ANALYSIS OF ENERGY, EXERGY, ENVIRONMENTAL, AND ECONOMICS (4E) ON PHOTOVOLTAIC-THERMAL COLLECTOR SYSTEM

by

Jitendra SATPUTE and John RAJAN *

School of Mechanical engineering, Vellore Institute of Technology, Vellore, India

Original scientific paper
https://doi.org/10.2298/TSCI210905010S

In this paper, a novel thermal absorber based photovoltaic-thermal system is presented. The thermal absorber is attached at the rear surface of photovoltaic, and water is re-circulated to extract heat. The outdoor experimentations are performed at Pune, India (18.7611° N, 73.5572°) on clear sky day, and water temperatures, surface temperature, radiation and flow rate are measured to analyse techno-economical performance at different operating conditions. The surface temperature of the photovoltaic module plummeted from 54.65 °C to 47.9 °C with the incorporation of a thermal absorber with flipside water cooling at a ranging flow rate of 0.03 to 0.06 kg per seconds. The result shows an average enhancement of 4.2 % in the electrical power output of the photovoltaic-thermal system. The maximum thermal and electrical efficiencies were 47.82 % and 9.88 %, respectively, at 0.06 kg per seconds. The exergy efficiency was found in the range of 9.85-14.30%. Based on the experimental evaluation, uncertainty analysis was performed. The results revealed that the annual CO_2 mitigation for photovoltaic and photovoltaic-thermal system was 225.46 kg annual and 464.8 kg annual, while simple payback periods were 4.53 years 3.03 years, respectively. The analysis offers an efficient estimate of experimental features of photovoltaic and photovoltaic-thermal systems from an energy-exergy, environmental and cost-benefit standpoint.

Keywords*: solar energy, photovoltaic, water-cooling, co-generation;*

Introduction

The technological advancement and peak of mobilization resulted in an upsurge in the energy requirement of the world. The utmost energy requirements of industrial and social activities of the globe are mainly fulfilled through conventional sources of energy, but the deterrence caused by these conventional resources is unceasing. To accomplish the world's energy requirements, developing alternative energy sources on a large scale becomes essential. For the last decade, solar energy has dominated the renewable energy sector, providing cheaper energy solutions and reducing energy security [1]. The cumulative achievement in solar energy-based electricity generation is exponential and reached around 821 TWh at the end of 2020, accounting for 3.1% of global electricity production [2]. Solar energy is unlim-

*Corresponding author, e-mail: ajohnrajan@gmail.com

ited in capacity, spread out across a large area, has a remarkable capability and can be extracted using multiple media with zero emission. Solar energy is harnessed in the valuable form of heat or electricity based on the type of the collector. Generating electricity with PV modules is always preferred owing to a higher potential for domestic and industrial operations. However, voltage capacity declines at PV higher top exterior surface temperature, resulting in electrical power loss [3]. To counterpart these problems, cooling agents are preferred to reject this heat and maintain the PV module's surface temperature. Satpute *et al.* [4] studied various effective and collectively accepted cooling methods like air, water, PCM, nanofluid, refrigerant, a combination of two or more fluids, and their applications. The front side cooling and flipside cooling are two preferred arrangements to cool and maintain optimum PV temperature. The front side cooling, also known as spray cooling, allows cooling of PV by spraying coolant on the top of the PV surface. The spray-based cooling technology has the advantage of self-cleaning, which augments electrical performance, whereas flipside cooling generates dual power from a single source and possesses multiple applications.

In flipside cooling, the PV system is cooled to optimize electrical power and extracted heat gives thermal power. The generation of thermal and electrical from solar energy is known as photovoltaic-thermal (PVT) or hybrid technology. Das *et al.* [5] investigated the latest trend in the operating parameters, thermal absorber design, tilt angle, thermodynamics management, energy-exergy analysis and development of flat plate PVT system and found affordable. The importance of tilt angle and optimum operating condition to enhance heat transfer capacity was highlighted in [6]. The solar water heating two-phase closed thermosyphon heat pipe of different designs and inclination angles was tested in Samsun, Turkey. Numerous investigations were noted in the literature regarding solar system advancement and applications like solar heating, electricity generation, power generation, refrigeration, water desalination [7, 8]. The feasibility of the PVT system was investigated by Modrek and Alili [9] for the UAE developing transient simulation.

The quantity of heat extracted from the PV surface determines the electrical and thermal gain of the PVT system, hence, the thermal absorber and flow pattern needs to be considered during PVT system design. Su *et al.* [10] presented four different dual-channel cooling such as air-air, air-water, water-air and water-water in the PVT system. From the investigation, the water showed better heat transfer characteristics. Tarabsheh *et al.* [11] proposed a water pipe at the flipside of the PV module to analyse energy performance and presented the highest electrical efficiency of 13.48% at elevated module temperature. Dumrul *et al.* [12] demonstrated a flat surface receiver for a concentrated PVT collector and analyzed energy performance for nanofluids and refrigerants at varying flow rates. They observed that the water-propylene glycol blend obtained maximum electrical power of 268 W at 0.06 m^3 per hour while thermal efficiency from all fluids was about 22%. The energy analysis of the PVT system by proposing a mini channel tube thermal absorber to improve heat transfer from PV module in the summer season was demonstrated [13]. The study reported electrical and thermal efficiency of 11.5%, 46.8%, respectively. Recently, Selimli *et al.* [14] analyzed the Water-PVT system's 2E (energy-exergy) performance at Karabuk, Turkey. The numerical and experimental study was performed with copper coil and polyamide box thermal absorber and found water cooling doubled the yield than conventional PV. The study presented the highest exergy and overall energy efficiency of 11.53%, 59.88%, respectively, with polyamide box thermal absorber. Similarly, the 2E (energy-exergy) performance of air-cooled PVT was studied at Gazi University, Ankara, Turkey [15]. The numerical model of Cu finned PVT was developed, and the result was validated at a mass-flow rate of 0.031081 kg per secund and

0.04533 kg per secund. Furthermore, the study obtained maximum thermal, electrical, and exergy efficiency of 49.5%, 13.98%, and 16.15%, respectively, at a higher mass-flow rate of 0.04533 kg per secund.

Zuhu and Ceylan [16] experimentally investigated 3E (energy-exergy-environmental cost) performance for concentrated air-based PVT systems in the winter season. They observed thermal and electrical efficiency of 50% and 12%, respectively, while exergy efficiency was 11-12%. The CO_2 mitigation up to 0.6 kg per hour was observed with economic saving up to 1 ¢ per hour. Ozturk *et al*. [17] performed a 3E (Energy, Exergy, and Economic) study for PVT system assisted heat pump at Hakkari and Trabzon climatic condition of Turkey. The TRNSYS model was developed, and maximum energy and exergy efficiency of 68% and 22% were observed. It has been seen that Hakkari had a low annual energy consumption cost of 67.14$ due to cold climate while 135.75$ for Trabzon. Arslan and Aktas [18] have performed 4E (Energy-Exergy-Economic-Environmental) analysis for PVT systems intended for drying application at different airflow rates. The study obtained thermal, electrical and exergy efficiency of 43.75%, 13.49%, and 15.03%. The designed PVT system prevented 1.98 kg/hCO_2 emission from the atmosphere and calculated CO_2 cost of 2.86 ¢ per second.

In the past and current decade, studies have been attempted across the globe with amending thermal absorber material, shape, size, flow pattern, thermal fluid, inlet fluid temperature, slope angle to evaluate the energy-exergy-environmental/economic behaviour of the PVT system. It is noticed that further development in the geometrical shape of the absorber and fluid-flow pattern can enhance heat withdrawal and performance efficiency. The present work aims to demonstrate the 4E performance of an environment-friendly, cost-effective W-PVT system with novel thermal absorber intended for heat and electricity generation. The study aimed to estimate experimental features of designed W-PVT system and compare with a conventional PV system. In the present study, a spiral rectangular thermal absorber of low cost, non-corrosive, readily available, and lighter weight aluminium material is developed. Water is preferred as a heat transfer medium to estimate outdoor performance for Pune, Indian climatic conditions. The study was performed at four mass-flow rates (0.03-0.06 kg per second) and aimed to determined the relation between flow rates and energy-exergy-environmental and economic performance. In the environmental analysis, amount of CO_2 mitigation was calculated and profit made from carbon credit was estimated. The economic analysis aims to determine cost-benefit, annual worth (AW), and payback period of PV and W-PVT system to study economic viability and commercialization perspectives.

Materials and methods

The outdoor trials were performed on a clear day to ensure maximum radiation. During the testing period, observation of the surface temperature of PV and W-PVT system, water inlet-outlet temperature, solar radiation, wind speed, and flow rate were noted to accomplish performance assessment. The readings were taken in the day (10.30-15.30 hours) with 30 minutes intervals. The two PV modules, one with a spiral rectangular with a square section thermal absorber known as a W-PVT system and another without a thermal absorber, is a simple PV system of the exact specification tested simultaneously for real-time performance, figs. 1 and 2. The position and inclination angle was evaluated according to geographical location. The commercially available m-crystalline PV system has a rated capacity of 100 W, total aperture area 0.66 m × 0.55 m, open-circuit voltage, V_{oc}, of 21.77 V, and short circuit current, I_{sc}, of 6.14 A. The water was used for heat extraction and circulated through the W-PVT system thermal absorber that acts as a heat sink and condenses PV temperature. Many researchers preferred an air-fluid medium to extract the heat; however, [13] shows water has better heat transfer characteristics than air. The experimentations were carried out for the mass-flow rates of 0.03-0.06 kg per second. The water flow circulation adopted is the close type and is re-circulated through connecting pipes arrangement. The pyranometer is placed parallel to the experimental setup to record solar radiation. The *k*-type thermocouple was placed at various locations of the setup such as the surface of PV, W-PVT system, outlet and inlet of water, water tank and connected to temperature acquisition system for display and storage. A separate thermocouple was placed adjacent to the setup and exposed to the atmosphere to record the ambient temperature. During experimentation, an ambient temperature was varied between 29-33 °C while the wind was observed to vary within the range of 1-2 m/s. The rotameter was used to measure and adjust the desired water mass-flow rate and placed near the water tank. The voltage-current characteristics of PV and W-PVT systems were measured with a multimeter. All the measuring instruments were calibrated with reference standards, and their uncertainties found were listed in tab.1

Table 1. List of instruments functionality in the experimental set-up

Objective	Instrument	Brand	Uncertainty
Recirculation of water	Pump	Kirloskar-kir, Centrifugal 0.25 hp	±2%
Control, vary water flow rate	Rotameter	Aster, Model F-500	±1%
Cogeneration of heat electricity	W-PVT	Eastman solar, Model EPP100	±1 %
Measurement of voltage, current	Multimeter	Maxtech, Model DT- 603	±2%
Measurement of temperature	Thermocouple	Omega, K-type, IEC 584-3	±1 %
Generation of electricity	PV module	Eastman solar, Model EPP100	±1 %
Storage of water	Water tank	Local made, a 100-litre capacity	±2%
Measurement of Radiation	Pyranometer	Eko instruments, Model ML01	±2%

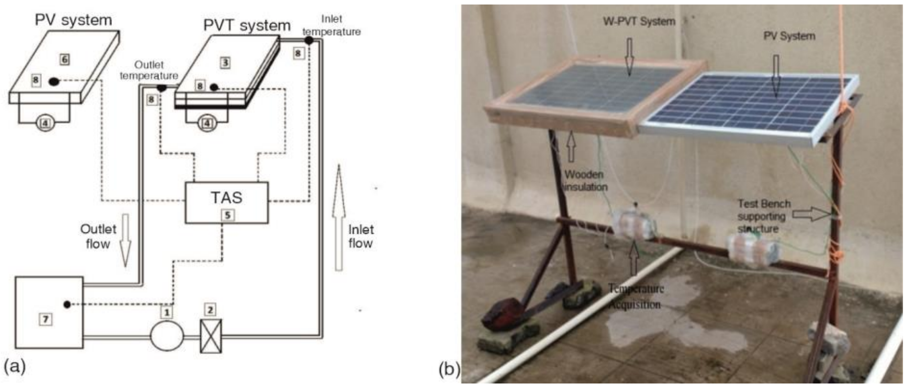

Figure 1. Schematic view of experimental work (a) and actual test rig (b);
1 – pump, 2 – flow control Valve, 3 – W-PVT system, 4 – multi-meter,5 – Temperature acquisition system, 6 – PV system, 7 – water Storage tank, and 8 – thermocouple

The thermal absorber of aluminium owning thermal conductivity of 229 W/mK was used and pasted to a flat sheet of the same material. In addition, the 0.01 m thick asbestos insulation was provided to conserve heat, and the W-PVT system was covered by plywood having 0.012 W/mK thermal conductivity from the bottom and side area. For the optimum thermal and electrical gain from the collector, the single glazed configuration was selected [19].

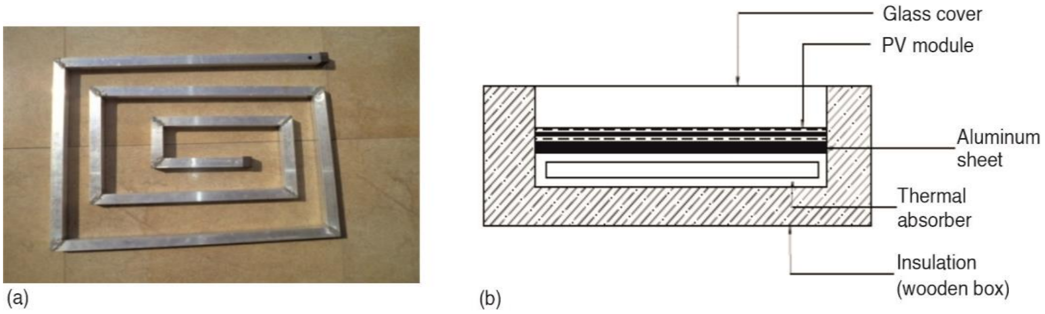

Figure 2. (a) Pictorial view of a spiral rectangular thermal absorber and (b) cross-section of W-PVT system

Energy analysis

The overall daily performance of W-PVT (η_{overall}) is the combined power output obtained through the solar system as a fraction of incident solar radiation for a given collector area and mathematically expressed as [18]:

$$\eta_{\text{overall}} = \eta_{\text{thermal}} + \eta_{\text{electrical}} \tag{1}$$

The rubrics of the PV solar system are to obtain electrical power through the PV effect. This useful electrical yield of the PV is the product of voltage and current output of the photovoltaic ($P_{\max}$ = IV) [18, 20]:

$$\eta_{\text{electrical}} = \frac{P_{\max}}{I_T A_c} \tag{2}$$

The fraction of solar energy collected is transformed into heat via absorber and collected in heated water form; this thermal performance, η_{thermal}, can be calculated as [18, 21]:

$$\eta_{\text{thermal}} = \frac{\dot{m} C_p \Delta T}{I_T A_C} \tag{3}$$

Exergy analysis

Exergy analysis is performed to estimate beneficial work potential and solar energy conversion performance from the newly developed W-PVT system. The exergy analyzes the exergy destruction indicators and maximum practical work obtained from the PV and PVT system as it is brought in equilibrium to the surrounding. The exergy balance eq. (15) is applied to the PVT system and expressed as:

$$\sum Ex_{\text{in}} - \sum Ex_{\text{out}} = \sum Ex_{\text{loss}} \tag{4}$$

where Ex_{out} is the exergy output from the energy system. In the case of a W-PVT system, simultaneous and separate cogeneration of thermal and electrical power is the desired yield and expressed as [15, 18]:

$$\sum Ex_{\text{out}} = \sum Ex_{\text{thermal}} + \sum Ex_{\text{electric}} \tag{5}$$

$$\sum Ex_{\text{in}} - \sum \left(Ex_{\text{thermal}} + Ex_{\text{electric}} \right) = \sum Ex_{\text{loss}} \tag{6}$$

The input exergy from for PVT system mainly include solar radiation received by the collector area and given by [15, 18]. The values of analytical and design parameters used in exergy analysis are enlisted in tab. 2:

$$Ex_{\text{in}} = AI_T\left[1-\frac{4}{3}\left(\frac{T_\text{a}}{T_\text{s}}\right)+\frac{1}{3}\left(\frac{T_\text{a}}{T_\text{s}}\right)^4\right] \tag{7}$$

$$Ex_{\text{thermal}} = Q_{u,\text{ex}}\left[1-\left(\frac{T_\text{a}+273}{T_\text{fo}+273}\right)\right] \tag{8}$$

$$Q_{u,\text{ex}} = \dot{m}C_p\left(T_\text{fo}-T_\text{fi}\right) \tag{9}$$

$$Ex_{\text{electric}} = \eta_\text{pv}N_c AI_T\left[1-\frac{4}{3}\left(\frac{T_\text{a}}{T_\text{s}}\right)+\frac{1}{3}\left(\frac{T_\text{a}}{T_\text{s}}\right)^4\right] \tag{10}$$

$$\eta_\text{pv} = \eta_\text{ref}\left[1-0.0045\left(T_\text{c}-T_\text{a}\right)\right] \tag{11}$$

where T_c is the PV cell temperature [22]:

$$T_\text{c} = \frac{P_\text{pf}I_g\left(\tau_g\alpha-\eta_\text{ref}\right)+\left(h_\text{convection}T_\text{a}\right)+\left(h_\text{radiation}T_\text{b}\right)}{\left(h_\text{Convection}+h_\text{radiation}\right)} \tag{12}$$

$$h_\text{convection} = 2.8+3V \tag{13}$$

$$h_\text{radiation} = 1.78\left(T_\text{m}-T_\text{a}\right) \tag{14}$$

The total Exergy efficiency of the W-PVT system can be calculated as [15, 18, 22]:

$$\eta_{Ex} = \left[1-\frac{Ex_\text{loss}}{Ex_\text{in}}\right] \tag{15}$$

Table 2. Analytical and design values used in experimentation

Parameter	Value	Parameter	Value
Sun temperature, T_s [℃]	5777	Number of glass cover, N_c	1
Absorptance, α	0.90	Packing factor, P_pf	0.8
Reference efficiency, η_ref	0.149	The transmittance of glass, τ_g	0.96
Wind velocity, V [ms^{-1}]	1.15	Reference temperature, T_ref	25 ℃
Power-plant conversion factor, P_f	0.38	Specific heat of Water, $C_{p,\text{w}}$ [kJkg^{-1}K^{-1}]	4.186

Economic analysis

Before executing the project on a large scale, studying economic feasibility and its benefits is vital. For the economic analysis, the AW method is incorporated for a life span of 25 years at an interest rate of 10% to evaluate and compare the better alternatives. Lenand and Anthony [23] defines AW and expressed as:

$$AW = A_{c,\text{revenues}} - A_{c,\text{expenses}} \tag{16}$$

$$AW_\text{PV/W-PVT} = -\left(C_p+C_i\right)\left(A/P,i,N\right)-C_{Arc}-\left(A/F,i,N\right) \tag{17}$$

$$A/P = \frac{i(i+1)^N}{(1+i)^N - 1} \tag{18}$$

$$A/F = \frac{i}{(1+i)^N - 1} \tag{19}$$

Environmental analysis

The current section executes environmental analysis for PV and W-PVT to estimate CO_2 mitigation, a robust tool to encourage renewable energy. The CO_2 mitigation is the quantity by which CO_2 emission is reduced by incorporating a clean solar power plant instead of a conventional thermal power plant. According to a carbon-neutral charitable fund organization, CO_2 equivalent intensity for coal-based electrical power (ϵCO_2) is 940 g CO_2eq/kWh while average of 31.25% Transmission and distribution losses during power production raise total figure around 1.58 kg CO_2eq/kWh. Therefore, annual CO_2 mitigation (φCO_2) from designed PV/W-PVT system [18]:

$$\varphi_{CO_2} = \in_{CO_2} \hat{\dot{E}}_{net} \tag{20}$$

where $\hat{\dot{E}}_{net}$ [kWh] is the annual energy generated from PV/W-PVT system can be calculated as [21]:

$$\hat{\dot{E}}_{net} = \hat{\dot{E}}_{electric} + \hat{\dot{E}}_{thermal} P_f \tag{21}$$

Carbon credits are the international trading term that describes reducing GHG achieved by substituting clean power generation sources. The international carbon trading price varies from 11.00 US\$/$t$$CO_{2eq}$ to 23.59 US\$/$t$$CO_{2eq}$, hence taking the average value of 17.30 US\$/$t$$CO_{2eq}$ and a conversion factor of 1 US\$ = INR 70, was used in the determination of carbon credits ($\dot{S}_{CO_2}$) is:

$$\dot{S}_{CO_2} = \zeta_{CO_2} \varphi_{CO_2} 70 \tag{22}$$

Uncertainty analysis

In the experimental set-up, the quantities are measured with physical instruments that have the least count, and it is essential to consider these accuracies. All the experimental parameters calculated are subjected to specific errors due to inaccuracies in the experimentation.

The overall yield of the W-PVT system is the function of independent variables like a mass-flow of water, m, temperature difference, T_{out}-T_{in}, PV area, A_c, solar radiation, I_T, open-circuit voltage, V_{oc}, of PV, and short circuit current, I_{sc}. The errors associated with each observation are w_m, w_{Tout}, w_{Tin}, w_A, w_{IT}, w_v, and w_I, respectively. According to Kline and McClintock [24] method, the general eq. for total uncertainty is:

$$W_R = \pm\sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} w_3\right)^2 + .. + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \tag{23}$$

where R= {m, T_{out}, T_{in}, A_c, I_T, V_{oc}, I_{sc}} are the average value of parameters.

$$W_{\eta T} = \pm\sqrt{\left(\frac{\partial \eta T}{\partial m} W_m\right)^2 + \left(\frac{\partial \eta T}{\partial T_{out}} WT_{out}\right)^2 + \left(\frac{\partial \eta T}{\partial T_{in}} WT_{in}\right)^2 + \left(\frac{\partial \eta T}{\partial A_c} WA_c\right)^2 \ldots + \left(\frac{\partial \eta T}{\partial I_g} wI_T\right)^2} \tag{24}$$

$$W_{\eta \mathbf{E}} = \pm \sqrt{\left(\frac{\partial \eta \mathbf{E}}{\partial P} W_p\right)^2 + \left(\frac{\partial \eta \mathbf{E}}{\partial V} W_V\right)^2 + \left(\frac{\partial \eta \mathbf{E}}{\partial A_C} W_{A_c}\right)^2 + \left(\frac{\partial \eta \mathbf{E}}{\partial I_g} w I_T\right)^2} \tag{25}$$

The maximum uncertainties for the W-PVT system are ±0.37 and ±0.51 for thermal and electrical efficiencies, whereas relative uncertainties are 0.88% for thermal efficiency and 3.46% for electrical efficiency.

Results and discussion

The yield of the solar power generation system depends on incident solar radiation that varies day by day and hour by hour; hence solar radiation observations of the global, beam and diffuse-type were shown in fig. 3(a). The beam radiations are non-scattered radiation, whereas global radiations are the sum of the beam and diffused radiation. In the total radiation, direct radiation is 83.73%, while diffuse radiation is about 16.23%. The ambient temperature was seen to follow a concurrent trend with radiation. The dome shape deviation of global and beam radiation was observed throughout the day, whereas minimal changes in diffuse radiations. The maximum global radiation of 952 W/m^2, was recorded with an ambient temperature of 32.9 ºC at noontime, and then it declined afterwards. The average daily value of global, beam, diffuse radiation and ambient temperature were 769 W/m^2, 645 W/m^2, 125 W/m^2, and 31.39 ºC, respectively.

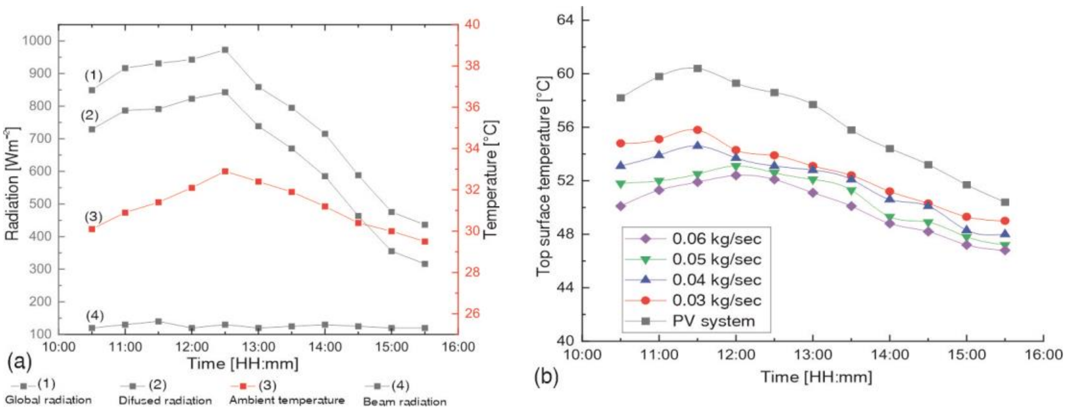

Figure 3. (a) Variation in the radiation and ambient temperature and (b) variation in the top exterior surface temperature of the PV (T-PV), W-PVT (T-WPVT) system

Figure 3(b) illustrated the variation in the T-WPVT system from 0.03-0.06 kg per second and compared with the T-PV temperature. The disparities in the solar radiation in fig. 3(a) caused variation in the surface temperature of the PV, W-PVT system. It is also seen that T-WPVT was lesser than T-PV for all time of experimentation. It shows that water extracted more heat from the PV surface at a high flow rate to reduce maximum surface temperature. The reduction of T-WPVT at elevated solar radiation is the central area of interest in the study. During the study, the T-WPVT surface temperature was reduced by an average of 12.18% with a water-cooling technique. The lowest surface temperature was observed in w-PVT system at 0.06 kg per second. The measured values of PV/W-PVT surface temperature,ambient temperature and water inlet-outlet temperature during experimentation at 0.06 kg per second mass-flow rate were tabulted in tab. 3.

Table 3. Measured values at the mass-flow rate of 0.06 kg per second

Time	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30
Radiation	849.1	916.7	931.3	942.8	972.8	858.8	795.2	715.3	588.4	475.5	436.5
T-PV, [ºC]	58.21	59.82	60.45	59.36	58.61	57.73	55.83	54.45	53.21	51.75	50.49
T-PVT, [°C]	50.12	51.32	51.98	52.45	52.17	51.11	50.14	48.82	48.21	47.23	48.81
T_a, [ºC]	30.74	31.11	31.45	32.15	32.97	32.41	31.92	31.22	30.91	30.52	30.22
T_{fi}, [ºC]	32.12	33.56	34.71	36.71	38.91	41.12	42.50	43.61	44.32	45.05	45.51
T_{fo}, [ºC]	32.44	34.02	35.24	37.42	39.68	42.02	43.21	43.92	44.63	45.27	45.76

As shown in fig. 4(a), the voltage, V_{oc}, producing capacity of simple PV system descends from the morning period reaches to least value, and then slightly swells in the afternoon period that collaborates with the previous study [25]. The extraction of heat from the W-PVT surface significantly reduces the temperature of T-WPVT that resulting in increasing voltage of the W-PVT system. It was also observed in fig. 4(b) that at a higher water flow rate, T-WPVT further augments heat transfer to attain better voltage. The voltage improvement of 4.04% was noted at a 0.06 kg per second flow rate.

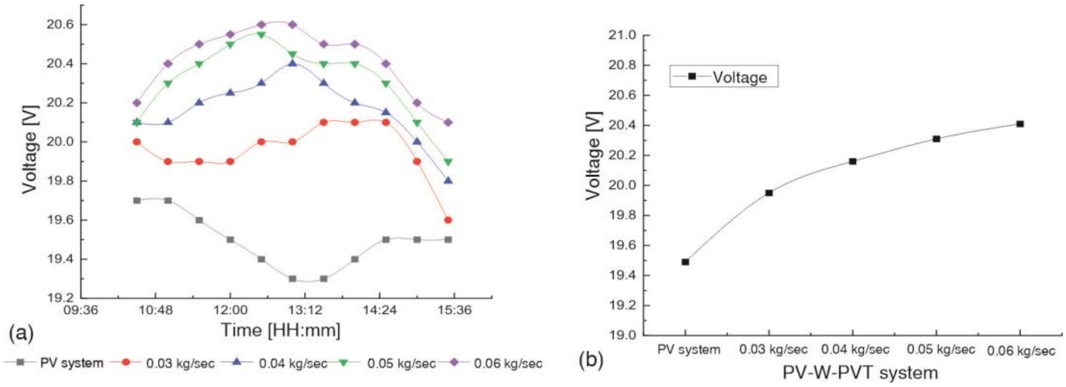

Figure 4. (a) Variation in the Voltage [V] producing capacity of simple PV and W-PVT system, and (b) voltage [V] producing capacity at varying the mass-flow rate

Figure 5(a) shows that the radiation causes augmenting the T-PV of a simple PV system during the morning period, thereby decreasing electrical performance. On the other hand, in the afternoon period, as the top exterior surface temperature of a simple PV reduces due to lower radiation value, the electrical efficiency increases and becomes almost constant. The reduction in the maximum PV temperature from the W-PVT system results in increasing the electrical yield. The highest electrical yield of 11.42% was achieved at 0.06 kg per second flow rate with the W-PVT system at 13:00 hours. A simple PV system obtained an average electrical efficiency of 5.67%, while 9.88% was achieved through W-PVT at an elevated water flow rate of 0.06 kg per second. It was observed that electrical performance amplifies with increasing water flow rate, but this increment is diminutive. The results achieved were in acceptable conformity with research work [26] done in Delhi, India.

The PV surface temperature characteristics have a significant consequence on conversion efficiency when exposed to outdoor radiation. With incorporating water coolant, the average temperature of the W-PVT surface starts dropping, resulting in improved electrical efficiency with supplementary thermal gain. During the test, the optimum efficiency of 9.88% electrical and 47.82% thermal was observed at a mean temperature of 47.9 °C, and additional temperature fall is possible by raising the flow rate of the water coolant.

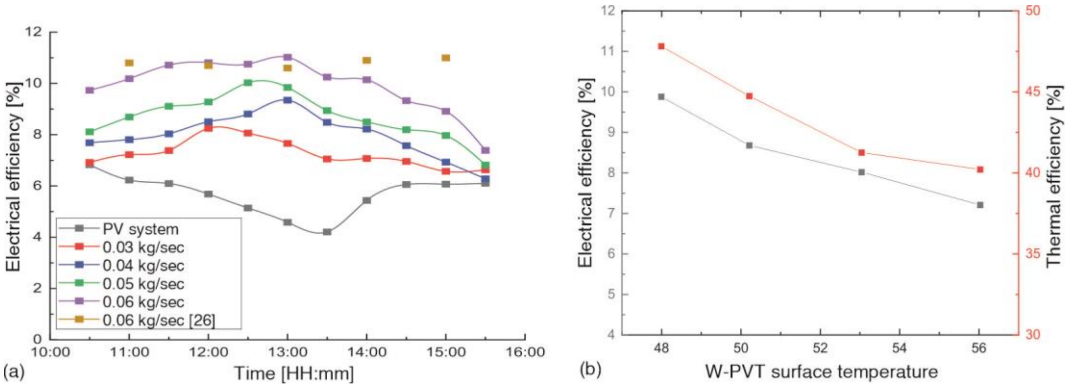

Figure 5. (a) Variation in electrical efficiency of PV and W-PVT system and (b) effect of PV temperature on the electrical-thermal performance

Exergy analysis

The maximum work potential at a known mass-flow rate or energy corresponding to ambient conditions was evaluated for PV and W-PVT systems to determine exergy efficiency. Figure 6 explains the energy, exergy efficiency of PV and W-PVT system at varying water flow rates. The total exergy efficiency is the combined electrical and thermal exergy for the W-PVT system, while it was just the electrical exergy for the PV system. It was noticed that the exergy efficiency of W-PVT is higher than the PV system. However, the rise of exergy efficiency with the mass-flow rate is shallow because the maximum work potential at a higher flow rate was restricted by exergy destruction caused by volume and irreversibility associated with the flow. Hence exergy efficiency was observed to vary in the range of 13.50-14.30% for the W-PVT system while it was 7.15% for the PV system. It was also observed that electrical exergy yield is the dominant part of total exergy output from the system. The tab. 4 shows comparative results of energy-exergy performance in literature and present study.

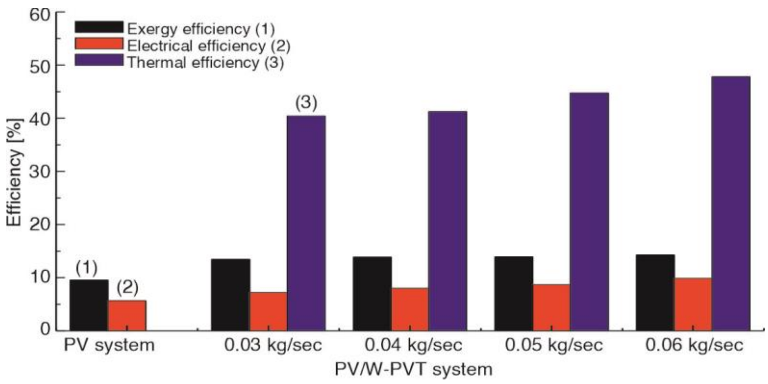

Figure 6. Variation in energy, exergy efficiencies of PV and W-PVT system

Table 4. Studies on W-PVT in literature and their results

Author	Type of cell	Absorber	Material	Location	Flow Rate [kgsec^{-1}]	Efficiency (%)		
						Electrical	Thermal	Exergy
Alomar and Ali [27]	Mono	Plate-pipe	Copper	Iraq	–	12-16	25-58	12-20
Fudholi *et al*. [28]	Poly	Spiral	Stainless Steel	Sultanate of Oman	0.011-0.041	13-13.8	45-55	25
Selimli *et al*. [14]	Poly	Spiral	Copper	Turkey	0.00166	9.74	29.08	10.64
		Box	Polyamide			10.19	49.69	11.53
Qingyang *et al*. [29]	Mono	Tube-sheet	Copper	Shenzhen, China	0.09	10.0	46.5	8.41
Kitanovski *et al*. [30]	Poly	Roll Bond-Bionic	Aluminium	Slovenia	0.007-0.009	9.9	33.5	12.7
Current study	Poly	Spiral-rectangular	Aluminium	Pune, India	0.03-0.06	7.21-9.88	40.51-47.8	13.6-14.3

Economic analysis

Figure 7(a) shows cash flow of PV and fig. 7(b) shows cash flow of W-PVT system for 0 to 25 years. The horizontal line indicates the life span of a PV/W-PVT system, and the downward lines indicate the cost incurred for the system. A Zero (0) year indicates that the system's commissioning year and capital, transport, and installation costs were expedited. The total cost of INR 11780.80 incurred for the purchase of the W-PVT system with INR 1300 installation cost and INR 500.00/annum was assumed to be spent on operation causes. The cost of INR 4872.8 occurred to purchase a PV system with INR 800 installation cost. In addition, an INR 500.00 was set aside for maintenance, breakdown, and replacement of some components for PV and W-PVT systems.

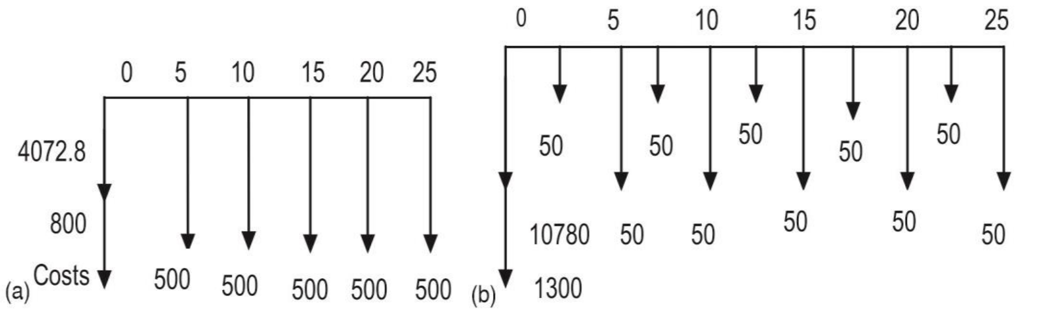

Figure 7. (a) Cash flow diagram for PV System and (b) cash flow diagram for W-PVT System

As shown in tab. 5, annual worth value for both cases of PV and W-PVT systems are negatives as they represent cost values. For annual revenues calculations, heat gain and electrical power obtained from the PV/W-PVT system during the experimental period have been taken for evaluation. In India, the average unit cost of electricity is INR 6.95. It was seen that though the initial investment cost of W-PVT is high, the simultaneous generation of heat and electricity from a single unit gives a payback period of 3.02 years which is smaller than a conventional simple PV system. The evaluated simple payback period for a PV system is 4.53 years. In early life years, cost-benefit is pessimistic for both cases; the value becomes positive

Table 5. The AW for the PV and W-PVTsystem

Period (Year)	5	10	20	25
PV System	–1524.64	–1170.12,	–1011.25	–985.67
W-PVT System	–2827.39	–2076.34	–1739.76	–1685.57

and demonstrates a growing trend. From the results, after the 7-years of use, cost-benefit values for PV and W-PVT system are INR 181.97 and 1774.29, respectively, rising to 416.35 and 2292.02 in the 14th year. In the preceding year, a linear swell in cost-benefit values was observed. The cost-benefit value was INR 473.18 for a PV system and INR 2412.42 for a W-PVT system in 19th years. In the 24th year, the PV and W-PVT system's cost-benefit value reaches 502.11 and 2473.71, respectively. The result shows that W-PVT possesses better-promising cost benefits and can be used for elevated lifespan.

Environmental analysis

The environmental analysis assesses the constructive impact of the newly designed PV and W-PVT solar system and the feasibility of economic gain through carbon credits. In India, 62% of power is generated from a conventional thermal power plant. An environmental analysis was performed by extending energy results for a year. The annual CO_2 mitigation from an energy perspective and annual economic gain from carbon credits are shown in fig. 8, respectively. The present study conducted in optimum sky and solar radiation state as reported in [21]. The annual CO_2 mitigation from a simple PV system was 225.46 kg annual, while in the W-PVT system, these values were 347.11, 402.24, 422.71 and 464.37 kg annual at 0.03, 0.04, 0.05 and 0.06 kg per second water flow rates, respectively. The additional economic benefits from selling carbon credits were evaluated using eq. (22). It was observed that annual gain for simple PV and W-PVT were 273.03, 453.04, 487.11, 511.90 and 562.71 INR annual, respectively. Based on the above analysis, it can be concluded that W-PVT proves significantly superior in CO_2 mitigation at higher water flow by energy approach.

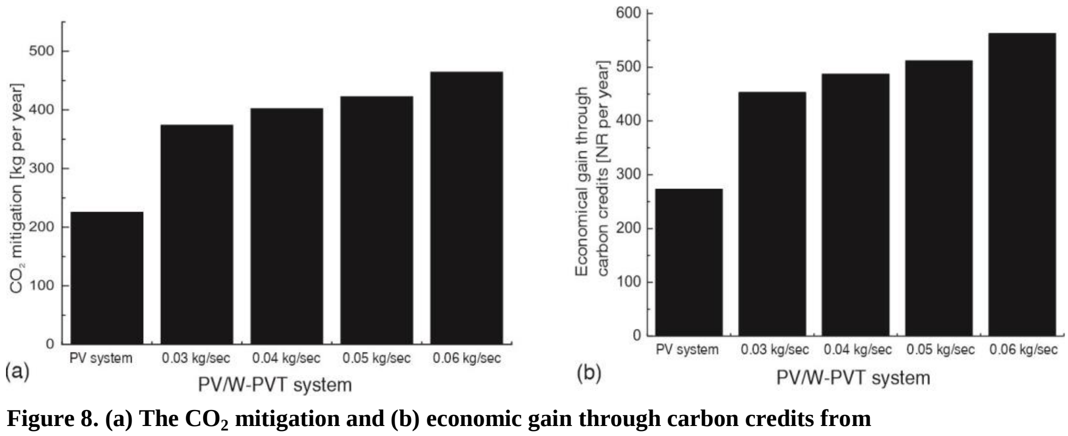

Figure 8. (a) The CO_2 mitigation and (b) economic gain through carbon credits from PV and W-PVT system

Conclusions

The W-PVT system enhanced cooling and improved energy, exergy, economic and environmental performance. The improvement in electrical efficiency was noted from 5.68%

of a simple PV system to 9.88% that of the W-PVT system at 0.06 kgper second, nearly 4.2% higher. It was seen that the change in electrical yield is much smaller compared to thermal yield. Every 1 °C decrease in surface temperature due to cooling is followed by a 0.28% increase in electrical and a 1.02% increase in thermal efficiency through recovered heat. It was observed that the electrical and thermal efficiency from the W-PVT was the function of mass-flow rate and found in range of 7.21-9.88% and 40.51-47.8%, respectively. The exergy efficiency was observed in the range of 9.85-14.30%. The market study shows that the initial cost of W-PVT was about 2.5 times more than the simple PV system. The analysis shows a payback period of 4.53 and 3.03 years for the PV and the W-PVT system. From the environmental analysis, W-PVT at 0.06 kg per second flow rate mitigated maximum CO_2 of 464.67 kg annual along with the economic return of INR 562.71 annual. Thus W-PVT system is a significant, feasible, and economical option than using a simple PV system alone in the long life span for better power generation and is recommended for household applications. The analysis can be carried out by adding extended surfaces further to boost the overall performance of the W-PVT system.

Nomenclature

A_c – area of PV [m^2]
C_p – specific heat of water [kJkg^{-1}K^{-1}]
$\hat{E}_{net}$ – annual energy generated [kWh]
$\hat{E}_{elec}$ – annual electrical energy generated [kWh]
$\hat{E}_{net}$ – annual thermal energy generated [kWh]
i – interest rate [%]
I_T – incident solar flux [Wm^{-2}]
$\dot{m}$ – mass-flow rate [kgsec^{-1}]
R – error [%]
V – velocity of air [ms^{-1}]

Greek symbols

α – absorptance
φCO_2 – annual CO_2 mitigation [kg annual^{-1}]
ϵCO_2 – CO_2 equivalent intensity [CO_2eqkWh^{-1}]
$\dot{S}_{CO_2}$ – carbon credits [UStCO_{2eq}^{-1}$]
ζCO_2 – international carbon trading price [US$]
ΔT – change in fluid temperature [°C]
τg – transmittance of glass
η – efficiency [%]
η_{ref} – reference efficiency [%]
$\eta_{thermal}$ – thermal efficiency [%]
$\eta_{electrical}$ – electrical efficiency [%]
η_{ex} – exergy efficiency [%]

Acronyms

A/F – sinking fund factor
A/P – capital recovery factor
AW –annual worth
N – life cycle
PVT – photovoltaic thermal system
T-PV – top surface temperature of a PV system [ºC]
T-PVT – top surface temperature of a W-PVT system [ºC]
W-PVT – water based photovoltaic thermal system

Subscripts

$A_{c,expenses}$ – annual expense cost [INR]
$A_{c,revenues}$ – annual revenues [INR]
C_i – installation cost [INR]
C_p – capital cost [INR]
C_{ara} – maintenence cost [INR]
Ex_{in} – input exergy
Ex_{out} – output exergy
Ex_{loss} – exergy loss [Wm^{-2}]
Ex_{therm} – thermal exergy [Wm^{-2}]
$Ex_{electric}$ – electrical exergy [Wm^{-2}]
$h_{convection}$ – convective heat transfer [Wm^{-2}K^{-1}]
$h_{radiation}$ – radiation heat transfer [Wm^{-2}K^{-1}]
I_{sc} – short circuit current [I]
N_c – number of glass cover
P_{max} – maximum power condition [W]
P_{pf} – packing factor
P_f – power factor
$Q_{u,ex}$ – experimental useful heat gain [W]
tCO_{2eq} – tonnes of CO_2 equivalent [tonnes]
T_{fi} – inlet temperature of water [°C]
T_{fo} – outlet temperature of water [°C]
T_a – ambient temperature [°C]
T_b – base PV temperature [°C]
T_c – PV cell temperature [°C]
T_m – mean temperature [°C]
T_s – avg. PV temperature [°C]
T_{Sun} – avg. Sun temperature [°C]
V_{oc} – open circuit voltage [V]
W_m – error with mass-flow rate [kgsec^{-1}]
$W_{T,fi}$ – error with inlet temperature of water [°C]
W_{Ac} – error with area of PV [m^2]

$W_{T,fo}$ – error with outlet temperature of water [°C]
W_{IT} – error with incident solar flux [Wm^{-2}]
W_v – error with incident voltage [V]
W_I – error with incident current [A]
$W_{\eta T}$ – uncertainty in thermal efficiency
$W_{\eta E}$ – uncertainty in electrical efficiency

Reference

[1] Iram R., *et al.*, Prioritization of Renewable Solar Energy to Prevent Energy Insecurity: An Integrated Role, *The Singapore Economic Review*, *66* (2021), 2, pp. 391-412
[2] Bojek P., Bahar H., Report, Solar PV, International Energy Agency, Paris, 2021
[3] Singh P., Ravindra N M, The Temperature Dependence of Solar Cell Performance an Analysis, *Solar Energy Material & Solar Cells 101* (2012), June, pp. 36-45
[4] Satpute, J. B., Rajan, A. J., Recent Advancement in Cooling Technologies of Solar Photovoltaic (PV) System, *FME Transactions*, *46* (2018), 4, pp. 575-584
[5] Das, D., *et al.*, Flat Plate Hybrid Photovoltaic- Thermal (PV/T) System: A Review on Design and Development, *Renewable and Sustainable Energy Reviews*, *84* (2018), Mar., pp. 111-130
[6] Ozbas E., *et al.*, Evaluation of Internal Structure Modifications Effect of Two-Phase Closed Thermosyphon on Performance: An Experimental Study, *Solar Energy*, *224* (2021), Aug., pp. 1326-1332
[7] Singh, I., *et al.*, A Review on Solar Energy Collection for Thermal Applications, *International Journal of Advance and Innovative Research*, *6* (2019), Apr., pp. 252-259
[8] Selimli, S, *et al.*, Solar Vacuum Tube Integrated Seawater Distillation - An Experimental Study, *Facta Universitatis Series: Mechanical Engineering*, *14* (2016), 1, pp. 113-120
[9] Modrek, M., Alili, A., Thermal and Electrical Performance of a Flat Plate Photovoltaic/Thermal Collector, *Proceedings*, ASME 2017 11th International Conference on Energy Sustainability ES2017, Charlotte, N. C., USA, 2017
[10] Su, D., *et al.*, Dynamic Performance Analysis of Photovoltaic–Thermal Solar Collector with Dual Channels for Different Fluids, *Energy Conservation and Management*, *120* (2016), July, pp 13-24
[11] Tarabsheh, A., *et al.*, Performance of Photovoltaic Cells in Photovoltaic Thermal (PVT) Modules, *IET Renewable Power Generation*, *10* (2016), 7, pp 1017-1023
[12] Dumrul, H., *et al.*, Energy Analysis of Concentrated Photovoltaic/Thermal Panels with Nanofluids, *International Journal of Thermodynamics 24* (2021), 3, pp. 227-236
[13] Zhou, J., *et al.*, Mathematical and Experimental Evaluation of a Mini-Channel PV/T and Thermal Panel in Summer Mode, *Solar Energy*, *224* (2021), Aug., pp. 401-410
[14] Selimli, S., *et al.*, Experimental and Numerical Analysis of Energy and Exergy Performance of Photovoltaic Thermal Water Collectors, *Solar Energy*, *228* (2021), 1, pp.1-11
[15] Arslan, E., *et al.*, Experimental and Numerical Investigation of a Novel Photovoltaic Thermal (PV/T) Collector with the Energy and Exergy Analysis, *Journal of Cleaner Production*, *276* (2020), 123255
[16] Zuhu, S., Ceylan, I., Energy, Exergy and Enviroeconomic (3E) Analysis of Concentrated PV and Thermal System in the Winter Application, *Energy Reports*, *5* (2019), Nov., pp. 262-270
[17] Ozturk, M., *et al.*, Energy, Exergy and Economic (3E) Evaluation of the Photovoltaic/Thermal Collector-Assisted Heat Pump Domestic Water Heating System for Different Climatic Regions in Turkey, *Journal of Thermal Analysis and Calorimetry*, *145* (2021), 3, pp. 1431-1443
[18] Arslan, E., Aktas, M., 4E Analysis of Infrared Convective Dryer Powered Solar Photovoltaic Thermal Collector, *Solar Energy*, *208* (2020), Sept., pp. 46-57
[19] Guarracino, I., *et al.*, Dynamic Coupled Thermal, Electrical Modelling of Sheet and Tube Hybrid Photovoltaic Thermal Collectors, *Applied Thermal Engineering*, *101* (2016), May, pp. 778-795
[20] Kasaeian, A., *et al.*, Effects of Forced Convection on the Performance of a Photovoltaic Thermal System: An Experimental Study, *Expt Thermal and Fluid Science 85* (2017), July, pp. 13-21
[21] Kazemian, A., *et al.*, Energy, Exergy and Environmental Analysis of Glazed and Unglazed PVT System Integrated with Phase Change Material: An Experimental Approach, *Solar Energy*, *201* (2020), May, pp. 178-189
[22] Hossain, M., *et al.*, Two Side Serpentine Flow-Based Photovoltaic-Thermal-Phase Change Materials System Energy, Exergy and Economic Analysis, *Ren Energy*, *136* (2019),June, pp.1320-1336
[23] Lenand, T., Anthony, J., *Engineering Economy*, 4th ed., McGraw-Hill Companies. New Delhi, 1998

[24] Kline, S., McClintock, F., Describing Uncertainties in Single Sample Experiments, *Mechanical Engineering*, 75 (1953), pp. 3-8
[25] Tripathi, A., *et al.*, Performance Analysis of PV Panel Under Varying Surface Temperature, *MATEC Web of Conferences, 144* (2018), 4, pp 1-8
[26] Dubey, S., Tiwari, G., Thermal Modelling of a Combined System of Photovoltaic Thermal Solar Water Heater, *Solar Energy 82* (2008), 7, pp. 602-612
[27] Alomar, O., Ali, O., Energy and Exergy Analysis of the Hybrid Photovoltaic Thermal Solar System Under the Climatic Condition of North Iraq, *Case Studies in Thermal Eng., 28* (2021), Dec., pp 1-12
[28] Fudholi, A, *et al.,* Energy and Exergy Analyses on Water based Photovoltaic Thermal (PVT) Collector with Spiral Flow Absorber, *Proceedings*, Recent Advances in Energy, Environment and Geology, Antalya, Turkey, 2013, pp. 70-74
[29] Qingyang, J., *et al.,* Energy and Exergy Analyses of PV, Solar Thermal and Photovoltaic/Thermal Systems: A Comparison Study, *Int. Journal of Low-Carbon Technologies 16* (2021), 2, pp. 604-611
[30] Poredoš, P., *et al.*, Numerical and Experimental Investigation of the Energy and Exergy Performance of Solar Thermal, Photovoltaic and Photovoltaic-Thermal Modules Based on Roll-Bond Heat Exchangers, *Energy Conversion and Management, 210* (2020), Apr., pp. 1-21

Paper submitted: September 5, 2021
Paper revised: October 11, 2021
Paper accepted: December 20, 2021