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Outdoor Testing to Compare the Technical and Economic Aspects of Single-and Dual-Fluid Photovoltaic/Thermal (PV/T) Systems

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Abstract: Integration of a dual-fluid heat exchanger with a photovoltaic/thermal (PV/T) system has become increasingly important because it not only significantly reduces the photovoltaic (PV) solar cells' temperature but also produces additional thermal energy. In this study, energy, exergy, and economic analyses of a dual-fluid (water/air) PV/T system are performed in comparison with a reference PV module and single-fluid PV/T systems for the climate of Cheonan, South Korea. Daily and yearly performance evaluations of all of the aforementioned PV/T systems were carried out through experimentation. Based on the experimental findings, the economic feasibility of the dual-fluid PV/T system is assessed in the context of its financial benefits over both a shorter and longer period of time. Results show that the energy and exergy efficiencies of the dual-fluid PV/T system are significantly higher than those of single-fluid PV/T systems, by 20% and 11%, respectively. In addition, relevant to local domestic electricity price, the cost of energy is reduced by 80%, 60%, and 45% with the dual-fluid PV/T system and water and air type PV/T systems, respectively. Furthermore, using the dual-fluid PV/T system, extra revenue is generated through carbon credit by mitigating CO_2 emissions into the atmosphere.

Keywords: outdoor testing; dual-fluid PV/T system; technical analysis; economic study

1. Introduction

The energy crisis is becoming a formidable challenge for the world, as depletion of fossil fuel reserves is increasing rapidly [1]. In fact, a rise in population coupled with a high rate of energy consumption in the industrial sector and in residential buildings is exacerbating this problem. Furthermore, the world is seeing a further expansion in its infrastructure. The substantial use of fossil fuels is meanwhile increasing global greenhouse gas emissions. Therefore, it is important to address the aforementioned energy crises by replacing fossil fuels with sustainable energy resources. Solar energy is considered the most promising substitute in the context of sustainability, unlimited availability, and diversity of its usage [2]. Sunlight consists of different wavelength spectra that enables it to produce heat and electricity. The light spectrum ranges that are favorable to photovoltaic (PV) solar cells are utilized for generating electricity [3], while the remaining wavelength ranges that cause heat are best suited for solar thermal collectors. By integrating a photovoltaic module with a solar thermal collector, the capacity to utilize the whole sunlight spectrum can be achieved [4]. Therefore, by providing simultaneous production of heat and electricity, the photovoltaic/thermal (PV/T) system is considered the best option thus far. Higher overall energy performance with limited physical space makes the PV/T system even more appealing.

The development of high quality and efficiency PV solar cells took a number of years, as various researchers and scientists contributed their time and knowledge. In the middle 1970's, scholars reported on theoretical and experimental work for PV/T technology. Wolf [5] was among the pioneers who in 1976 investigated the energy performance of PV/T systems for residential buildings. In the late 1970's, Florshuetz [6] analyzed the PV/T collector through the famous Hottel-Whillier model for thermal analysis, by modifying it according to hybrid solar collector suitability. Further, Hendrie [7] accessed the technical feasibility of the hybrid PV/T system; since then, the research and development work on PV/T design has continued to change and evolve as the demand arises. The benefits of PV/T technology can be identified through a life cycle cost analysis based on the energy and exergy of the proposed system's configurations. Taking into consideration initial cost, annual savings, and return on investment, energy and exergy analyses of the double and single pass PV/T air collectors have been carried out by Raman and Tiwari [8]. On the basis of experimental findings from different locations, they concluded that the life cycle cost of the PV/T system is affected greatly by the heat exchanger design and the climatic conditions. A comparative exergy evaluation of a PV/T system using (PCM) phase change material/water as coolants in comparison with a reference PV module was presented by Hossain et al. [9]. The proposed PV/T system was also assessed further for economic feasibility in the context of possible commercialization. They proposed that in the long run the PV/T system is more economical compared to the reference PV module.

There are several heat transfer fluids, but water and air are commonly used coolants for harvesting heat from the PV module. An enormous amount of research work has been carried out on the aforementioned coolants with the intention to maximize the usage of solar energy [10,11]. Ibrahim et al. [12] investigated and compared the performance of a PV/T system with seven design configurations of liquid fluid carrier absorbers. Under varied operating and climatic conditions, the spiral flow design outperformed its rivals with the highest thermal efficiency and electrical efficiency. The low thermal conductivity problem in the case of air can be overcome by introducing a double pass air channel, where both the top and rear surfaces of the PV module exchange heat with the circulating air. Based on experiments, Omojaro and Aldabbagh [13] analyzed the thermal efficiency of single and double pass solar air heaters by varying the channel height and air mass flow rate. They concluded that the thermal efficiency decreases by decreasing the air channel height, and the temperature rises along with the flow decrease as the mass flow rate increases. Elsafi and Gandhidasan [14] compared the thermal and electrical performance of a double pass PV/T system with and without a compound parabolic concentrator (CPC). Furthermore, better heat exchange is obtained by incorporating fins in the lower air channel. It is observed that the electrical and thermal gains for PV/T with CPC/fins are 8% and 3% higher, respectively, than those of PV/T without CPC/fins. When water and air are utilized simultaneously as the coolants for the PV module, the solar collector is called a bi-fluid PV/T system. Tripanagnostopoulos [15] was the first who came up with the idea of bi-fluid (water and air) as the working fluids for the cooling of the PV module. Othman et al. [16] introduced a bi-fluid heating system fabricated by integrating a copper water tube with a double-pass air collector, and then the whole unit was assembled with transparent photovoltaic modules to produce heat/electricity. However, with this configuration, the fluid with high thermal conductivity is not in physical contact with the PV module, which may affect the PV/T performance.

In this study, comparative technical and economic analyses are performed based on energy and exergy of the PV/T system with dual-fluid and single-fluid heat exchangers for the climatic conditions of Cheonan, South Korea. Most importantly, the dual-fluid heat exchanger is designed in such a way that both circulating fluids are in physical contact with the rear surface of the PV module so that the heat extraction from its surface can be maximized. Compared to a single-fluid PV/T system, an economic analysis of the dual-fluid PV/T system showed a notable decrease in energy cost and discounted payback time (DPBT) relative to the domestic electricity price.

2. Experimental Details

2.1. Methodology

- The PV module temperature and thermal and electrical gains are calculated based on hourly variations of solar radiation and dry bulb temperature. Summation of hourly data is used to obtain daily outputs, and subsequently the daily outputs are summed up for calculating the monthly gains.
- The proposed PV/T system is designed to be used for all aforementioned flow schemes such as air, water, and air plus water. During single-fluid operation, the second fluid is kept stagnant, with a zero mass flow rate.
- In the case of the dual-fluid heat exchanger, the optimal flow rate for each fluid is identified in such a way that the flow rate of any of the two fluids is varied over a range from 0 to 0.03 kg/s for water and 0 to 0.06 kg/s for air, while during this variation the second fluid is kept fixed at different flow regions such as laminar, transitional and turbulent.
- Exergy efficiency is calculated based on solar radiation and the thermal and electrical outputs.
- An economic analysis is performed based on energy and exergy performance of a PV/T system with dual and single fluid heat exchangers, and considering life cost analysis parameters such as initial cost, annual savings, and return on investment.

2.2. Design and Operation Details

The dual-fluid heat exchanger for the cooling of the PV module was constructed using serpentine shaped copper pipes as the liquid fluid carrier and a rectangular duct made of PVC for an air carrier. The inner diameter of the copper pipe was 8 mm and the height and width of the air passage were 50 mm and 979 mm, respectively. The absorber sheet with 1 mm thickness was attached at the rear surface of the PV module by means of adhesive and then the copper tube was glued to the absorber sheet. A mono-crystalline PV module with a surface area of 1619 × 979 mm was covered with tampered glass having a thickness of 4 mm. The specifications of the PV module is given in Table 1. An air duct was arranged directly below the copper pipes such that both fluids exchanged heat with each other without any physical interaction. In addition, a set of baffles was introduced inside the air passage to enhance the heat exchange across the channel's surfaces.

Table 1. Specifications of the photovoltaic (PV) module.

Cell Type Silicon	Mono-Crystalline
Module size	1619 × 979 mm
P_{max}	260 W
V_{max}	31.6 V
I_{max}	8.23 A
V_{oc}	38.1 V
I_{sc}	9.27 A
Aperture ratio	48% (8 mm holes)

The PV module and the two fluids-based heat exchanger were assembled to form a dual-fluid PV/T system that was installed at the College of Engineering, Kongju National University, Cheonan campus, as shown in Figure 1. The coordinates of Cheonan city are 36.8151° N, 127.1139° E. Experimental data were collected in four different phases. The starting experiments used a reference PV module without any cooling medium; then in the 2nd and 3rd phases solely air and water, respectively, were tested for PV cooling. Lastly, the performance of the dual-fluid (water plus air) heat exchanger was studied. The thermal and electrical performance of the proposed PV/T system was evaluated across different flow regimes. The tested flow rate ranges for water and air were 0 to 0.032 kg/s and 0 to 0.05 kg/s, respectively. Considering the freezing-cold climate of Korea in winter, an antifreeze liquid was mixed with water to lower the freezing point of the mixture. A mixture of water and antifreeze was used as a circulating fluid which was stored in an auxiliary tank as shown in Figure 2. Temperature variations across different components of the PV/T system were recorded by means of thermocouples. Quantities and employed positions of the temperature sensors were as follows: two PT100 Ω temperature sensors were positioned each at the inlet and outlet of the water component; six thermocouples were mounted each at the inlet and outlet of the air cooling unit; four thermocouples were attached each at the top surface of the PV module; and three thermocouples were installed both at the absorber sheet and the tubes carrying water. Daily current and voltage outputs from the PV module were monitored by a PV Module I-V measurement system (TNE TECH CO. LTD, Yongin, South Korea) and stored in a computer via a data acquisition unit (Agilent 34970A, Santa Clara, CA, United States). Solar radiation was measured with the help of a first class pyranometer mounted parallel to the PV module. Digital flow meters were used to measure air and water flow rates. Wind speed, ambient temperature, and humidity were measured with a weather station installed near the test rig. Data collection of the aforementioned parameters involves instrumentation, and therefore, prior to experiments, all measuring instruments were calibrated properly following standard procedures. The uncertainty related to measuring equipment is given in Table 2.

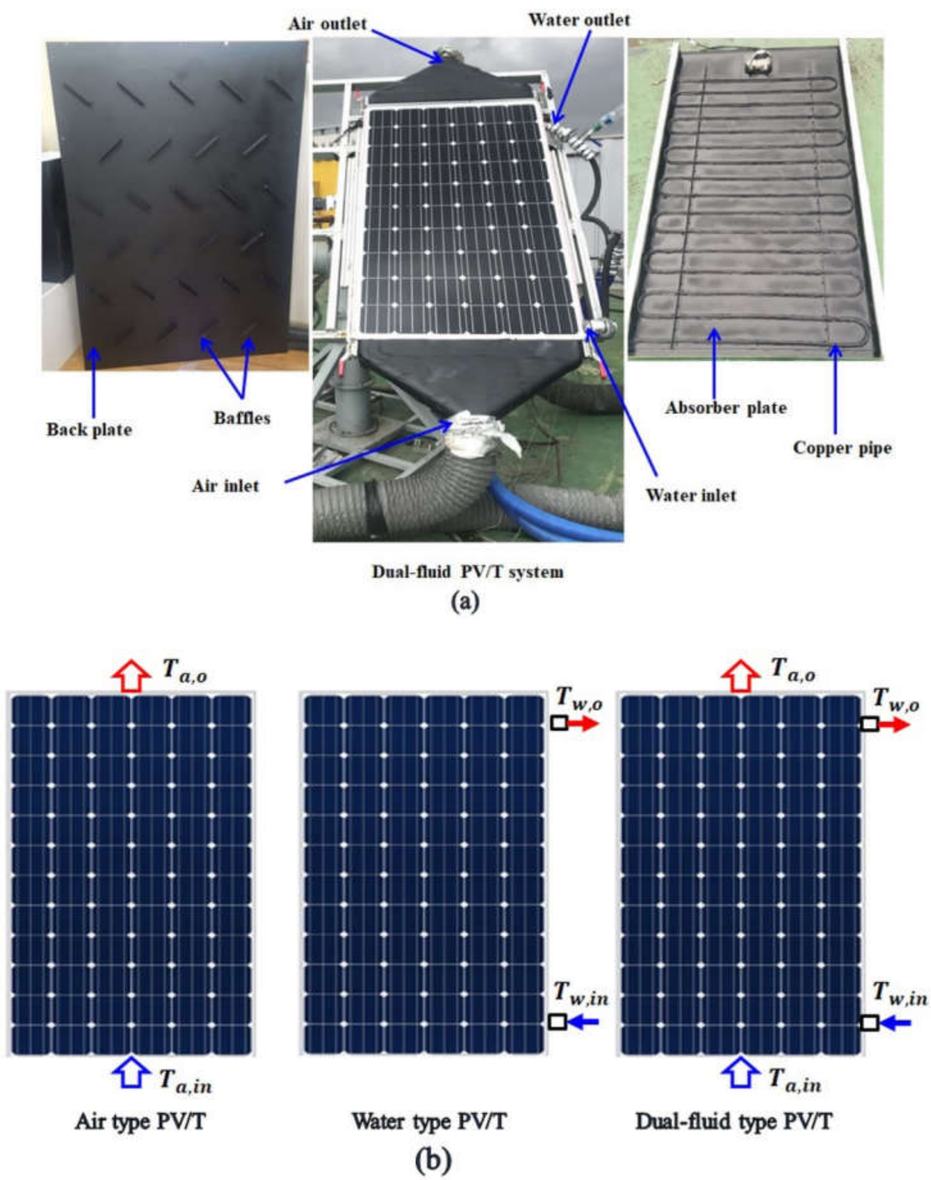

Figure 1. (**a**) Experiment setup and (**b**) flow schemes.

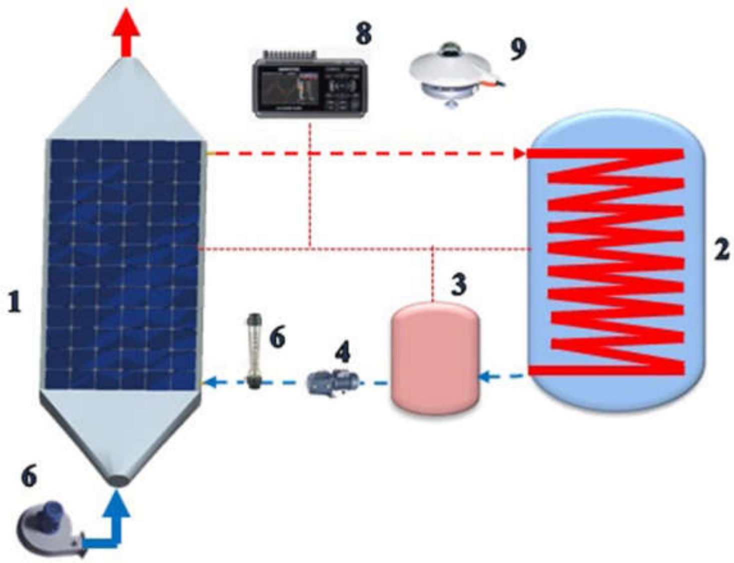

Figure 2. Schematic diagram of the dual-fluid photovoltaic/thermal (PV/T) system.

Table 2. Uncertainty related to the measuring equipment.

Equipment	Uncertainty
Pyranometer	<±1.5% per year
K-type Thermocouples	±0.25–0.5 °C
PT100 Ω	±0.1 °C
Flow meter	±0.5% at full scale
Multi-meter	±0.1%
Data logger	K-type: ± (0.05% of reading + 1.0 °C); PT100: ±0.8 °C
Fitting of elements	±0.1 °C

3. Analysis

3.1. Energy Study

As the two fluids operated simultaneously, the thermal power gained by the dual-fluid solar collector is different compared to a conventional flat plate collector. In the proposed PV/T system, the net thermal gain is calculated as a sum of thermal energy contributed by the air part and the water part, as given below [17].

$$P_{th} = \dot{m}_w C_w \left(T_{w,o} - T_{w,in}\right) + \dot{m}_a C_a \left(T_{a,o} - T_{a,in}\right) \quad (1)$$

where P_{th} is thermal power, $\dot{m}$ and C are the fluid mass flow rate and specific heat, respectively, and T is temperature. Subscript w and a denote the water and air, respectively; w,o and w,in are outlet and inlet temperature of the water, respectively; and a,o and a,in are outlet and inlet temperature of the air, respectively. Considering the proposed design, the thermal efficiency of the collector can be calculated as:

$$\eta_{th} = \frac{P_{th}}{A_c G} \quad (2)$$

$$\eta_{th} = \frac{\dot{m}_w C_w \left(T_{w,o} - T_{w,in}\right) + \dot{m}_a C_a \left(T_{a,o} - T_{a,in}\right)}{A_c G} \quad (3)$$

where η_{th} is thermal efficiency, A_c is surface area of the collector, and G is the incident solar radiation. Under these conditions the electrical efficiency is given as:

$$FF = \frac{I_{max} \times V_{max}}{I_{sc} \times V_{oc}} = \frac{P_{el}}{I_{sc} \times V_{oc}}$$

$$P_{el} = I_{sc} \times V_{oc} \times FF$$

$$\eta_{el} = \frac{P_{el}}{A_c G} \quad (4)$$

where FF is the fill factor, and I_{max} and V_{max} are the maximum current and voltage, respectively. The terms I_{sc} and V_{oc} are the short circuit current and open circuit voltage, respectively. The terms η_{el} and P_{el} are the electrical efficiency and power, respectively. Hence, the overall output (P_{tot}) produced by the PV/T system can be described as:

$$P_{tot} = P_{el} + P_{th} \quad (5)$$

3.2. Exergy Study

The exergy is the maximum amount of energy that can be achieved in relation to ambient temperature, from the PV/T system. The difference of the maximum amount of exergy to the supplying exergy is called the exergy loss.

$$\dot{E}_{loss} = \dot{E}_{in} - \dot{E}_{out} \quad (6)$$

where $\dot{E}_{loss}$ is exergy loss, and $\dot{E}_{in}$ and $\dot{E}_{out}$ are the exergy supply and output, respectively. Following Yazdanifard et al. [18] the thermal exergy rate can be modified for the dual-fluid PV/T system as:

$$\dot{E}_{th} = \dot{m}_w C_w \left(T_{w,o} - T_{w,in}\right)\left(1 - \frac{293}{293+(T_{w,o}-T_a)}\right) + \dot{m}_a C_a \left(T_{a,o} - T_{a,in}\right)\left(1 - \frac{293}{293+(T_{a,o}-T_a)}\right) \quad (7)$$

where $\dot{E}_{th}$ is the thermal exergy rate. Using the thermal exergy rate and the total exergy input, the thermal exergy efficiency can be written as:

$$\eta_{ex,th} = \frac{\dot{E}_{th}}{\dot{E}_{in}} \quad (8)$$

where $\eta_{ex,th}$ is the exergy thermal efficiency. The electrical output is in the form of exergy, therefore, the electrical exergy efficiency can be expressed as:

$$\eta_{ex,el} = \frac{\dot{E}_{el}}{\dot{E}_{in}} = \frac{P_{el}}{\dot{E}_{in}} \quad (9)$$

where $\eta_{ex,th}$ is the exergy electrical efficiency. The total exergy efficiency is sum of thermal and electrical exergy rates:

$$\eta_{ex,PVT} = \frac{\dot{E}_{th} + \dot{E}_{el}}{\dot{E}_{in}} = \eta_{ex,th} + \eta_{ex,el} \quad (10)$$

The expression for the exergy of absorbed irradiance or the exergy input can be written as.

$$\dot{E}_{in} = [1 + \frac{1}{3}\left(\frac{T_\infty}{T_{sun}}\right)^4 - \frac{4T_\infty}{3T_{sun}}]GA_c \quad (11)$$

where T_{sun} is the temperature of the sun.

3.3. Economic Study

The main aim of the life cycle analysis is to exhibit the economic feasibility of the dual-fluid PV/T system in comparison with single-fluid PV/T systems. The net present value (NPV) of a PV/T system is calculated using the annual discounted cash flow (DCF) parameter [1].

$$NPV_y = \sum_{y=1}^{n} DCF_y \quad (12)$$

$$DCF_y = \frac{CF_y}{(i_d + 1)^y} \quad (13)$$

where i_d is discount rate, CF_y is the cash flow for year y and it is calculated through:

$$CF_y = E_{s,y} - MC_y \quad (14)$$

where MC_y is the maintenance cost for year y and $E_{s,y}$ is annual electricity saved per year by the PV/T system.

$$MC_y = MC(1 + i)^y \quad (15)$$

where i is inflation and annual maintenance cost (MC) can be evaluated using the expression given by Lari and Sahin [1]:

$$MC = 2.76\%\ of\ the\ PV\ cost + 2.3\%\ of\ heat\ exchanger\ cost + 0.75\%\ of\ pump\ cost \quad (16)$$

$E_{s,y}$ can be expressed as:

$$E_{s,y} = [E_{el}(1 + D_{el})^y + E_{th}(1 + D_{th})^y] \times COE_i(1 + i_{el})^y \quad (17)$$

where E_{el} and E_{th} are the annual electricity saved by electrical and thermal loads, respectively. D_{el} and D_{th} are the annual degradation of electrical and thermal performances, respectively, of the PV/T system. COE_i and i_{el} are the domestic electricity cost and the inflation rate, respectively. The energy production factor (EPF) is calculated using the following expression:

$$EPF = \frac{P_{lifetime}}{P_{ee}} \quad (18)$$

where $P_{lifetime}$ is the lifetime energy performance of the PV/T system and P_{ee} is the embodied energy or energy utilized by the PV module during its production processes. Based on the embodied energy, the net CO_2 mitigation over the system's lifetime can be calculated as:

$$Net\ CO_2\ mitigation = (P_{tot} \times lifetime - P_{ee}) \times 0.98 \times 10^{-3} \quad (19)$$

where 0.98×10^{-3} is tons of CO_2 emission per kWh when generating electricity from coal [19]. Finally, the net CO_2 credit can be earned through carbon emission trading as follows [20].

$$Net\ CO_2\ credit = Net\ CO_2\ mitigation \times 20 \quad (20)$$

The net CO_2 is traded at 20 euro/ton [20].

4. Results and Discussion

It is obvious that the overall efficiency (thermal plus electrical) of the photovoltaic/thermal (PV/T) system is affected greatly by the fluid type and the flow rate; therefore, tracking of the optimal flow rate against each heat transfer fluid is important. Due to this reason, in the first phase of the experiments, the optimal flow rates for air and water were tracked by varying the fluid flow rate from laminar to turbulent ranges. With the help of a control panel, the fluid flow through the pump was controlled and monitored using a digital flow meter, and six flow rates were selected, two for each flow regime: laminar, transitional, and turbulent. In the case of water plus air as dual fluid, either fluid was varied while the second fluid was kept fixed in different flow regimes as shown in Figures 3 and 4. It is noticed that a higher fluid flow rate caused higher thermal efficiency, as expected; however, considering pump power consumption and the vibration effect in the photovoltaic (PV) module, the highest yield optimal flow rates for solely air or solely water were 0.055 kg/s and 0.032 kg/s, respectively. In addition, for the dual-fluid heat exchanger when both fluids are operating simultaneously, the optimal flow rates are 0.04 kg/s for air and 0.024 kg/s for water, considering both flow schemes such as varied air and fixed water, and fixed air and varied water. The selection of optimal flow rates for the dual-fluid is purely based on performance and electricity consumption. The electricity cost to pump water/air simultaneously at high flow rates of 0.032 (kg/s)/0.055 (kg/s) is significantly higher than that of 0.024 (kg/s)/0.04(kg/s), and the difference between the overall efficiencies using both flow schemes was marginal.

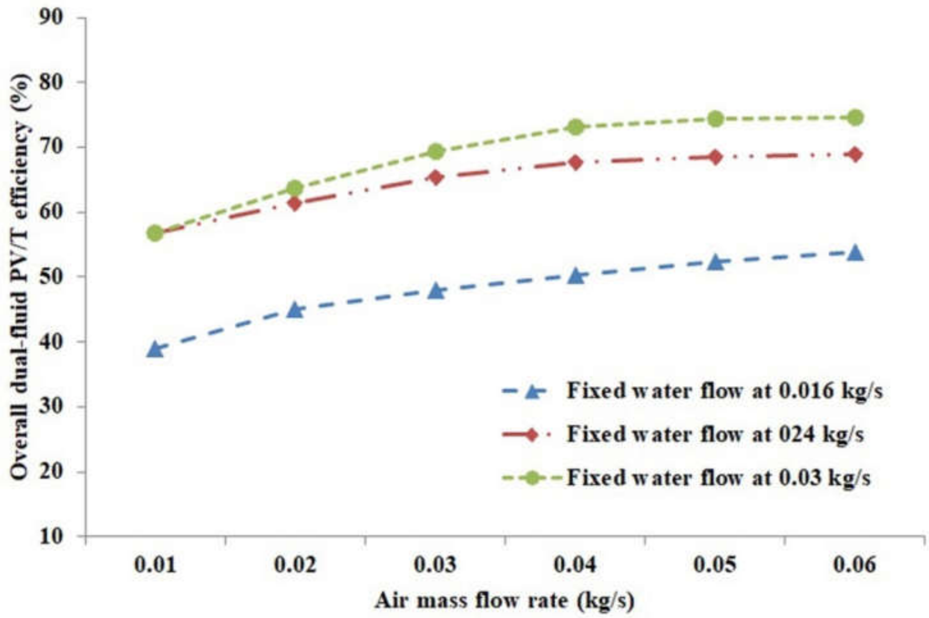

Figure 3. Variations of overall efficiency of the dual-fluid PV/T system at variable air flow rate and fixed water flow rate.

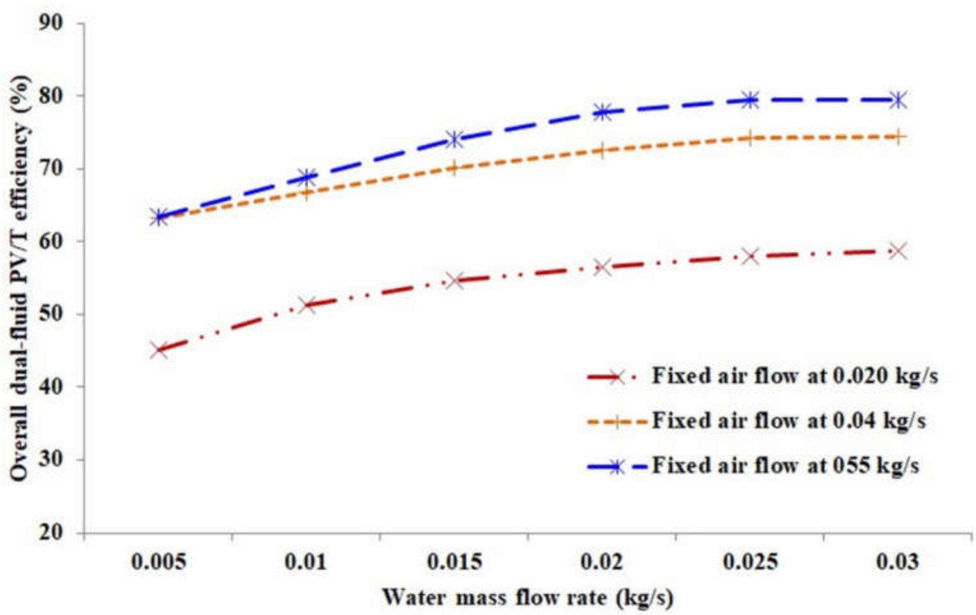

Figure 4. Variations of overall efficiency of the dual-fluid PV/T system at variable water flow rate and fixed air flow rate.

The aforementioned optimal flow rates against different modes of fluid operations are used to evaluate the PV temperature at daily variable ambient temperature and irradiance. For a comparative performance analysis, a PV module without a cooling medium is also taken into consideration during experiments. Figure 5 shows that the PV temperature for all cases varies directly with incident solar radiation; however, the individual PV module showed the highest temperature. This is because the individual PV module was cooled by the surrounding air. The maximum PV temperature with the reference case, air, water, and water plus air heat exchangers was found to be 69.4, 52.3, 50.1, and 44.4 °C, respectively. It is concluded that the higher specific heat made the water type heat exchanger more effective than the air type heat exchanger as a result of minimizing the PV module temperature. Furthermore, the dual-fluid heat exchanger (water plus air) caused more solar heat to be extracted from the PV module because of its larger surface area for heat exchange than that of an exchanger using solely water or air.

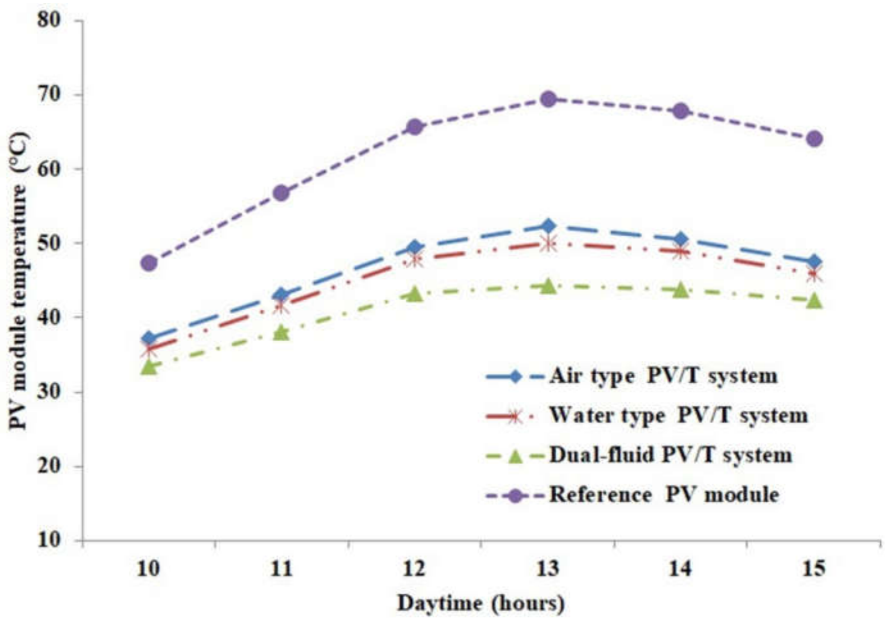

Figure 5. Daily photovoltaic (PV) module temperature plotted against different fluid operations.

The simultaneous fluid operation of water and air helped to remove the trapped, accumulated energy from the PV module, even during solar noon operation. As shown in Figure 6, introduction of air with water caused a significant improvement in the heat transfer rate. This additional heat drawn from the PV module has a benefit in the form of increased thermal gain. In other words, with a greater heat transfer rate, there will be greater opportunities to keep the PV module temperature close to standard conditions. In addition, the use of the dual-fluid heat exchanger mitigates the non-uniformity of the temperature distribution, which usually results from incident solar radiation intermittency. The daily average thermal energy achieved by air, water, and dual-fluid type PV/T systems are 569.2, 649.8, and 695.3 W, respectively. When a single-fluid heat exchanger is used, the excess heat from the PV module is lost into the surrounding air, whereas the dual-fluid heat exchanger did not allow excess heat to be trapped in cells or dissipate to the ambient air.

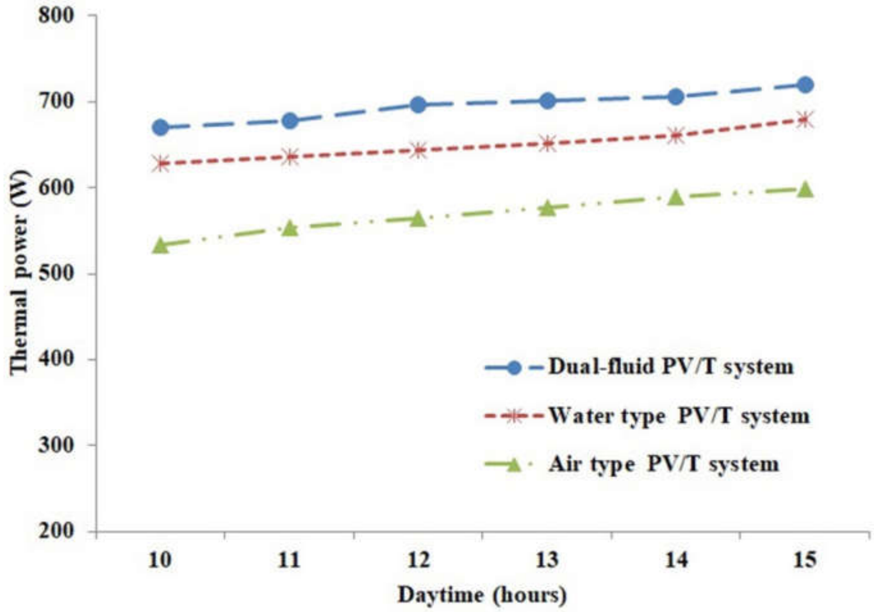

Figure 6. Daily thermal power of PV/T systems plotted against different fluid operations.

Figure 7 demonstrates the effect of hourly solar radiation variations on the electrical performance of the PV/T system. Simply put, the relation between daytime solar radiation and electrical energy at different fluid operations has been evaluated. As shown, the air-based PV/T system has the lowest performance and the dual-fluid PV/T system achieves the maximum electrical productivity. It is observed that the daily average electrical energy for the dual-fluid PV/T systems is 227.8 W, followed by the water type PV/T system with an efficiency value of 219.1 W and the air type PV/T system at third with 205.9 W. The increased electrical efficiency with dual-fluid confirms that simultaneous application of two fluids is a good choice as it maximizes the heat exchange rate and hence reduces the PV module temperature. Fluctuation in daily solar radiation and ambient temperature causes inconsistency in production and also temperature non-uniformity across the PV module, which can be overcome by application of the dual-fluid heat exchanger.

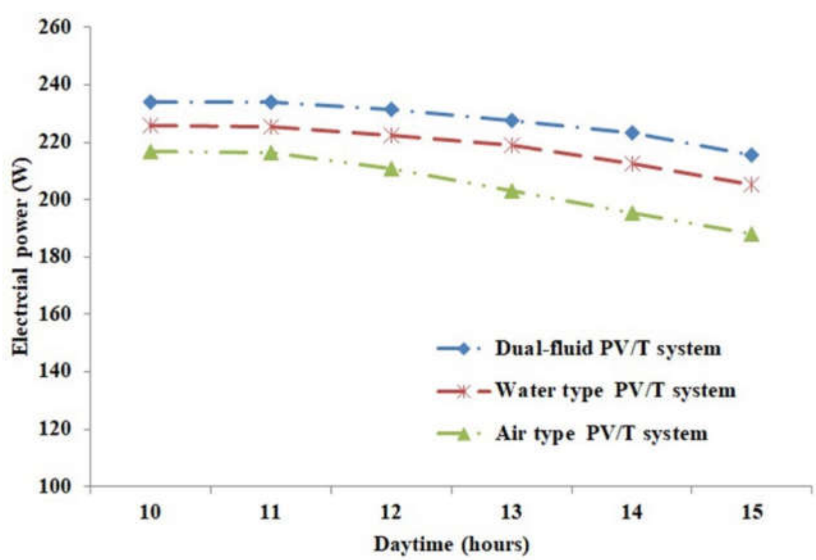

Figure 7. Daily electrical power of PV/T systems plotted against different fluid operations.

Exergy energy is considered an important part of engineering system analysis because it is helpful in achieving the maximum possible improvement in the PV/T performance. Exergy is a thermodynamic property that addresses both the quantity and quality of energy. In simple terms, the maximum useful work can be obtained until the system is brought to equilibrium with the surroundings or a reservoir. Figure 8 illustrates the effect of different fluid operations on the exergy efficiency of a PV/T system. Unlike thermal energy, the electrical energy is considered to be in the form of exergy energy, and therefore both follow the same trajectory when they are plotted in relation with solar radiation. The maximum exergy efficiency for the air, water, and dual-fluid PV/T systems are 11.5%, 12.9%, and 13.8%, respectively. The lower rate heat losses to ambient air and the higher rate of heat exchange between the PV module and circulating fluids can be attributed to an increase of exergy efficiency, especially in the case of dual-fluid PV/T systems. Furthermore, the monthly thermal and electrical efficiencies for the PV/T system with dual and single fluid heat exchangers were calculated for a period of one year so that the impact of these parameters on the system's life cycle cost can be analyzed. The monthly data obtained from the energy analysis is given in Figure 9. It is evident that the thermal and electrical performance of the dual-fluid PV/T system for all months is better than the PV/T system using air and water independently.

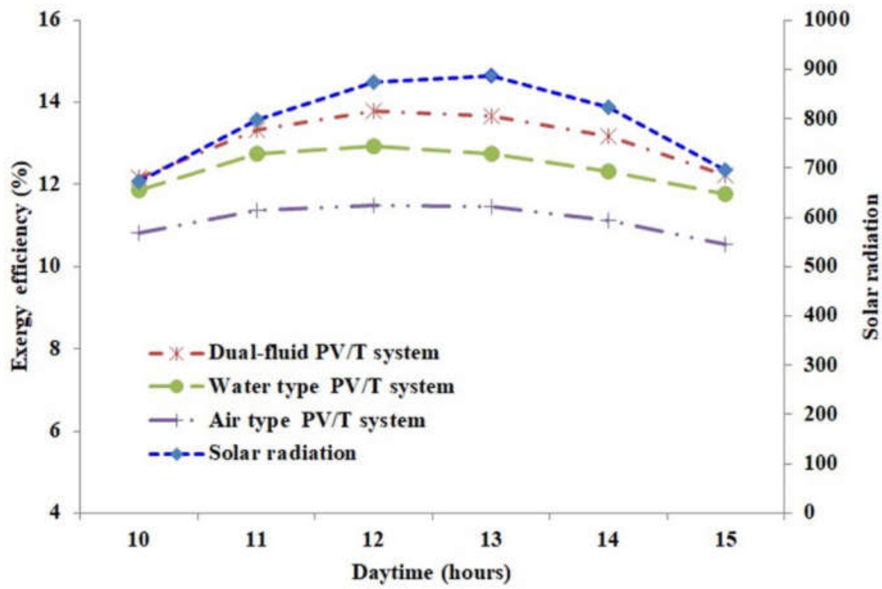

Figure 8. Daily exergy efficiency of the PV/T systems plotted against different fluid operations.

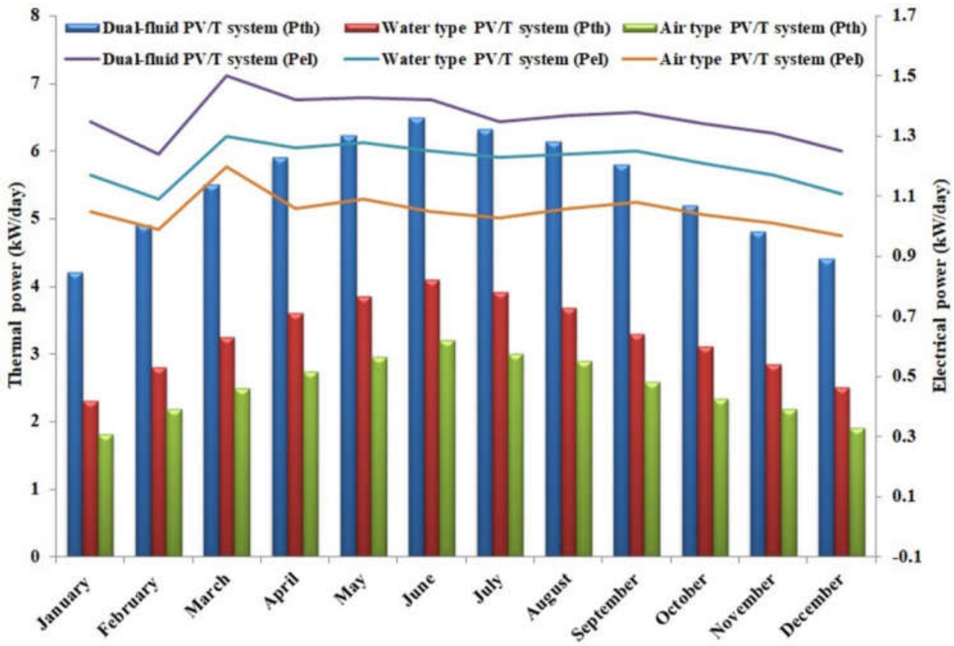

Figure 9. Monthly variations of thermal and electrical powers of the PV/T systems across the year.

A payback period in real terms represents the economic analysis of any system, especially in the context of its performance assessment. The findings from the economic analysis can help to set a clear understanding for the selection of an appropriate system from the available options. In this study, the cash flow for the assumed years is used to calculate the total cost of air, water, and dual-fluid type PV/T systems over their lifespans. The initial investment of the PV/T system is calculated by summing up the cost of each component used in assembly. Table 3 shows the initial investment cost breakdown; the presented prices of all components were obtained from local suppliers. The annual maintenance cost is the sum of the PV module, heat exchanger, and pump costs. For the simplicity of analysis, the annual maintenance cost is assumed to be 15 USD. Both the battery and inverter are not considered during the life cycle cost analysis; therefore, the annual replacement cost of the components is taken as zero. Other information for the cost analysis such as the domestic cost of energy or electricity, the discount rate, and the inflation rate specific to a region has been taken from the local government and private departments and is given in Table 4.

Table 3. Total Initial Investment.

	Dual-Fluid PV/T System	**Single-Fluid PV/T System**
Components	**Price (USD)**	**Price (USD)**
PV module	150	150
Heat exchanger	530	290 for water type and 260 for air type
Charge controller	150	150
Digital flow meter	120	120
Pump	90	-
Air blower	60	-
Pump or Air blower	-	90 or 60
Water Tank (for water-type only)	100	100
Piping or ducting	90	60 for piping and 50 for ducting
Installation	150	150
Total	1440	1100 for water type and 940 for air type

Table 4. Parameters for life cycle cost analysis.

Description	Values
Total investment	1440 USD for dual-fluid, 1100 USD for water type, and 940 USD for air type
Annual maintenance cost	15 USD
Cost of electricity [21]	0.077 USD per kW/h
Domestic electricity inflation rate	2.0%
Inflation rate [22]	1.5%
Discount rate [22]	0.5%
Annual degradation of PV & heat exchanger performances [1]	1% and 1.5%
Life of system	25

In finance, a discounted cash flow (DCF) is a widely used method because it estimates the current value of an investment based on expected outcomes that investment can produce. In fact, DCF values a project considering the concept of the time value of money. Variations of DCF across the 25-year life span of the PV/T system with dual and single fluid heat exchangers are presented in Figure 10. There is no component to be replaced, therefore, the value of DCF for all systems increases linearly without any decrease throughout the 25-year life. The performance of each system is reflected in the form of life cycle cost; this means higher energy output will lower the cost payback time. In addition, Figure 11 compares the net present value (NPV) of the aforementioned systems from the 1st year to the 25th year. The point where the line crosses the *x*-axis depicts the DPBT for the corresponding system. The DPBT for the PV/T system with dual-fluid, water, and air are 3, 5, and 6 years, respectively. It is observed that the dual-fluid PV/T system produces additional thermal and electrical energy due to efficient cooling performance, which results in a higher present value and a lower cost payback period compared to the water and air-based PV/T systems.

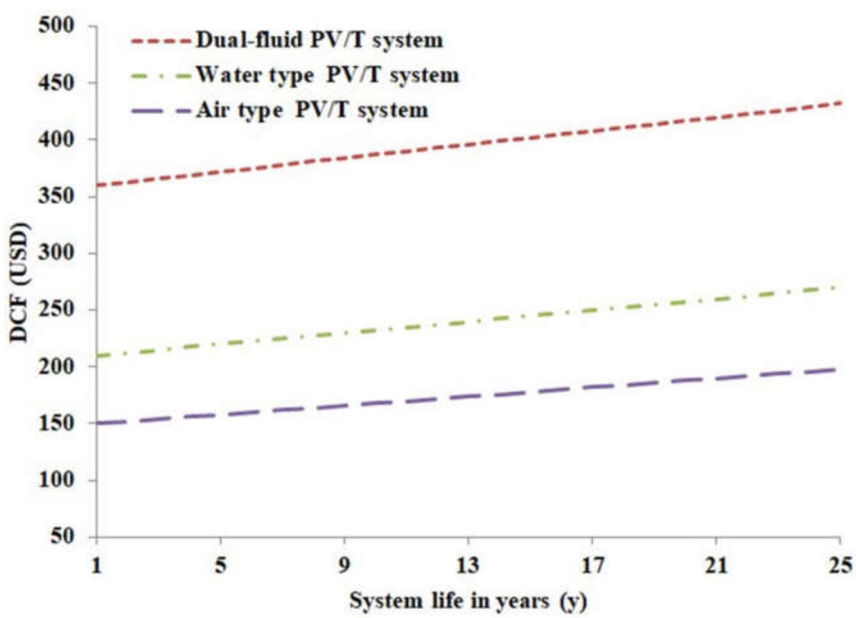

Figure 10. Variations of the discounted cash flow (DCF) of the PV/T systems across 25 years.

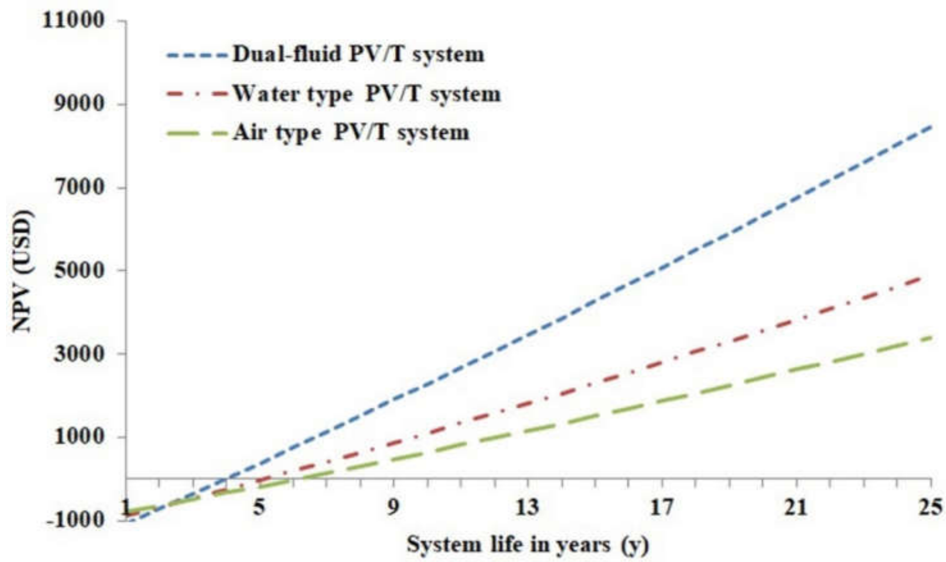

Figure 11. Variations of the net present value (NPV) of the PV/T systems across 25 years.

The energy production factor (EPF) is an important energy matrix that defines the relationship between the overall energy yields by the system and the invested energy over the 25 years of the system's life. It is defined as the ratio of energy gain to input energy. Furthermore, from an environmental perspective, the PV/T systems can also earn carbon credits by mitigating CO_2 emissions into the atmosphere. EPF, CO_2 mitigation, and carbon credits considering the life of the PV/T system with dual-fluid, water, and air heat exchangers for 20 and 25 years are given in Figures 12 and 13. For the dual-fluid, water, and air type PV/T systems considering a 25 year lifetime, the highest values of EPF and carbon credits are 5.1 and 175.9; 4.4 and 142.4; and 3.8 and 127.7; respectively. It is observed that the dual-fluid PV/T system has the highest EPF and carbon credits. This can be interpreted as higher EPF and carbon credits being associated with additional thermal energy produced by the dual-fluid heat exchanger.

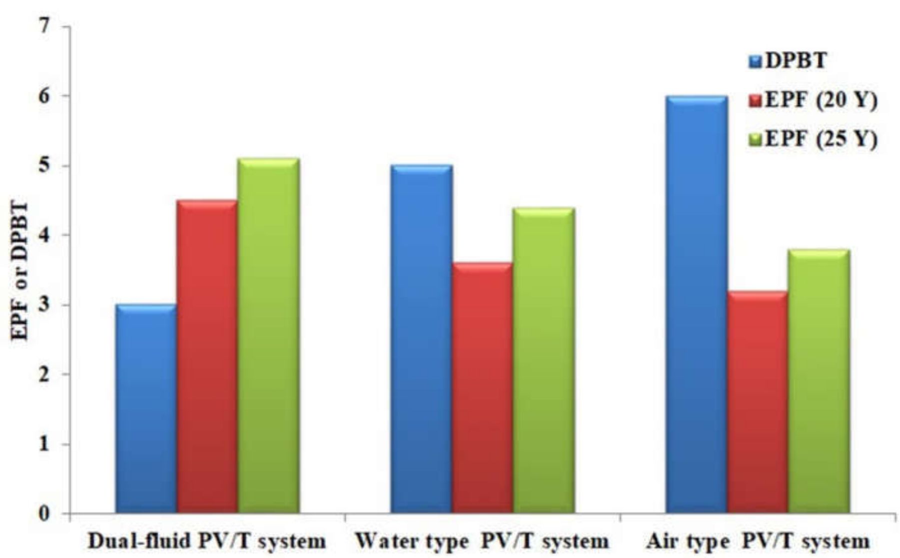

Figure 12. Energy production factor (EPF) and discounted payback time (DPBT) for different PV/T systems at 20 and 25 years.

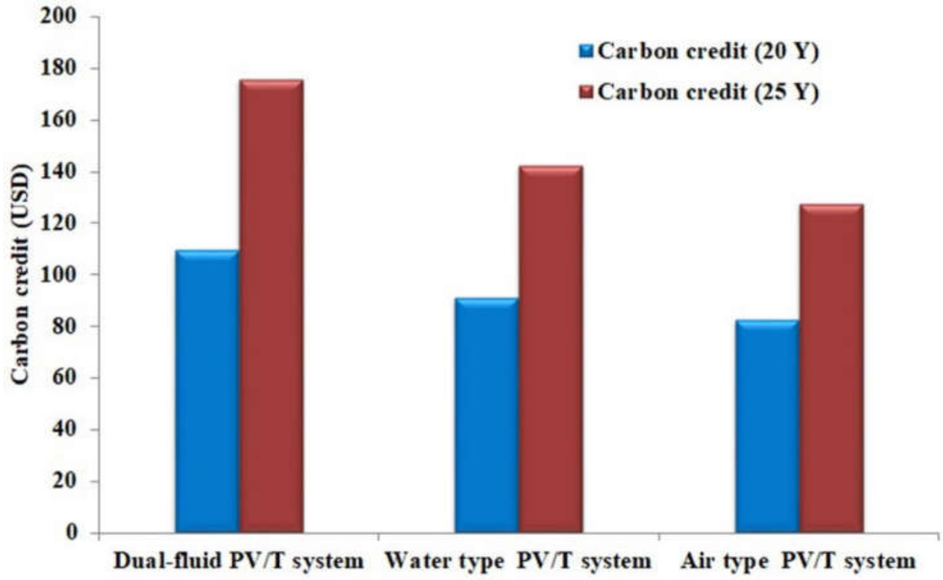

Figure 13. Carbon credits earned by different PV/T systems at 20 and 25 years.

5. Conclusions

In this study, a dual-fluid heat exchanger was used as an alternative to the conventional single-fluid heat exchanger for the cooling of a PV module, and its financial benefits were addressed relative to the domestic electrical price. It is observed that the dual-fluid PV/T system performs better than the solely water and air type PV/T systems considering energy, exergy, and economical points of view. For the dual-fluid PV/T system, results show the electrical and thermal efficiencies improved by 4% and 7%, and 10% and 21%, over water and air type PV/T systems, respectively. Considering the domestic electricity price, the electricity cost per kWh of the dual-fluid PV/T system is significantly lower when compared with the electricity cost per kWh of the water and air type PV/T systems. The discounted payback periods for the dual-fluid, water, and air type PV/T systems were 3, 5, and 6 years, respectively, which means that the total initial investment is recovered in merely three years in particular by the dual-fluid heat exchanger. Furthermore, the dual-fluid PV/T system has the highest values of EPF and also decreases significantly the cost of energy relative to the local electricity cost.

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Nomenclature

$\dot{m}$	mass flow rate (kg/s)
C	specific heat (J/kg °C)
T	temperature (°C)
A_c	surface area (m^2)
P	power (W)
G	solar radiation (W/m^2)

NPV	net present value
DCF	discounted cash flow
CF	cash flow
$E_{s,y}$	annual electricity saved by PV/T system
E_{el}	annual electricity saved by electrical load
E_{th}	annual electricity saved by thermal load
D_{el}	annual degradation of electrical performance
D_{th}	annual degradation of thermal performance
COE_I	domestic electricity cost
P_{ee}	embodied energy (J)
Greek	
$\dot{E}$	exergy rate
ŋ	efficiency
$ŋ_{ex,th}$	exergy thermal efficiency
$ŋ_{ex,el}$	exergy electrical efficiency
$ŋ_{ex,PVT}$	total exergy efficiency by PV/T system
i	inflation rate
i_d	discount rate
i_{el}	domestic electricity inflation rate
Subscripts	
w	circulating water
a	circulating air
in	Inlet
o	Outlet
∞	ambient air
th	thermal
el	electrical
tot	Total
max	maximum
sc	short circuit
oc	open circuit

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