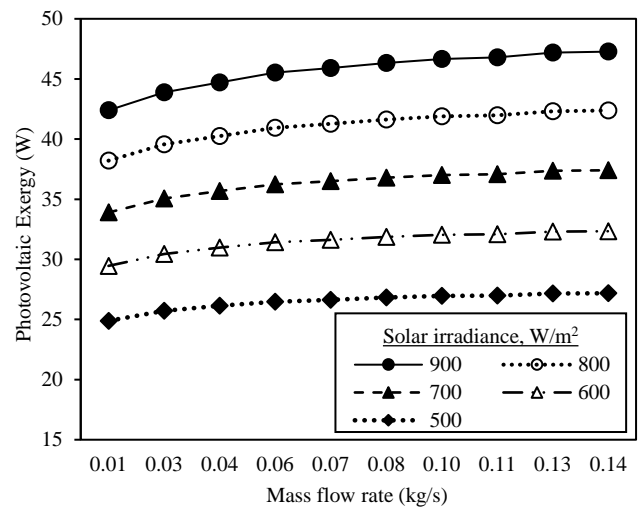

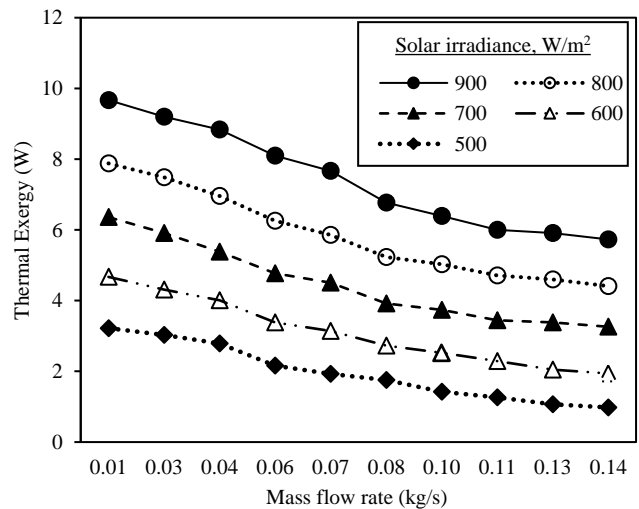**Fig. 5** RCFJI bifacial PVT solar collector photovoltaic exergy.

Fig. 4 RCFJI bifacial PVT solar collector thermal efficiency.

Fig. 6 RCFJI bifacial PVT solar collector thermal exergy.

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Meanwhile, the analysis reveals a downward trend in thermal exergy as the mass flow rate increases, as depicted in Fig. 6. The decrease in thermal exergy with a higher mass flow rate can be attributed to the increased airflow within the systems. As the mass flow rate rises, a higher air volume passes through the bifacial PVT collector, which leads to a decrease in the temperature of the bifacial PVT collector. The reduced temperature of the bifacial PVT collector leads to a decline in thermal exergy. On the other hand, it is observed that higher thermal exergy can be achieved when operating at higher solar irradiance. This is because higher solar irradiance implies a larger amount of heat input into the system. The highest thermal exergy obtained was 9.67 W at 900 W/m^2 and 0.01 kg/s, while the lowest thermal exergy achieved was under 500 W/m^2 and 0.14 kg/s with a thermal exergy of 4.6 W.

7.3. Economic Performance

The annual energy gain (AEG) of the RCFJI bifacial PVT solar collector is positively correlated with the solar irradiance levels, as higher solar irradiance results in increased photovoltaic and thermal energy production. Moreover, optimizing the airflow inside the bifacial PVT collector at an increased mass flow rate enhances the heat transfer efficiency, resulting in an improved rate of thermal energy exchange and ultimately leading to a higher AEG. Fig. 7 shows that higher AEG can be achieved with a higher solar irradiance. The AEG for the bifacial PVT solar collector under the highest solar irradiance of 900W/m^2 ranges from 1544.49-2465.70 kWh/year, while the AEG under the lowest solar irradiance of 500 W/m^2 ranges from 950.90-1479.76 kWh/year.

However, it was observed that the utilization of higher solar irradiance levels and mass flow rate resulted in a lower cost-benefit ratio (CBR), as shown in Fig. 8. This can be attributed to the fact that increased solar irradiance leads to greater heat accumulation within the bifacial modules, necessitating higher pumping costs for cooling and, thus, adversely affecting the energy performance. Therefore, in terms of achieving maximum energy performance and annual energy gain, prioritizing higher mass flow rates and solar irradiance is recommended, while from an economic standpoint, favoring lower values of both factors is preferable. The CBR value when operating at the highest solar irradiance of 900 W/m^2 ranges from 0.57-0.92 RM/m^2.kWh, whereas the CBR value when operating at the
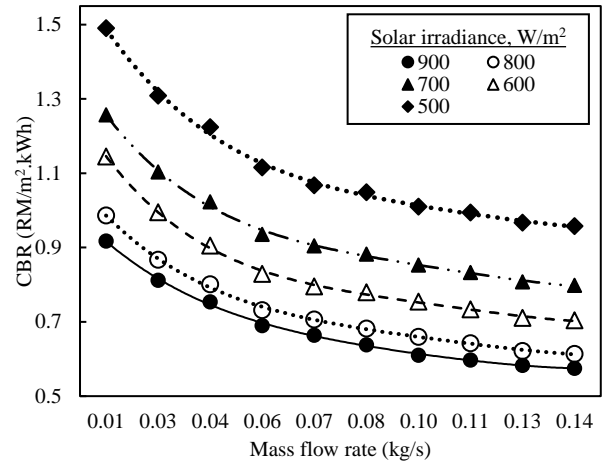

Fig. 7 RCFJI bifacial PVT solar collector energy CBR.

lowest solar irradiance of 500W/m^2 ranges from 0.96-1.49 RM/m^2.kWh.

Meanwhile, it was observed that the highest annual exergy gain (AEXG) was obtained under solar irradiance of 900W/m^2, whereas the lowest AEXG was obtained under solar irradiance of 500W/m^2. The results and findings in Fig. 9 are consistent with those in subsection 7.2 Exergy Analysis. Notably, the AEXG was optimal at a mass flow rate of 0.04-0.07 kg/s for all solar irradiance levels tested. The highest AEXG recorded was at a solar irradiance of 900 W/m^2 and a mass flow rate of 0.06kg/s, yielding a 412.03 kWh/year value. On the other hand, when operating under the lowest solar irradiance of 500W/m^2, the highest AEXG obtained was 222.32 kWh/year at a mass flow rate of 0.04 kg/s.

The exergy cost-benefit ratio (CBRX) for the RCFJI bifacial PVT solar collector is presented in Fig. 10. The maximum CBRX value achieved was under solar irradiance of 500 W/m^2, with a value of 6.56 RM/m^2.kWh at a mass flow rate of 0.01 kg/s. Conversely, operating under a solar irradiance of 900 W/m^2 yielded the lowest CBRX value compared to other solar irradiance levels tested with a maximum CBRX value of 3.54 RM/m^2.kWh at a mass flow rate of 0.01 kg/s.
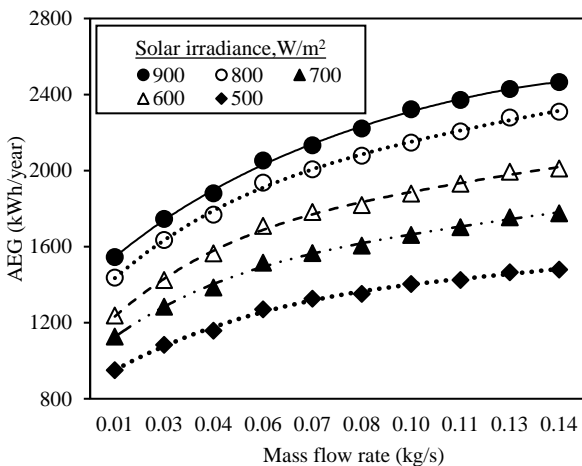

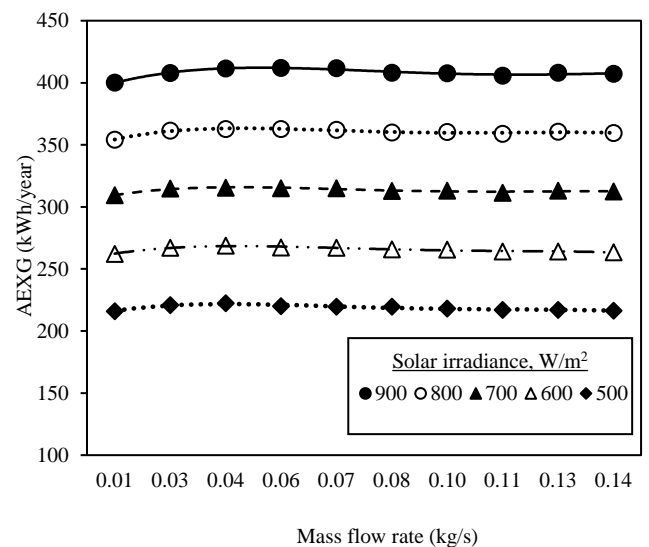**Fig. 8** RCFJI bifacial PVT solar collector AEG.

Fig. 9 RCFJI bifacial PVT solar collector AEXG.

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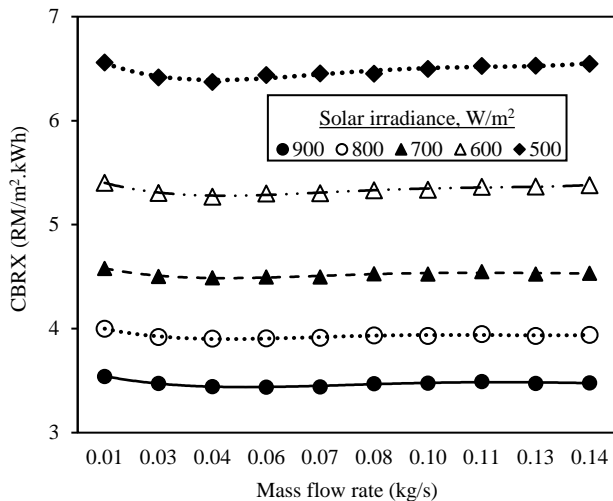
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Fig. 10 RCFJI bifacial PVT solar collector exergy CBRX.

8. Conclusion

In conclusion, the energy performance analysis revealed that the maximum photovoltaic efficiency was attained at 500W/m^2 with a mass flow rate of 0.14 kg/s, resulting in a photovoltaic efficiency of 11.38%. On the other hand, the highest thermal efficiency was observed at 900 W/m^2 and 0.14 kg/s, with a thermal efficiency of 61.4%. The RCFJI bifacial PVT solar collector exhibited an improved energy performance due to the high-velocity air and impinging effects on the bifacial PV module induced by the RCFJI. The swirling effect produced by the RCFJI further enhances the turbulent flow, effectively preventing the establishment of boundary layers and thereby improving the heat transfer rate.

A higher exergy performance is preferable as it requires less input energy to produce the same amount of output, indicating that more potential work is being extracted and converted into usable energy to achieve effective performance. In terms of exergy performance, the highest photovoltaic exergy was obtained at 0.14 kg/s mass flow rate and 900W/m^2 with a value of 47.27 W. On the other hand, the lowest photovoltaic exergy was achieved at 0.01 kg/s and 500 W/m^2, with a value of 28.10 W. Additionally, the highest thermal exergy was recorded at 0.01kg/s and 900 W/m^2, with a value of 9.67 W, while the lowest thermal exergy was observed at 0.14 kg/s and 500 W/m^2, with a value of 4.6 W. Based on the exergy performance, the optimal mass flow rate was 0.06 kg/s.

The highest AEG was observed under 900 W/m^2, which resulted in a range of 1544.49-2465.70 kWh/year, while the lowest AEG was achieved under 500 W/m^2 with a range of 950.90-1479.76 kWh/year. Additionally, operating at lower solar irradiance results in a higher CBR value. The highest CBR value was achieved under 500 W/m^2 with a CBR value ranging from 0.96-1.49 RM/m^2.kWh. On the other hand, the highest AEXG was observed under 900W/m^2 with an AEXG of 412.03 kWh/year at 0.06kg/s, while the lowest AEXG achieved was under 500 W/m^2 with 222.32 kWh/year. The highest CBRX value achieved was 6.56 RM/m^2.kWh at 500W/m^2 and a mass flow rate of 0.01kg/s. In summary, higher solar irradiance leads to higher AEG and AEXG, making it a more desirable option from an energy and exergy generation standpoint. However, when considering the economic performance, lower solar irradiance is preferred due to lower heat gain resulting in reduced pumping costs required for cooling the RCFJI bifacial PVT solar collector.

From an environmental perspective, various issues tend to be disregarded during PVT technologies' production, assembly, and operation. Mitigating these concerns necessitates implementing sustainable measures such as recycling and conscientious waste disposal. In addition, assessing present and future PVT technologies have great scaling potential and identify significant difficulties in real-world applications. Innovative ideas can solve urban problems, but industrial and commercial sectors require a tailored approach to meet the energy demand and overcome financial hurdles. Globally, PVT technologies can diversify energy sources and fight climate change.

References

Adebayo, V. & Koçyiğit, K. (2017). Techno-economic Analysis of an Off-grid Solar Photovoltaic Energy System for a Typical Rural Household in Adamawa State, Nigeria Techno-economic Analysis View project Techno-economic Analysis of an Off-grid Solar Photovoltaic Energy System for a Typical R., 1–14. https://www.researchgate.net/publication/319470224

Adu-Kankam, K. O., & Camarinha-matos, Luis. (2022). Delegating Autonomy on Digital Twins in Energy Ecosystems. *International Journal of Smart Grid*, 6(4). https://doi.org/10.20508/ijsmartgrid.v6i4.257.g253

Ahmad, M., & Zeeshan, M.. (2022). Multi-objective optimization of concentrated solar power plants from an energy-water-environment nexus perspective under distinct climatic conditions – Part A: Techno-economic analysis. *Journal of Cleaner Production*, 375, 134099. https://doi.org/10.1016/j.jclepro.2022.134099

Ahmed, Omer K., Daoud, Raid W., Bawa, Shaimaa M., & Ahmed, Ahmed H. (2020). Optimization of PV/T solar water collector based on fuzzy logic control. *International Journal of Renewable Energy Development*, 9(2), 303–310. https://doi.org/10.14710/ijred.9.2.303-310

Alsaqoor, S., Alqatamin, A., Alahmer, A., Nan, Z., Al-Husban, Y., & Jouhara, H.. (2023). The impact of phase change material on photovoltaic thermal (PVT) systems: A numerical stud. *International Journal of Thermofluids*, 18(April), 100365. https://doi.org/10.1016/j.ijft.2023.100365

Bassam, A. M., Sopian, K., Ibrahim, A., Fauzan, M. F., Al-Aasam, A. B., & Abusaibaa, G.Y. (2023). Experimental analysis for the photovoltaic thermal collector (PVT) with nano PCM and micro-fins tube nanofluid. *Case Studies in Thermal Engineering*, 41. https://doi.org/10.1016/j.csite.2022.102579

Bisengimana, E., Zhou, J. Binama, M., Nyiranzeyimana, G., & Yuan, Y.. (2023). Numerical investigation of PVT coverage on an integrated building-solar-heat pump system: Technical and economic study. *Solar Energy*, 249, 507–520. https://doi.org/10.1016/j.solener.2022.12.005

Cabral, D. (2022). Development and performance comparison of a modified glazed CPC hybrid solar collector coupled with a bifacial PVT receiver. *Applied Energy*, 325, 119653. https://doi.org/10.1016/j.apenergy.2022.119653

Cabral, D. & Karlsson, B.O. (2018). Electrical and thermal performance evaluation of symmetric truncated C-PVT trough solar collectors with vertical bifacial receivers. *Solar Energy*, 174(August), 683–690. https://doi.org/10.1016/j.solener.2018.09.045

Caruso, M., Miceli, R., Romano, P., Schettino, G., & Viola, F.. (2018). Technical and Economical Performances of Photovoltaic Generation Facades. *International Journal of Smart Grid*, 2(2).

M.A.A.B. Ishak et al   Int. J. Renew. Energy Dev 2023, 12(4), 780-788

|787

https://doi.org/10.20508/ijsmartgrid.v2i2.19.g19

Choudhury, C., & Garg, H. P. (1991). Evaluation of a jet plate solar air heater. *Solar Energy*, 46(4), 199–209. https://doi.org/10.1016/0038-092X(91)90064-4

Dwivedi, P., Sudhakar, K., Soni, A., & Solomin, E. (2020). Case Studies in Thermal Engineering Advanced cooling techniques of PV modules : A state of art. *Case Studies in Thermal Engineering*, 21, 100674. https://doi.org/10.1016/j.csite.2020.100674

Elfeky, K. E., & Wang, Q.. (2023). Techno-economic assessment and optimization of the performance of solar power tower plant in Egypt's climate conditions. *Energy Conversion and Management*, 280, 116829. https://doi.org/10.1016/j.enconman.2023.116829

Ellabban, O. & Alassi, A. (2019). Integrated Economic Adoption Model for residential grid-connected photovoltaic systems: An Australian case study. *Energy Reports*, 5, 310–326. https://doi.org/10.1016/j.egyr.2019.02.004

Esmer, S. (2022). Design of PMaSynRM for Flywheel Energy Storage System in Smart Grids. *International Journal of smart grid*. 6(4), 1–7. https://www.ijsmartgrid.org/index.php/ijsmartgridnew/article/view/255

Ewe, W. E., Fudholi, A., Sopian, K., Moshery, R., Asim, N., Nuriana, W. & Ibrahim, A. (2022). Thermo-electro-hydraulic analysis of jet impingement bifacial photovoltaic thermal (JIBPVT) solar air collector. *Energy*, 254, 124366. https://doi.org/10.1016/j.energy.2022.124366

Faizal, M., Saidur, R., Mekhilef, S., & Alim, M. A. (2013). Energy, economic and environmental analysis of metal oxides nanofluid for flat-plate solar collector. *Energy Conversion and Management*, 76, 162–168. https://doi.org/10.1016/j.enconman.2013.07.038

Fudholi, A., Sopian, K., Othman, M.Y., Ruslan, M. H., & Bakhtyar, B. (2013). Energy analysis and improvement potential of finned double-pass solar collector. *Energy Conversion and Management*, 75, 234–240. https://doi.org/10.1016/j.enconman.2013.06.021

Fudholi, A., Sopian, K., Ruslan, M.H., & Othman, M. Y. (2013). Performance and cost benefits analysis of double-pass solar collector with and without fins. *Energy Conversion and Management*, 76, 8–19. https://doi.org/10.1016/j.enconman.2013.07.015

Fudholi, A., Zohri, M., Rukman, N. S. Bt, Nazri, N., S., Mustapha, M., Yen, C., H., Mohammad, M., & Sopian, K.. (2019). Exergy and sustainability index of photovoltaic thermal (PVT) air collector: A theoretical and experimental study. *Renewable and Sustainable Energy Reviews*, 100, 44–51. https://doi.org/10.1016/j.rser.2018.10.019

Guno, C. S., Agaton, C.B., Villanueva, R. O. & Villanueva, R. O.. (2021). Optimal investment strategy for solar pv integration in residential buildings: A case study in the philippines. *International Journal of Renewable Energy Development*, 10(1), 79–89. https://doi.org/10.14710/ijred.2021.32657

Hussein, N. F., Ahmed, S.T., & Ekaid, A.L. (2023). Thermal Performance of Double Pass Solar Air Heater With Tubular Solar Absorber. *International Journal of Renewable Energy Development*, 12(1), 11–21. https://doi.org/10.14710/ijred.2023.46328

Jang, J., Pfreundt, A., Mittag, M. & Lee, K. (2021). Performance analysis of bifacial pv modules with transparent mesh backsheet. *Energies*, 14(5). https://doi.org/10.3390/en14051399

Javed, F. (2022). Impact of Temperature & Illumination for Improvement in Photovoltaic System Efficiency. *International Journal of Smart Grid*, 6(v6i1). https://doi.org/10.20508/ijsmartgrid.v6i1.222.g185

Jha, P., Mondol, J. D., Das, B., & Gupta, R. (2020). Energy metrics assessment of a photovoltaic thermal air collector (PVTAC): a comparison between flat and wavy collector. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 0(0), 1–19. https://doi.org/10.1080/15567036.2020.1809563

Ji, J., Lu, J.P., Chow, T.T., He, W., & Pei, G. (2007). A sensitivity study of a hybrid photovoltaic/thermal water-heating system with natural circulation. *Applied Energy*, 84(2), 222–237. https://doi.org/10.1016/j.apenergy.2006.04.009

Kaci, K., Merzouk, M., Merzouk, N.K., Missoum, M., Ganaoui, M. El., Behar, O., & Djedjigd, R.. (2023). Design, optimization and economic viability of an industrial low temperature hot water production system in Algeria: A case study. *International Journal of Renewable Energy Development*, 12(3), 448–458.

https://doi.org/10.14710/ijred.2023.49759

Kingsley-amaehule, M., Uhunmwangho, R., Nwazor, N. & Kenneth, E. (2022). Smart Intelligent Monitoring and Maintenance Management of Photo-voltaic Systems. *International Journal of Smart Grid*. 6(4). https://doi.org/10.20508/ijsmartgrid.v6i4.260.g246

Lee, J.W., Song, M.S., Jung, H.S., & Kang, Y.T. (2023). Development of solar radiation spectrum-controlled emulsion filter for a photovoltaic-thermal (PVT) system. *Energy Conversion and Management*, 287, 117087. https://doi.org/10.1016/j.enconman.2023.117087

Li, J., Zhang, W., Xie, L., Li, Z., Wu, X., Zhao, O., Zhong, J., & Zeng, X. (2022). A hybrid photovoltaic and water/air based thermal(PVT) solar energy collector with integrated PCM for building application. *Renewable Energy*, 199, 662–671. https://doi.org/10.1016/j.renene.2022.09.015

Lin, B., & Chen, Y. (2019). Does electricity price matter for innovation in renewable energy technologies in China ? *Energy Economics*, 78, 259–266. https://doi.org/10.1016/j.eneco.2018.11.014

Luque, A., Cuevas, A., & Ruiz, J. M. (1980). Double-sided n+-p-n+ solar cell for bifacial concentration. *Solar Cells*, 2(2), 151–166.https://doi.org/10.1016/0379-6787(80)90007-1

Madas, S. R., Narayanan, R., & Gudimetla, P. (2023). Numerical investigation on the optimum performance output of photovoltaic thermal (PVT) systems using nano-copper oxide (CuO) coolant. *Solar Energy*, 255, 222–235. https://doi.org/10.1016/j.solener.2023.02.035

Mohammadpour, J., Salehi, F., Sheikholeslami, M., & Lee, A. (2022). A computational study on nano fl uid impingement jets in thermal management of photovoltaic panel. *Renewable Energy*, 189, 970–982. https://doi.org/10.1016/j.renene.2022.03.069

Moshery, R., Chai, T.Y., Sopian, K., Fudholi, A., & Al-Waeli, A.H.A. (2021). Thermal performance of jet-impingement solar air heater with transverse ribs absorber plate. *Solar Energy*, 214, 355–366. https://doi.org/10.1016/j.solener.2020.11.059

Mustapha, M., Fudholi, A., & Sopian, K.. (2020). Mathematical modelling of bifacial photovoltaic-thermal (BPVT) collector with mirror reflector. *International Journal of Renewable Energy Research*, 10(2), 654–662. https://doi.org/10.20508/ijrer.v10i2.10603.g7936

Naveen, S., Aravind, S., Yamini, B., Vasudhareni, R., Gopinath, K. P., Arun, J., & Pugazhendhi, A. (2023). A review on solar energy intensified biomass valorization and value-added products production: Practicability, challenges, techno economic and lifecycle assessment. *Journal of Cleaner Production*, 405(April), 137028. https://doi.org/10.1016/j.jclepro.2023.137028

Nazri, N. S., Fudholi, A., Bakhtyar, B., Yen, C. H., Ibrahim, A., Ruslan, M.H., Mat, S., & Sopian, K. (2018). Energy economic analysis of photovoltaic-thermal-thermoelectric (PVT-TE) air collectors. *Renewable and Sustainable Energy Reviews*, 92, 187–197. https://doi.org/10.1016/j.rser.2018.04.061

Obraztsova, A. A., Barettin, D., Furasova, A. D., Voroshilov, P. M., Maur, M.A.D., Orsini, A., & Makarov, S. V. (2022). Light-Trapping Electrode for the Efficiency Enhancement of Bifacial Perovskite Solar Cells. *Nanomaterial,* 1–14. https://doi.org/10.3390/nano12183210

Ooshaksaraei, P. (2015). Evaluation Of Air-Based Photovoltaic Thermal Collectors With Bifacial Solar Cells. Thesis, Universiti Kebangsaan Malaysia.

Ooshaksaraei, P., Sopian, K., Zaidi, S. H., & Zulkifli, R. (2017). Performance of four air-based photovoltaic thermal collectors configurations with bifacial solar cells. *Renewable Energy*, 102, 279–293. https://doi.org/10.1016/j.renene.2016.10.043

Panchal, R., Gomes, J., Cabral, D., Eleyele, A., & Lança, M. (2020). Evaluation of symmetric C-PVT solar collector designs with vertical bifacial receivers. *Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry* 2019, 165–176. https://doi.org/10.18086/swc.2019.05.02

Rahimi, I., Nikoo, M. R., & Gandomi, A. H. (2023). Techno-economic analysis for using hybrid wind and solar energies in Australia. *Energy Strategy Reviews*, 47, 101092. https://doi.org/10.1016/j.esr.2023.101092

Rahmat, M. A. A., Abd Hamid, Ag. S., Lu, Y., Ishak, M. A. A., Suheel, S. Z., Fazlizan, A., & Ibrahim, A.. (2022). An Analysis of Renewable

M.A.A.B. Ishak et al   Int. J. Renew. Energy Dev 2023, 12(4), 780-788

|788

Energy Technology Integration Investments in Malaysia Using HOMER Pro. *Sustainability* (Switzerland), 14(20). https://doi.org/10.3390/su142013684

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W. P., Suh, S., Weidema, B. P., & Pennington, D. W. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, 30(5), 701–720. https://doi.org/10.1016/j.envint.2003.11.005

Ren, M., Mitchell, C. R., & Mo, W.. (2020). Dynamic life cycle economic and environmental assessment of residential solar photovoltaic systems. *Science of the Total Environment*, 722, 137932. https://doi.org/10.1016/j.scitotenv.2020.137932

Saini, P., Ghasemi, M., Arpagaus, C., Bless, F., Bertsch, S., & Zhang, X.. (2023). Techno-economic comparative analysis of solar thermal collectors and high-temperature heat pumps for industrial steam generation. *Energy Conversion and Management*, 27. https://doi.org/10.1016/j.enconman.2022.116623

Singh, P.K., Sahu, S.K., Upadhyay, P.K., & Jain, A.K. (2020). Experimental investigation on thermal characteristics of hot surface by synthetic jet impingement. *Applied Thermal Engineering*, 165, 114596. https://doi.org/10.1016/j.applthermaleng.2019.114596

Sopian, K., Liu, H. T., Kakac, S., & Veziroglu, T. N. (2000). Performance of a double pass photovoltaic thermal solar collector suitable for solar drying systems. *Energy Conversion and Management*, 41(4), 353–365. https://doi.org/10.1016/S0196-8904(99)00115-6

Touti, E., Masmali, M., Fterich, M., & Chouikhi, H.. (2023). Experimental and numerical study of the PVT design impact on the electrical and thermal performances. *Case Studies in Thermal Engineering*, 43, 102732. https://doi.org/10.1016/j.csite.2023.102732

Vengadesan, E., & Senthil, R. (2020). A review on recent developments in thermal performance enhancement methods of flat plate solar air collector. *Renewable and Sustainable Energy Reviews*, 134, 110315. https://doi.org/10.1016/j.rser.2020.110315

Wai, O. J., Gunnasegaran, P., & Hasini, H. (2022). Effect of Hybrid Nanofluids Concentration and Swirling Flow on Jet Impingement Cooling. *Nanomaterials,* 12(19), 3258; https://doi.org/10.3390/nano12193258

Wattana, B., & Aungyut, P.. (2022). Impacts of Solar Electricity Generation on the Thai Electricity Industry. *International Journal of Renewable Energy Development*, 11(1), 157–163. https://doi.org/10.14710/ijred.2022.41059

Yadav, S., & Saini, R. P. (2020). Numerical investigation on the performance of a solar air heater using jet impingement with absorber plate. *Solar Energy*, 208, 236–248. https://doi.org/10.1016/j.solener.2020.07.088

Zarei, A., Liravi, M., Babaie Rabiee, M., & Ghodrat, M.. (2020). A Novel, eco-friendly combined solar cooling and heating system, powered by hybrid Photovoltaic thermal (PVT) collector for domestic application. *Energy Conversion and Management*, 222, 113198. https://doi.org/10.1016/j.enconman.2020.113198