Experimental investigation on the thermal and exergy efficiency for a 2.88 kW grid connected photovoltaic/thermal system

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Abstract. Photovoltaic-thermal (PV/T) systems have been introduced recently for waste heat extraction, to improve electricity generation from photovoltaic (PV) systems and simultaneously utilize it for potential hot water for domestic or industrial use. This study investigated a 2.88 kW grid-connected PV/T system in the terrestrial weather conditions of Sharjah, UAE. The study was experimentally investigated during December when water as a working base fluid was evaluated for waste heat recovery. The electrical, thermal, and exergy efficiencies were examined for the given system, under five different hourly intervals across the experimental period. The results have shown a notable effect of the PV/T cooling method on the terrestrial weather conditions of the UAE. A peak total efficiency of 60% was observed, showing the effectiveness in improved thermal performance because of the active cooling procedure.

Introduction

Coal, oil, and natural gas are examples of fossil fuel resources that have actively supported the world's need to produce power [1]. Because of the world's population growth, it is predicted that this demand will increase by 48% in the next 20 years [2]. Global energy demand has accelerated the use of fossil fuels and their depletion, which has accelerated the rise in carbon emissions which has been a major factor in the phenomenon of global warming [3–5]. The rapid rise in global warming has resulted in significant changes to the climate that have been observed globally over the last ten years.

Solar technologies are now a vital source of electricity production for consumers, having advanced and grown tremendously over the last ten years [6]. To address the negative effects that fossil fuels have on pollution and climate change, photovoltaic plants have been installed and deployed at a rapid pace throughout the world [7]. Photovoltaic (PV) technology has become the dominant low-carbon technology in the world due to a noticeable drop in development costs. By the end of 2020, 627 GW of PV system installations are expected to have been installed globally. PV system installations have been deployed more often. It is anticipated that within five years, the ambitious deployment of PV system installations will rise globally by at least an average of 125 GW [8].

However, PV system technologies are highly dependent on environmental parameters particularly module temperature, which contributes to their degradation and longevity [9–11]. Photovoltaic-thermal (PV/T) systems have been introduced to tackle such a dilemma by introducing cooling methods to extract the dissipated heat generated from the PV cell's surface [12–14]. Various studies have demonstrated the use of PV/T systems using different cooling methodologies to discuss the thermal and electrical efficiencies of their demonstrated systems. A study was conducted by [15] demonstrating the performance of a PV/T system under open-loop and closed-loop connections. The study demonstrated the impact of open loop configuration in improving overall thermal efficiency. Another study demonstrated the use of nanofluids to observe the efficiencies of a PV/T system [16]. The study demonstrated that the exergy efficiency was 50% higher as compared to the non-cooling conditions. The demonstration of PV/T heat pipe for heat extraction was demonstrated in [17]. The useful exergy generated by the system were considered as objective functions, to assess the performance of the optimal systems. The optimal PVHT system demonstrated a 5.1% higher exergy as compared to other proposed designs. Moreover, a spray cooling-based system is proposed as a PV/T and heat recovery system for domestic applications, as reported in [18]. The exergy losses were computed based on simulation for four different seasons. A numerical and experimental investigation of a PV/T system was studied by [19]. The study utilized a mini-channel PV/T for waste heat recovery. The results demonstrated an electrical and thermal efficiency of 12% and 47%, respectively.

The literature has demonstrated that PV/T systems present large potential, particularly for harsh regions such as the United Arab Emirates [20]. The review didn't show a prior study discussing the electrical, thermal, and exergy efficiency of a PV/T system in the UAE. Therefore, this paper experimentally investigates the performance of a 2.88 kW PV/T system installed in the University of Sharjah main campus, in the terrestrial weather conditions of Sharjah, UAE. The system is exposed to the UAE weather conditions and examined using water as a cooling fluid.

Methodology

The University of Sharjah is located at the main campus in Sharjah, United Arab Emirates. The experimental setup was built on the rooftop of the central laboratories W12 building [21]. The site of the setup is located at a latitude coordinate of 25.34° N, whereas the longitude coordinate is 55.42° E [22]. The demonstrated PV/T system has of 2.88 kW capacity, where the system is connected to the local electrical grid for clean electricity supply [23–25]. Two separate PV modules of 320 W electrical rating are used during experimentation. The PV modules are raised above the ground with a tilt angle of 20°, to ensure the stable flow of fluid on the front surface of the PV module.

Experimental Procedure

The experimental measurements were conducted during the winter weather conditions, in December. The cooling methodology was conducted across five hourly intervals between 10 AM to 2 PM, for observation of thermal and electrical characteristics.

The electrical measurements are continuously measured through a Profitest PV analyzer, which provides an accurate capacitive load for DC power, voltage, and current measurements. Whereas K-type thermocouples are utilized to measure the thermal parameters such as inlet and outlet fluid temperature, PV module front and back surface temperature, and ambient temperature. A demonstration of the experimental procedure is presented in Fig. 1. Moreover, Table 1 briefly demonstrates the technical specifications utilized for the experimentation.

Table 1. Technical Specifications of 2.88 kW PV/T system experimental setup

Description	Specifications
PV Modules	Nine PV modules are connected in series. 320 W electrical rating per module. Tilt Angle 20°
Cooling Method	Fluid Type: Water. Inlet/Outlet Fluid Tank Capacity: 200 Gal. Inlet/Outlet Pump Capacity: 1 hp
Profitest PV Analyzer	P-V and I-V curve tracing
K-Type Thermocouples	Measurement range between -200° C to 1300 °C
HPS3008 Data logger	Temperature Data logging (8 Channels)
Irradiance Sensor	Solar Irradiance measurement (W/m^2)
Anemometer	Wind speed measurement (m/s)

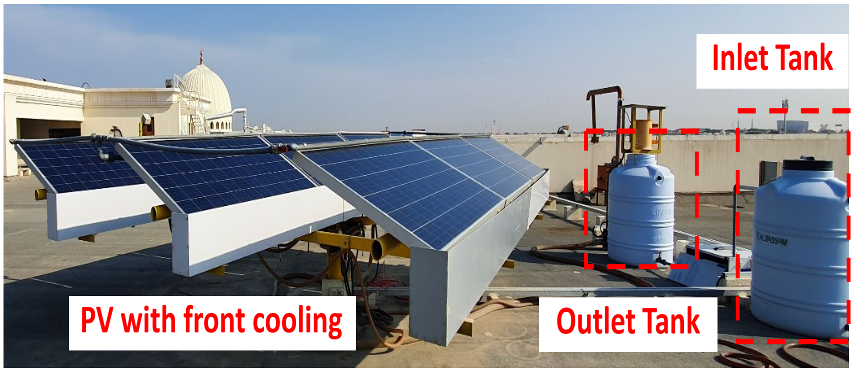


Fig. 1. Demonstration of Experimental Setup for the 2.88 kW PV/T system

Mathematical Model

The analysis results displayed in the subsequent sections are obtained by applying the following mathematical relations, equations, and formulas.

Electrical Performance

The solar-generated power (P_{in}) is a product of the solar irradiance (G) and the module area (A), which is expressed as follows:

$$P_{in} = G\,A \tag{1}$$

The maximum theoretical power (P_{theo}) can be computed based on the open circuit voltage (V_{oc}) and the short circuit current (I_{sc}), which is expressed as follows:

$$P_{theo} = I_{SC}\,V_{OC} \tag{2}$$

Similarly, the maximum output power (P_{max}) is computed based on the product of the maximum output voltage (V_{mp}) and maximum output current (I_{mp}), which is presented as follows:

$$P_{max} = I_{mp}\,V_{mp} \tag{3}$$

The electrical efficiency (η) is expressed as a ratio between P_{max} and P_{in}, represented as follows:

$$\eta_{Electrical} = P_{max}/P_{in} \tag{4}$$

Fill factor can be derived from the following equation:

$$FF = P_{max}/P_{theo} \tag{5}$$

Thermal Performance

Eq. 6 is used to determine the amount of solar heat Q_{solar} that the cooling water has captured. After differentiating it with respect to time, $m = \rho\dot{V}$, the mass flow rate, m, is computed using the mass formula. The volumetric flow rate is represented by $\dot{V}$, while the water density is denoted by ρ.

The specific heat capacity at constant pressure, $c_p = 4.18$ [J/kg. C], is used to analyze the heated property of water. By deducting the outflow temperature (T_{out}) and the input temperature (T_{in}), one may find the temperature difference (ΔT), which is then equal to $T_{out} - T_{in}$

$$Q_{solar} = m\, c_p\, \Delta T \tag{6}$$

Thermal Efficiency (η_t) can be computed through the following expression:

$$\eta_t = m\, c_p\, \Delta T\ /\ G\ A \tag{7}$$

The overall efficiency (U_F) by summing both electrical and thermal efficiencies can be described as the utilization factor as follows:

$$U_F = \eta_{Electrical} + \eta_{Thermal} \tag{8}$$

This overall efficiency represents the energy analysis that comprises of the electrical, thermal, and total efficiencies of the PV/T system.

Exergy Analysis

In this work, the second law of thermodynamics is utilized to perform exergy analysis. Calculating exergy is useful for energy systems to improve the sustainability and efficiency of the system, therefore utilizing the resources effectively and reducing the impact on the environment. The exergy analysis is typically used to mate the available energy. Therefore, the overall exergy balance for the given PV/T system is defined based on the following expression:

$$\begin{gathered} \sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \sum \dot{E}x_{loss} \\ \Rightarrow \dot{E}x_{sun} + \dot{E}x_{mass,in} = \dot{E}x_{elc} + \dot{E}x_{mass,out} + \dot{E}x_{loss} \end{gathered} \tag{9}$$

The in and out exergies are represented as Ex_{in} and Ex_{out}, respectively, the exergy destruction (Entropy) due to irreversibility is described as the exergy loss Ex_{loss}. Entropy is a measure of the disorder or randomness in an energy system due to irreversibility, such as heat transfer across finite temperature gradients, friction, and mixing; the relationship between exergy and entropy can be understood from the second law of thermodynamics. This irreversibility leads to the loss of available work (exergy) and increased entropy. This study used the Petela exergy conversion coefficient [26], which is described in the following expression:

$$\psi_s = 1 - \frac{4}{3}\left(\frac{T_{out}}{T_s}\right) + \frac{1}{3}\left(\frac{T_{out}}{T_s}\right)^4 \tag{10}$$

T_s represents the solar radiation temperature from the sun, which is previously reported to be equivalent to 5777 [K] as reported in [27,28]:

$$\begin{gathered} \dot{E}x_{in} = \dot{E}x_{sun} = \psi_s AG \\ \text{Or } \dot{E}x_{sun} = G\left(1 - \frac{T_{amb}}{T_{sun}}\right) \end{gathered} \tag{11}$$

The thermal exergy $\dot{E}x_{th}$ typically represents the heat loss from the PV system exterior surfaces to the cooling fluid and ambient, which can be described as follows:

$$\begin{gathered} \dot{E}x_{mass,out} - \dot{E}x_{mass,in} = \dot{E}x_{th} = \dot{m}_{f,out}\left[\left(h_{f,out} - h_{f,in}\right) - T_{amb}\left(s_{f,out} - s_{f,in}\right)\right] \\ h_{f,out} - h_{f,in} = C_{p,f}\left(T_{f,out} - T_{f,in}\right) \\ s_{f,out} - s_{f,in} = C_{p,f}\ \ln\left(\frac{T_{f,out}}{T_{f,in}}\right) \\ \dot{E}x_{th} = \dot{m}_{f,out}\left[C_{p,f}\left(T_{f,out} - T_{f,in}\right) - T_{amb}\, C_{p,f}\ \ln\left(\frac{T_{f,out}}{T_{f,in}}\right)\right] \end{gathered} \tag{12}$$

The exergy output for PV systems is typically equivalent to the total electrical energy $\dot{E}x_{ele}$, which can be described as follows:

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{ele}} = \mathrm{V}_{\mathrm{m}}\mathrm{I}_{\mathrm{m}} \tag{13}$$

Therefore, the exergy losses of the PV system can be computed through the following expression:

$$\dot{\mathrm{E}}\mathrm{x}_{\mathrm{loss}} = \left(1 - \frac{T_{amb}}{T_{sun}}\right) G - \dot{E}_{ele} - \dot{m}_{f,out}.\, C_{p,f} \left[\left(T_{f,out} - T_{f,in}\right) - T_{amb} \ \ln\left(\frac{T_{f,out}}{T_{f,in}}\right)\right] \tag{14}$$

Therefore, the computation of entropy generation by the PV system can be done as follows:

$$\dot{S}_{gen} = \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{loss}}}{T_{amb}} \tag{15}$$

As a result, the thermal and electrical exergy efficiencies can be computed based on the following equations:

$$\xi_{th} = \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{th}}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{sun}}} \tag{16}$$

$$\xi_{ele} = \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{ele}}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{sun}}} \tag{17}$$

Finally, the overall exergetic efficiency ξ of the PV/T system is computed based on a ratio of the output and input exergies of the system

$$\xi_{total} = \frac{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{ele}} + \dot{\mathrm{E}}\mathrm{x}_{\mathrm{th}}}{\dot{\mathrm{E}}\mathrm{x}_{\mathrm{sun}}} \tag{18}$$

Results and Discussion

The closed-loop tests for front surfacing cooling are presented in Table 2. The experimental test was conducted on a fixed tilt angle of 20°. The experimental parameters are variable with time as demonstrated in Table 2, demonstrating the variability of different environmental and electrical parameters with time. Moreover, the weather profile is presented in Fig. 2(a), presenting a peak solar irradiance at noon.

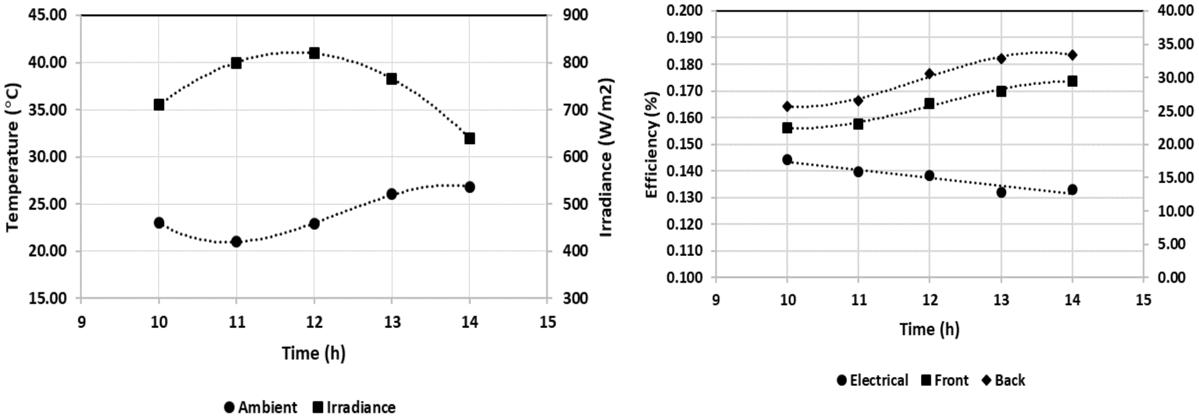
The experimental measurements show the effectiveness of water as a working base fluid, by maintaining low front and back surface temperatures. This would reflect on enhancing the electrical efficiency of the PV/T system as illustrated in Fig. 2(b). The electrical efficiency (η) can be computed based on the numerical relations that were discussed in the previous section.

As demonstrated in Fig. 4, the PV/T system under cooling conditions would contribute significantly to maintaining high electrical efficiency, with a peak of 14.5%. Thereby, the effectiveness of water as a working base fluid can be attributed to the increase in electrical efficiency throughout the day, through the maintenance of the front and back surface temperatures. An inverse relationship between the module temperature and electrical efficiency can be observed, hence its reduction as the experimentation approaches noon time.

The observation of thermal performance is essential when discussing the performance of PV/T systems. The thermal study is conducted on the given PV/T system, as demonstrated in Fig. 3. The thermal investigation is computed based on the numerical equations presented in Eq. 6-7. Commenting on Fig. 3, an inversely proportional relationship between the thermal efficiency and the thermal energy losses can be observed. The highest losses are experienced during noon time due to the reduction of the cooling effect because of the increase in water temperature, thereby affecting the thermal and total efficiency of the system.

Table 2. Experimental measurements from 2.88 kW PV/T system

Experimental Measurements								
Time	G [W/m2]	T_A [°C]	T_{in} [°C]	T_{out} [°C]	T_{PVB} [°C]	T_{PVF} [°C]	I_{SC} [A]	V_{OC} [V]
10.00	709.81	23.01	20.32	21.84	25.75	22.52	6.48	45.02
11.00	800.02	21.07	20.61	21.57	26.58	23.03	7.27	44.79
12.00	820.50	22.89	24.80	25.78	30.60	26.17	7.53	44.51
13.00	765.24	26.05	25.16	26.28	32.87	28.00	6.94	44.15
14.00	639.94	26.83	26.17	27.38	33.46	29.54	5.24	43.87



(a) (b)

Fig. 2. Demonstration of (a) Weather profile for day of experimentation (b) Comparison of electrical efficiency with front and back module temperature

The exergy efficiency was computed based on the previously discussed numerical equations and illustrated in Fig. 4. A negative relation is presented between the exergy efficiency and exergy destruction, which are lost due to the irreversibility effect. Similarly, the highest exergy destruction is experienced during noon time, presenting the minimum exergy efficiency. In this notion, the thermal efficiency demonstrates the experimental test at the given weather conditions. Therefore, as the ΔT between inlet and outlet water temperature is significantly large, the higher the thermal efficiency. Additionally, ambient conditions are to be considered a critical factor for the thermal performance of any PV/T system.

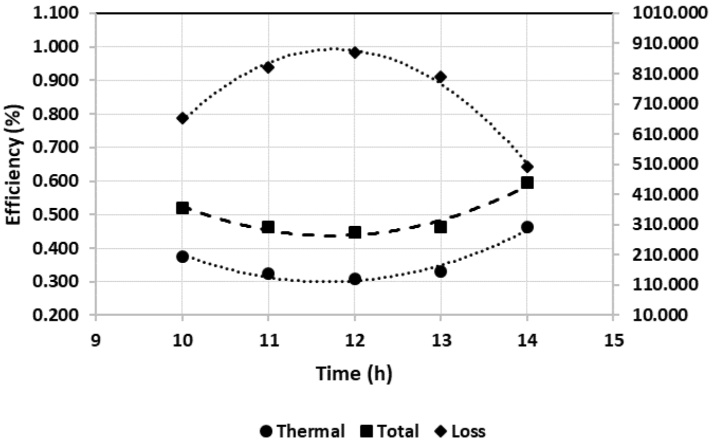


Fig. 3. Thermal performance across the period of experimentation

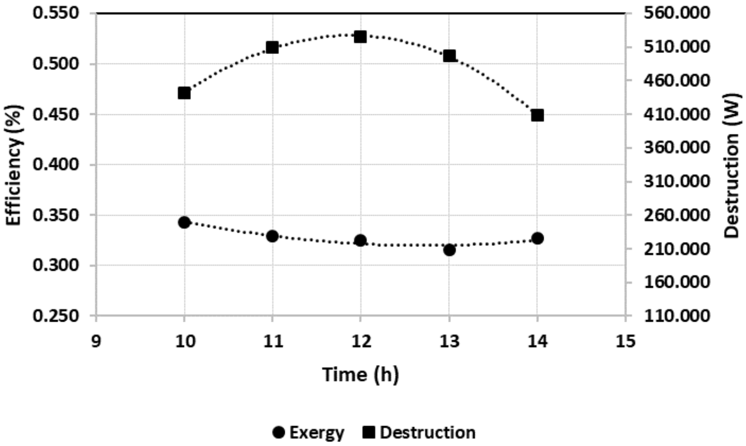


Fig. 4. Comparison of exergy efficiency with exergy destruction

Summary

This study discussed the electrical, thermal, and exergy performance of a 2.88 kW PV/T system in the terrestrial conditions of Sharjah, UAE. The experimental study was conducted during the winter conditions to assess the impact of water as a cooling fluid on both electrical and thermal efficiencies. The experimental measurements have concluded the inverse proportionality of the electrical efficiency with respect to the operating temperature, with a starting peak of 14.5%, which is close module efficiency described by the manufacturer. Moreover, a peak thermal efficiency of 48% is achieved, showing the beneficial use of PV/T systems in capturing waste heat for potential domestic applications. As a future work, the exergy analysis can be conducted for different seasons, to assess the significance of temperature difference in waste heat recovery, for total system efficiency enhancement.

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