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Numerical Investigation of a Photovoltaic Thermal System Performance under Irbid-Jordan Climate Conditions

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ABSTRACT

The performance of a photovoltaic/thermal (PVT) system in Irbid - Jordan climate conditions is numerically investigated using TRNSYS Software. The PVT system is designed to produce both electricity and hot water simultaneously. In this research work, a PVT system is tested in Irbid, which is located in the northern region of Jordan (32.50 N, 35.90 E). The effects of the factors that affected the performance of PVT were theoretically studied. They included global solar radiation, water temperature, mass flow rate, wind speed, and tilted angle. The type of PV cell under consideration is polycrystalline (Po-Si). The results show that the maximum electrical efficiency was 18% and the thermal efficiency was 42%. The optimum tilt angle for thermal efficiency was nearly 28°, while electrical efficiency was 44%. The mass flow rate of water under which the thermal and electrical efficiencies are at their maximum is equal to 20 kg/hr. Also, the results reveal that as the temperature of the city water decreases, the electrical efficiency rises and the thermal efficiency drops.

1. INTRODUCTION

Currently, wind energy [1], solar energy [2-4], geothermal energy, and biomass energy [5, 6] are the most widely used renewable energy sources. It’s a fact that the common source of heat energy from renewable sources is the sun. which can be utilized in many ways to fulfill the daily needs of human beings. The sun performs fusion reactions to heat radiation, which is a form of energy conversion [7, 8]. There are many successful solar energy conversion systems, but conversion is not limited to the sun as the primary source; wind, biomass, geothermal, hydropower, and ocean sources are also competitors [9]. Furthermore, these energy inputs have the potential to meet the entire world's energy requirements [10].

There are various key components in the solar thermal system; out of all solar collectors, one is unique, which transforms solar energy into heat energy [11, 12]. Collectors can be categorized broadly as uncovered, flat-plate, and evacuated tubular types of collectors. These three types of collectors can be considered the main classification, but special design collectors do exist. These three types of collectors are the most common, but special designs do exist. The special collector functions to serve medium to high - temperature applications, which include parabolic and Fresnel types of collectors. In nature, these collectors can be either concentrating or non-concentrating [13].

The most popular type of collector among different types is flat-plate collectors, which can offer many advantages as compared to others. Its main contractions involve an absorber which is a dark flat plate and a cover that is transparent in nature. Typical absorbers can be thin in construction and made up of metal. Aluminum and copper are two commonly used metals because of their superior heat conductivity with anti-corrosion [13, 14]. In order to get better heat energy, most absorber plates are coated with selective coatings. The heat generated by the absorber plate should be carried out by the liquid within the tube [15-17].

In the case of solar PV electric power generation, solar energy can be consumed to produce electrical or thermal energy, through either thermal or photovoltaic panels. On the other hand, these systems can also be integrated together to generate both electricity and heat [17-22].

The temperature is one of the main factors that prevent PV panels from producing electricity at high efficiency. Tan et al. [22, 23] reported that when the temperature of the surface of solar panels rises above 25℃, the panel efficiency drops by approximately 0.5%. Photovoltaic Thermal collectors (PVT) can be shortlisted as better collectors since they can achieve thermal as well as electrical energy with an average efficiency in the range of 45-70% [24].

TRNSYS software is the most widespread and common method to evaluate the performance of the solar thermal system [25]. Several authors have utilized TRNSYS (Transient Systems Solution Program) to investigate the effects of PV orientation angle, wind, radiation, ambient temperature, and PV materials (nano-SiC, nano-CuO, Si) on their performance. For example, Hussein et al. [26] utilized TRNSYS to investigate the performance of monocrystalline silicon PV modules at different tilt angles and orientations based on the meteorological conditions of Cairo (Egypt).

Ampuno et al. [27] studied a solar thermal energy generation plant that consists of a solar collector, a storage tank, and an energy conversion system. They used TRNSYS to evaluate their solar model in different coastal cities and on an island in Ecuador. They found that the efficiency of the electric power rate obtained varied between 31.1% and 41.1%.

Alobaid et al. [28] estimated the inlet temperature for the PVT efficiency. They reported that the PVT temperature (range of 45℃ to 115℃) increased because of increases in water temperature, and they obtained an average electrical and thermal efficiency of 13.7% and 65%, respectively. Different literature has considered models for the selection of the optimum tilt angles, by converting the horizontal surface to a tilted surface [28, 29]. Some studies have found that as the orientation angle increases, the higher outlet temperature decreases (1.5% decreases in Tout) [30].

According to the above literature review, several studies have been showed that addressing the effect of radiation, wind speed, inlet temperature of the thermal fluid, tilt angle, and mass flow rate of the thermal fluid on PV performance. However, these studies did not consider the consequence extensively on PV electrical parameters such as open-circuit voltage, short-circuit current, fill factor, and so on, and most importantly on solar cell temperature. Furthermore, a comparative simulation investigation of various parameters in Irbid conditions has yet to be executed. As a result, the purpose of this article is to investigate the effect of varying module radiation, wind speed, inlet temperature of the thermal fluid, tilt angle, and mass flow rate of the thermal fluid on PV cell temperature and electrical parameters using TRNSYS software at Irbid outdoor conditions in order to determine the best tilt angle for best performance. The results of this simulation will be useful in determining optimal harvesting times.

2. THEORETICAL ANALYSIS

The design aspect of the PVT collectors is an important issue. These are used in PV/collection systems for hot water. Firstly, based on the PVT units, the complete mathematical model is set. Various methods are available to carry out optimization of the design for the PVT components. The recommended methods can be multi parametric analysis to get better results [19-22]. Many parameters can be involved in the current work, but for better control, the ambient temperature, which is the city's water temperature, is taken into account. In addition to this, wind speed, mass flow of water, global solar radiation [24]. Furthermore, the surface tilt as well as solar radiation are factors to be considered.

The detailed study for this proposed research work was carried out in Irbid, Jordan. The transient system used in the present work was TRNSYS. This tool provides better flexibility in handling simulation programs by considering the modular structure. It provides complete control over the components and the connections between system-components. It is also very well integrated with the system description language.

The TRNSYS is a powerful library, which comes with compatibility for both thermal and electrical systems. Suitable options are provided to incorporate input weather data, time-dependent functions, and simulation results. Next, the weather data, which is referred to as the Meteorological Year data (TMY) file for Irbid, Jordan, was generated from Meteonorm 7 [31].

2.1 Mathematical analysis of PV-T model

The efficiency of the system influences the behavior of PVT collectors. This system efficiency includes thermal efficiency η_{th} as well as electrical efficiency η_{ele}. It is also determined by the ratio of the system's value-added thermal gain and electric gain to the incoming solar irradiation between collector gaps over a given time or period.

To get overall performance of the system, η_{total} can be as shown below:

$$\eta_{total} = \eta_{thermal} + \eta_{electrical} \tag{1}$$

Various factors deviate from the performance of the PVT including its design and operating conditions. Some of them are variations in ambient temperature, fluctuations in solar radiation and flow rate. Here, the collector was identified as a flat plate collector. It is further attached to a single glazing sheet. Additional, thermal efficiency $\eta_{thermal}$ is considered for steady state, which can be related to the following Eq. (2) [32].

$$\eta_{thermal} = \dot{m}c_p(T_0 - T_i)/(GA_a) \tag{2}$$

where, $\dot{m}$ refers to flow rate of fluid mass, c_p indicates specific heat of the working fluid, T_i and T_0 are the input and output temperatures of the fluid, respectively. While, A_a and G refer to the aperture area of the PVT model under consideration and solar radiation energy, respectively.

Thermal efficiency of PVT systems was computed based on the function of the ratio ΔT/G, where $\Delta T = T_i - T_a$, where T_a indicates ambient temperature. The electrical efficiency (the maximum generated power P_m to total solar energy) can be found using Eq. (3) [33]:

$$\eta_{electrical} = P_m/(GA_a) = I_m V_m/(GA_a) \tag{3}$$

In order to evaluate the PV module temperature T_{PV}, Amori and Al-Najjar [34] used this formula in Eq. (4) which is depends on the ambient temperature T_a and solar radiation energy G:

$$T_{PV} = 30 + 0.0175(G - 30) + 1.14(T_a - 25) \tag{4}$$

2.2 Description of the PVT system

The schematic arrangement of all the major components can are represented in Figure 1. The main component of the system are PVT collectors, storage take was made available for the hot water. A differential controller was integrated with pump so that the prevention of heat rejection from the tank to the surrounding space. The inverter is used to get stable connection across the system and house.

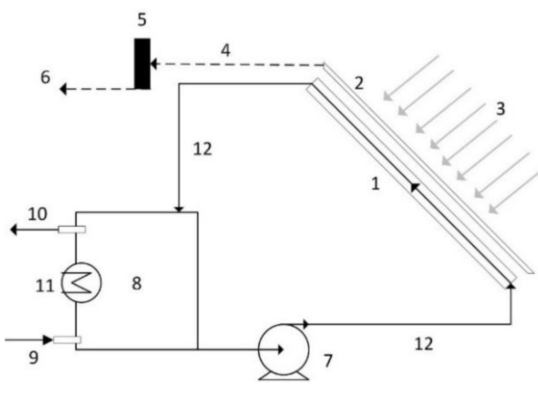


Figure 1. Schematic of PVT system: (1) Thermal plate, (2) PV panels, (3) Solar radiation, (4) Electricity, (5) Inverter, (6) Energy storage, (7) Pump, (8) Water tank, (9) Tap water, (10) Hot water outlet, (11) Electrical heater, (12) Pipe lines

The hot water generated from the system can my utilized in many ways. One of the ways is by supplying to home use with the help of additional heater so that the user get complete control on the temperature and uniformity can be maintained. In the present work the temperate was kept at 55°C with the help of controller. The allotted area for the collector was 4 x 6 m^2.

2.3 Simulation of the PVT system using TRNSYS and main components

The system is modeled by TRNSYS program, it is a highly adaptable visually based software framework for simulating the behavior of transient systems. Initially, the program identifies the components, and then a mathematical description of each component can be made available.

Figure 2 is a flow diagram that provides an overview of the main components and their improved interactions. The depicted flow diagram aids in determining the relationship between the components as well as the flow of information between them. A deck file can be used to capture incoming and outgoing information. As a consequence, data files and output formats are possible. Previously, comparable work was carried out utilizing a PVT system with an optimal water mass flow rate of 20 kg/hr and a collector size of 1.9 m^2. Because the system was in thermosyphon mode, the low flow rate may be understood. The TRNSYS Type 45 was recognized as a finalist for

The system used as illustrated in Figure 2 is an active system, and the units are primarily designed with a number of system components in consideration. The system includes a TYPE 50 PVT collector, TYPE 2b differential temperature, TYPE 3 circulation pump, TYPE 14d electricity consumption, TYPE682 from the TESS TRNSYS model for hot water load consumption, TYPE 14 b for city water load, and TYPE 38 storage tank (2 in 2 out). All the relevant data can be inserted into equation 2 and, finally, an output result from a TYPE 65 plotter printer can be achieved. This system is hourly simulated at the Irbid, Jordan location at a latitude of 32.545°.

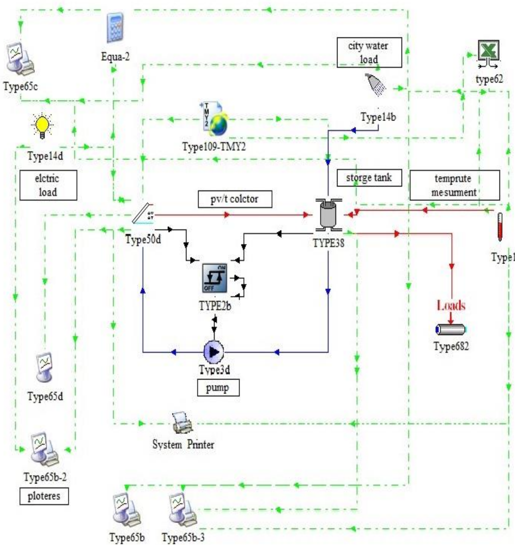


Figure 2. TRNSYS information flow diagram of PVT system

2.3.1 Parameters in TRNSYS

The present work focuses on the characteristics or design parameters of the hybrid PVT system. It is involved with computer modeling of the solar collector, storage tank, and pump, which is shown in Table 1. In PVT systems, a complete grid connection is to be maintained, which can be achieved by connecting the collector to the allotted mains electrically. Meanwhile, hydraulics for the hot water storage tank were made available.

Table 1. Design parameters in computer modeling

Mode number type	4	
Collector Area (m^2)	1.9	Flat Plate Collectors PARAMETERS (TYPE50)
Collector Efficiency Factor	0.7	
Fluid Thermal Capacitance	4.19	
Collector plate absorbance	0.90	
Number of glass covers	1	
Collector plate emittance	0.9	
Loss coefficient for bottom and edge losses	1.1	
Collector slope (deg)	30	
Extinction coefficient thickness product	0.9	
Temperature coefficient of PV cell efficiency	-0.0003	
Temperature for cell reference (c)	20	
Concentration factor	1.0	
2 Inlet 2 outlet position mode	1	Storage tank parameters (TYPE38)
Tank volume (m^3)	2	
Tank height (m)	1.2	
Height of collector return (m)	1	
Fluid density (kg/m^3)	1000.0	
Thermal conductivity (kW/m.K)	1.5	
Tank configuration	1	
Overall Loss Coefficient	5.0	
Insulation ratio	1.0	
Initial temperature (C)	25.0	
Auxiliary height	0.5	
Thermostat height	0.75	
Set point temperature	55.0	
Temperature dead band	20.0	
Flue loss coefficient	0	
Maximum flow rate (kg/hr)	100.0	Pump parameters (TYPE3)
Fluid specific heat (kJ/kg.k)	4.190	
Maximum power (W)	600	
Conversion coefficient	0.05	

PV cells used in the present case study were Amorphous Silicon (a-Si). With the assistance of software, all necessary data were extracted from the deck file. Both the collectors and the PVs have the same area. Hence, the concentration factor is considered to be 1, since it is defined as the ratio of the total area of solar cells to the area of the PV module. The input data is computed by conducting a trial-and-error method. Technical values for the temperature coefficient of solar cell efficiency and the reference temperature for cell efficiency were continuously monitored. The efficiency of the cell was calculated using PV's catalog. In total three sets of experimental data for the collector's outlet temperature were noted and compared. Furthermore, the data was extended to include all experimental data, allowing for result validation.

2.3.2 Typical Meteorological Year (TMY)

The Typical Meteorological Year data is one of the most common sources of data for the local solar climate (TMY). To collect data from TMY, meteorological measurements must be accurate. The data is presented in the form of images based on the local climate, and a simple annual average can assess the amount of fluctuation. The venue can be shortlisted for each month using this information. The average value for the predefined duration is used to calculate the reading. Furthermore, the average level of radiation during the time period is taken into consideration. When the value for a given month is close to the monthly average, the data for that month is considered.

This information is then taken up by TMY data for that month. Throughout the year, the month of computing data is completed. In the present study, the TMY file was connected to the TYPE 109 weather data. The database collection was carried out in Irbid, Jordan. All the information was investigated by the Energy Center at Jordan University of Science and Technology and the Royal Scientific Society.

Afterward, regarding domestic hot water load, a defined and steady quota was considered, according to the PVT surface; the collectors' number and dimensions of the system components (storage, pump, auxiliaries, etc.) were specified. Therefore, the load profiles were analyzed; the thermal energy to heat water is affected by the rate of consumption and the inlet and outlet temperature of water. A domestic hot water consumption of 40 l/day was assumed as 6 people's domestic hot water needs. The average temperature of the inlet water was assumed to be 25°C, and the required utilization water temperature was around 40°C [35]. During the day, the average distribution was set to be considered in accordance with the values found in the literature [36]. The volume of the tank was equal to 2 m^3, which is equal to 40-50 l/person of daily domestic hot water consumption [37]. To reduce heat loss, the thermal coefficient of the insulating layer of the tank was considered to be 0.5 W/m^2. The auxiliary heater is connected to the highest part of the heat exchanger in the tank. It is required to supply thermal energy which cannot be provided by the PVT collector [38].

2.3.3 Verification of simulation model

The simulation model at hand can be verified as shown in Figure 3 below. By comparing the results of this study with that reported in references [7, 8]. A schematic diagram of computer (TRNSYS) modeling that was used in this study for verification is shown in Figure 3.

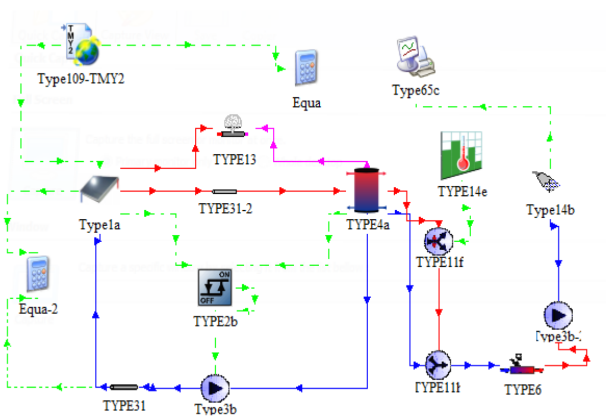
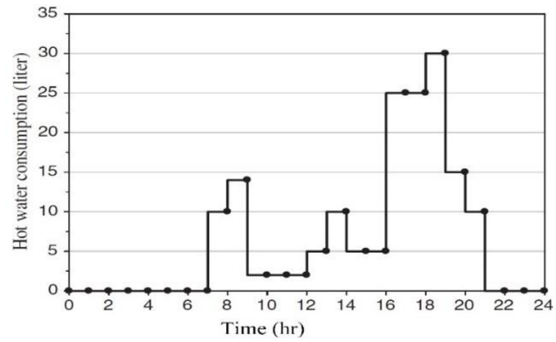
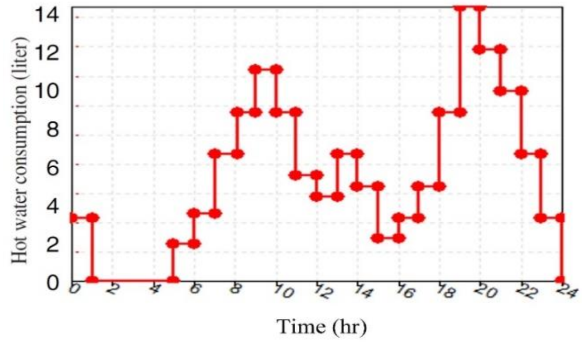


Figure 3. Verification schematic diagram of computer (TRNSYS) modeling

The average daily water consumption profile was studied over a 24-hour period (Hot water consumption), and we obtained nearly the same result by using the same simulation, as shown in Figure 4 (a & b).



(a)



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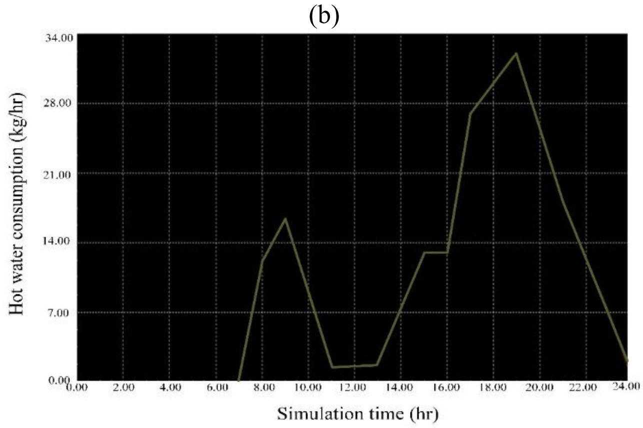


(c)

Figure 4. (a) Simulation verification result [1]; (b) Verification result by TRNSYS modeling [8]; (c) Present simulation verification result by TRNSYS modeling

From the verification of the previous studies [7, 8]. (Hybrid PVT solar systems for domestic hot water and electricity production), the absolute error was calculated and found nearly 14.7% and it was an acceptable value.

3. RESULTS AND DISCUSSION

The simulation was implemented to obtain the maximum total efficiency. the main parameters which affect the PV performance were studied. In addition, the thermal and electrical efficiency was investigated. The TRNSYS model was developed to simulate the electrical and thermal performance in this study. The PV cell type of polycrystalline (po-Si) was chosen, with electrical efficiency of around 18% and thermal efficiency of around 42%.

3.1 Effect of global solar radiation

The maximum solar intensity in the summer from 21/3 to 21/6 is nearly 1,220 W/m^2. During the winter, the minimum solar intensity is nearly equal to 620 W/m^2, from 21/9 to 21/12 as illustrates the global solar radiation in Irbid-Jordan [38, 39].

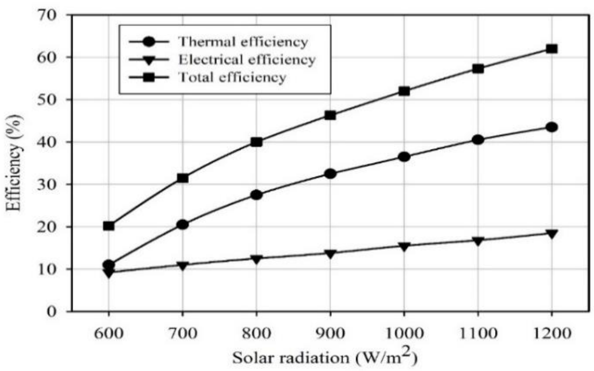


Figure 5. Effect of solar radiation on thermal, electrical, and total efficiencies

Figures 5 depict the effect of solar radiation on thermal, electrical, and total efficiency, respectively. It is self-evident that as solar radiation increases, so does electrical and thermal efficiency, and thus total efficiency.

The effect of solar radiation on the efficiency of the solar model is illustrated in Figure 5. The efficiency of electrical and thermal is increased as the solar radiation increases. Increasing the solar radiation from 700 to 1,000 W/m^2 (43%) caused an increase in electrical, thermal and total efficiencies by 45.4%, 85%, and 67.7% respectively. This result is accomplished by the result obtained by the studies [40-43]. the impact of increasing irradiation intensity on the thermal and electrical efficiency of a PV module; efficiency is reduced as irradiation is increased. The explanation for this steady increase in power output is the growing tendency of both voltage and current to rise with irradiation, with current increasing linearly and voltage increasing logarithmically [44]. On the contrary, the total efficiency trend, increases at a low rate with increasing irradiance levels. This is due to the limited capability of cell power conversion. The Shockley-Queisser limit, which is further reduced by cell temperature increase and other factors, states that PV solar cells cannot convert more than 33.7 percent of the light from the sun into electricity generated. While the reason behind the increasing in thermal efficiency is due to temperature raising.

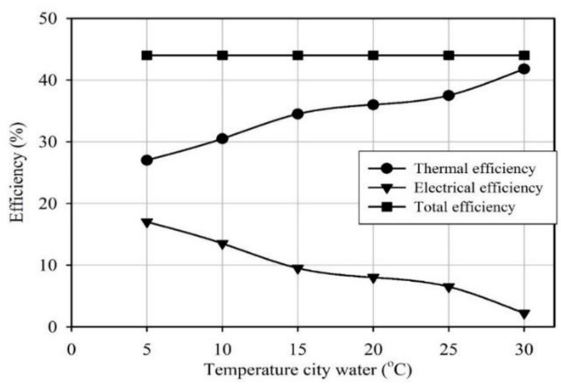


Figure 6. Effect of temperature city water on thermal, electrical, and total efficiencies

3.2 Effect of city water temperature

The effect of city water temperature (CWT) on the thermal, electrical, and total efficiency of the PVT system is shown in Figure 6. According to the results, the thermal efficiency of the CWT will improve as the temperature of the CWT rises. While increases in the value of PVT will reduce electrical efficiency. Meanwhile, as the flow rate increases, total efficiency remains constant. These findings are encouraging when compared to the findings of Al-Odat et al. [42].

3.3 Effect of mass flow rate water

The effect of water flow rate on thermal, electrical, and total efficiencies is presented in Figure 7. As illustrated in Figure 7, the PV panel's electrical efficiency increases as the flow rate increases. This is because the panel is operating at a lower temperature. The output of thermal efficiency rises and then falls. The total efficiency increases and remains constant at a flow rate of 20 kg/s, which is related to the extra electrical energy utilized to cover the thermal loads after a flow rate of 20 kg/s. the same behavior of PVT was reported by Kasaeian et al. [45]. Also, this result agrees with the findings [45, 46].

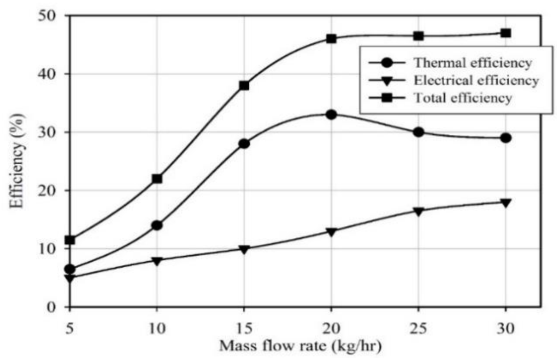


Figure 7. Effect of mass flow rate on thermal, electrical, and total efficiencies

3.4 Effect of wind speed

The influence of wind speed on thermal, electrical, and total efficiency is plotted as shown in Figure 8. Wind speed has a significant impact on thermal efficiency, which has decreased dramatically. This relates to heat losses caused by heat transfer to the surrounding environment. Also, the results show that the overall efficiency remains constant. These findings were in agreement with those reported by the researchers [29, 36-37, 39].

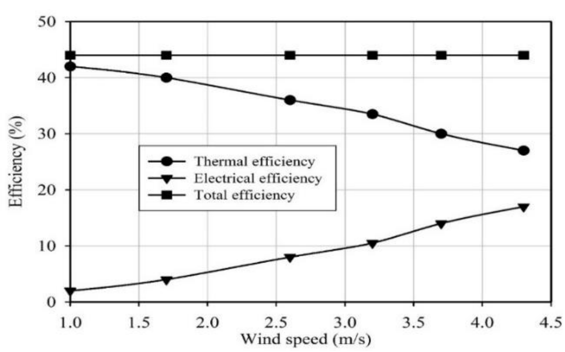


Figure 8. Effect of wind speed on thermal, electrical, and total efficiencies

3.5 Effect of tilt angle

The effect of varying module tilt angle under a particular irradiation condition has been investigated. Because the peak radiation intensity of 1,200 W/m^2 exists for a very short period of time, while the mean irradiance level over the 6 hours of a sunny day is 1,000 to 600 W/m^2, an analysis has been performed at this irradiation.

The influence of the tilt angle on thermal and electrical efficiencies is shown in Figure 9. It is clear that the best slop angle for thermal efficiency it is nearly 28°, and e the optimum angle for electric efficiency is about 42°. Figure 9 depicts the thermal performance of the module under variable tilt angles in Irbid outdoor conditions. As shown, as the tilt angle increases, the temperature of the PV cell decreases, and this is more noticeable at 40° to 48° angles. The cell temperature and thermal efficiency both decrease when the tilt angle is less than 20°. At optimum tilt, the module confronts regular to the sun's rays, allowing the system to intercept the maximum amount of irradiation. As a result, the temperature of the module surfaces and PV cell is the highest at this position. Jamil Ahmad and Tiwari [47] revealed a 1% drop in electricity due to a rise in cell temperature caused by a fixed tilt. Also, the tilt angle affected the electrical efficiency, it increased until 45 then decreased.

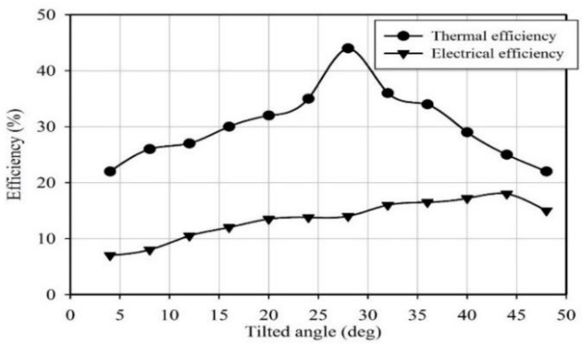


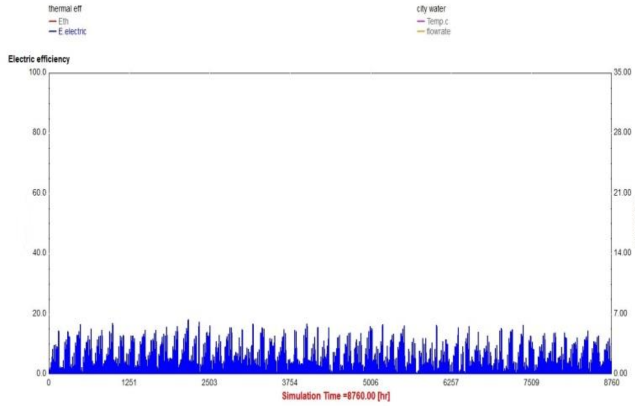
Figure 9. Effect of tilted angle on thermal and electrical efficiencies

3.6 Electrical and thermal efficiency of PVT cell

Every type of PVT cell has its own physical characteristics, but its performance is influenced by the previously discussed factors. Figure 10 (a & b) depicts transient electrical and thermal efficiencies over the span of 1 year.

As illustrates in Figure 10 (a), The maximum efficiency was achieved about 18%. Despite the fact that in the winter there are fewer sunny hours, the lower solar intensity and lower average solar cell temperature at Irbid result in slightly greater than expected electrical efficiency. It has been observed that during non-sunny hours, efficiency drops to zero. In addition, the performance of PV is influenced by the ambient temperature during the summer season, resulting in a drop in electrical efficacy.

The generation of thermal energy varied greatly depending on the season, as reported in Figure 10.b. During the winter, the proposed system only meets a small portion of the thermal load. This is due primarily to the low ambient temperature and sun intensity. The greatest thermal efficiency of the PVT system was 42 percent. The thermal efficiency rises during the day and falls at night to lower levels. The same trends and results of electrical and thermal efficiency were observed by Sheshpoli et al. [48].



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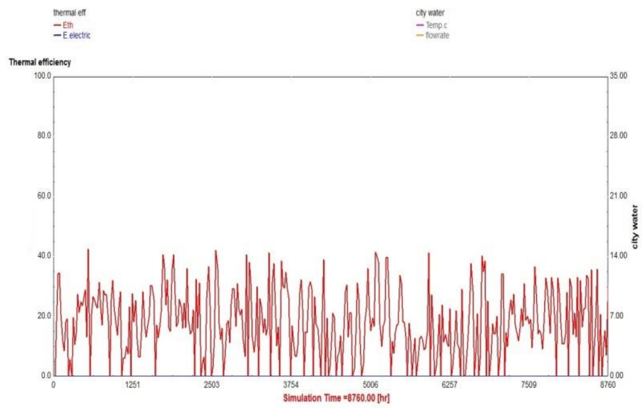
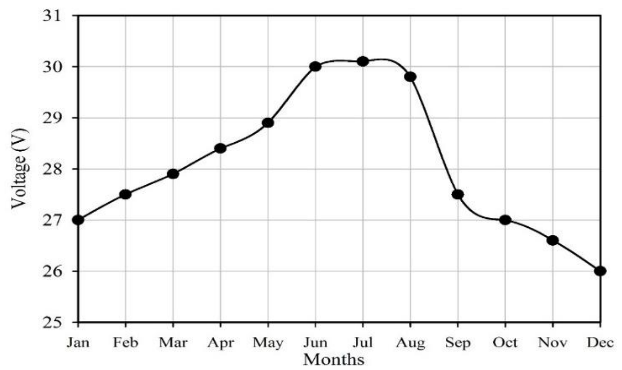


(b)

Figure 10. (a) Transient electric efficiency over the span of 1 year; (b) Transient thermal efficiency over the span of 1 year



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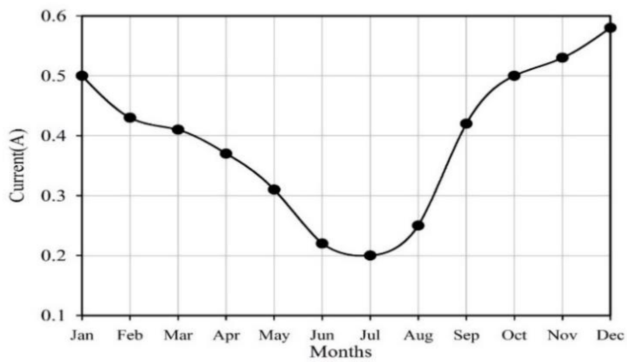


(b)

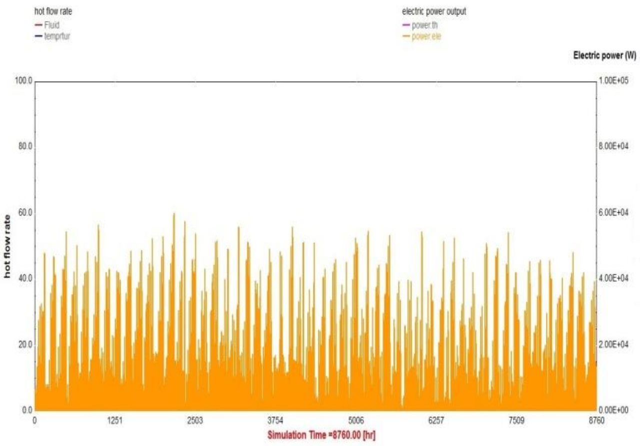
Figure 11. (a) Average voltage gained for each month of the year; (b) Average current gained for each month of the year

3.6.1 Current and voltage

It is clear that the current variation with voltage. This relation is almost constant up to 18 V. Figure 11 illustrates the average voltage variation during the months of the year, and it can be seen that the maximum voltage output is in June, July and August. Whereas the current values in these months are minimal as shown in Figure 11 (b).

3.6.2 Power output

The output power obtained from the PVT system is displayed in Figure 12 (a & b). The results indicate the PVT should be installed with optimum tilt angle (oriented up to 28° for thermal production and 42° for electrical production), and it was determined that there is less than 1.45% decrease in outlet temperature for PVT oriented more than 42° for electrical efficiency and over 28° for thermal efficiency. This is supported by the findings of [28, 29]. They have reported that the best tilt angles for electrical efficiency are between 37 and 44 degrees. The results show that the thermal efficiency of the PVT increases from 28% to 40% as the water inlet temperature increases. Electricity efficiency has dropped from 0.15% to 0.02%.



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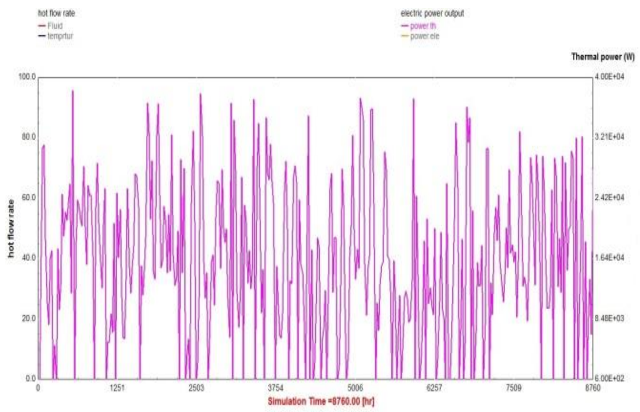

(b)

Figure 12. (a) Electric power output during one year; (b) Thermal power output during one year

4. CONCLUSIONS

The performance of a photovoltaic/thermal (PVT) system in Irbid. Jordan Climate conditions are numerically investigated under the Irbid- Jordan climate conditions. The effect of the factors that affected the problem under consideration were theoretically studied. The results show that the high electrical efficiency was 18% and the thermal efficiency was 42%. The optimum tilt angle for thermal efficiency was nearly 28o, while electrical efficiency was 43%. Increasing the CWT can lead to higher electrical efficiency and thereby reduction of thermal efficiency of PVT system.

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NOMENCLATURE

T_a	Temperature, ℃
G	Solar radiation energy, $W.m^{-2}$
C_p	Specific heat capacity at constant pressure, $kj.(K.kg)^{-1}$
A	Area, m^2
I	Current, A
V	Volt, V
PVT	Photovoltaic Thermal collectors

Greek symbols

η	Efficiency, %
$\dot{m}$	Flow rate of fluid mass, $kg.s^{-1}$

Subscripts

i	Input
o	Output
a	Ambient
m	Maximum