Performance Optimization of Photovoltaic Thermal System under UAE Climate Condition: Experimental and Simulation Analysis

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Abstract: ***One of the worldwide challenges is reducing energy consumption to reduce greenhouse gas (GHG) emissions that are associated with energy production and use. This research focused on evaluating and assessing both electrical and thermal performance of the PVT system, under UAE climate conditions, in the first phase of the study. Then, enhance the performance of PVT, by optimizing some of the design parameters. In the first part, the performance of PVT, in comparison with PV panel, was tested experimentally. The collected data from the experiment were utilized to develop a simulation model to represent PVT by using TRNSYS software. The simulation model was used to optimize the PVT performance by changing some of the design parameters. The design parameters were: number of collector tubes, tubes diameter, and PVT panel area, and water flow rates. Experimental results showed that the enhancement in electrical efficiency of PVT in winter was 0.7%, which is equal to 5% more in comparison with PV. The results in summer were 1.2%, which is equal to 8.9% more in comparison with PV panel. The overall PVT efficiency in winter was 53.8%, and in summer the overall PVT efficiency was 57.1%. The simulation results showed that the optimum number of collector tubes was 12 tubes; the optimum tube diameter was 0.04 m; and the water flow rate was 2.5 GPM in both winter and summer. In addition, results showed that changing the PVT area was not feasible. There was no enhancement in the overall efficiency. Based on the identified optimum values of design parameters, the optimized model was created. The results from the optimized model showed further enhancement in comparison with the reference model. The percentage of electrical efficiency enhancement of PVT was 7.2% in winter and 7.5% in summer, compared to the reference model. In addition, the research compared the electrical performance of the PV panel with the PVT optimized model. The electrical efficiency of the PVT optimized model provided higher electrical efficiency than the PV panel by 6% during winter and 10% during summer.***

Keywords: PVT, Experiment, Simulation, TRANSYS, UAE

1. Introduction

Globally there are increasing concerns related to the catastrophic effect of increasing CO_2 emission. During the United Nations Climate Change Conference, COP 21, in 2015, over 190 countries signed an agreement to keep global warming below 2°C by 2050 (Guarracino, 2017). The agreement goal cannot be achieved unless all the countries locally limit CO_2 emission. Accordingly, many countries around the world initiated green agendas to mitigate the effects of increasing CO_2 concentration. The agenda included initiatives that focus on energy conservation and the use of renewable energy sources.

The UAE is committed to the COP 21 agreement, through establishing Energy Strategy 2050 (National Climate Change Plan of the United Arab Emirates 2050, 2017). The UAE energy strategy aims to produce energy from mixed renewable sources (solar and nuclear) sources. Therefore, the UAE increased the renewable energy share by implementing a series of initiatives on different scales (Kazim, 2015). One of the best renewable energy solutions is solar energy, as it is available in the UAE and GCC areas all around the year.

Despite the fact that earth receives a huge amount of solar energy on daily basis (Bagher & others 2015), utilization of solar energy is marginal. Mainly sun light can be utilized in two ways; either generating electricity by using photovoltaic, or heat by using a solar collector. In the case of a water collector, working fluid is used to transfer the absorbed heat from solar radiation to be utilized in different applications. The type of application determines the type of solar collector that needs to be used. Solar collectors and photovoltaic both have a variety of types available in the market, with different specifications and efficiencies. Boubekri (2009) stated that, at the peak time the highest efficiency of PV panels can reach only up to 20%. The rest of the absorbed solar energy is wasted as heat. The wasted heat affects the PV panel's electrical performance negatively (Sciubba and Toro, 2011). The electrical efficiency of the PV panel loses about 0.25% to 0.5% if the surface temperature of the panel increases by 1 degree Kelvin above the reference temperature.

Therefore, the idea of attaching PV panels with solar collector panels was initiated. The panel is called PVT hybrid which can produce both electrical and thermal energy simultaneously (Allan, 2015). Coupling PV panel with solar collectors, removes the excess heat from the back of the panel, which results in higher produced voltage. Figure 1.1 PVT Hybrid basic components.

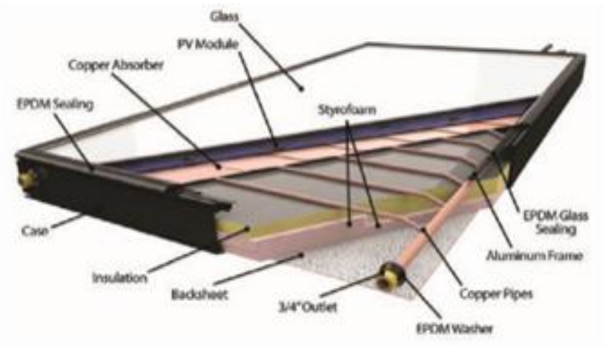


Figure 1: PVT Hybrid basic components (www.solarpowerworldonline.com)

Since the UAE has the vision to achieve 50% clean energy by 2050, adopting a system such as PVT, would be feasible. However, PVT performance is affected by changing geographical location and climate conditions. Geographical location affects the solar intensity and climate condition affecting the surface temperature of the PVT panel. The UAE has hot climate conditions. There are inadequate studies performed in the UAE to study the performance of the PVT system. Therefore, the current study will focus on testing PVT under UAE climate conditions. In addition to the performance evaluation, optimization for PVT will be conducted in the same study. This study aims to main activities experimental test for two panels the PVT panel and conventional PV panel in Dubai. The experiment will be conducted twice during summer and winter to compare the performance during different season. Then, Develop simulation model on TRNSYS by using the collected data from the field experiment. The simulation model will be used to assess the impact of some of design on overall PVT performance.

2. Data and Methodology

2.1 Experimental test and Data Collection

The methodology followed in order to achieve project objectives is divided into two parts. The first part was a field experiment of a PVT system in comparison with PV. The second part is developing a simulation model based on the data collected from part one (experimental test). The test procedure for the field test was developed based on (BS EN12975-2:2006 and IEC 61215-1-1). Up-to-date, there is no defined standard to evaluate the PVT performance. Hence, the best way to evaluate the performance of the PVT is to assess both the electrical and thermal performance of the system separately. The adapted method for evaluating the thermal performance of the PVT was the steady-state. The steady-state suggests that all the solar collector characterization remains constant with time during the test. EN12975-2:2006 standard was used to develop the thermal test procedure. IEC 61215-1-1 was used to evaluate the electrical output of the system. In the experiment, two PV and PVT were used with identical electrical specifications and areas. The data were collected and used to develop the TRNSYS model. In this section, the experimental setup will be explained in detail. Data were collected in two seasons summer and winter. The comparison between collected data was conducted based on the electrical performance, thermal performance, and overall performance. In the simulation part, the developed model was optimized by changing design parameters of PVT such as number of water tubes, water tubes diameters, PVT panel Area, and water flow. The objective of changing design parameters is to further enhance and optimize PVT performance. Finally, all the optimized parameters were combined in one model, and the results will be compared with the original model.

2.2 Test Rig Description:

The test rig consisted of a PV panel and PVT panel fixed on the same frame with the same tilt angle and with the same fixation height. Both (PV and PVT) panels are identical in size with a 1.2 m^2 gross area and the same electrical specification. The only difference is that one of them is attached to the solar collector to form PVT. The main aim of the field test is to collect sufficient realistic data to develop a simulation model and validate it. Therefore, the test rig was connected to the data logger and storage batteries. Both panels were connected to batteries to store the generated power and separate energy meters. The batteries were connected to a light fixture as a load. Each one of the panels is connected to an energy meter to record the generated power instantly (voltage, current, and output power). The inlet and outlet water temperature of the PVT panel were measured by using thermocouples. Thermocouples were connected to the data logger. In addition, a pump and flow meter were installed at the inlet line of the PVT panel. Two water storage tanks were attached to the PVT. The experimental setup is mainly open-loop test type as there is no feedback water return to the feeding water tank. The data collected every two minutes started from 07:00 AM time and ended at 18:00. Data for the full two days were collected one day during the winter season on 07/02/2020 and the second day during the summertime on 24/08/2020. The aim of the testing during the different seasons with the same setup was to compare the performance of PVT in both weather conditions and find the enhancement in the electrical and thermal performance. These two days were selected as one of the coldest days during winter and one of the warmest days during summer. Both days represent the least and highest weather temperatures all over the year in the UAE. Weather data were collected on site. The measurements such as air temperature (t_a) was recorded onsite by using weather station. In addition to the ambient temperature the wind speed, wind direction, and diffuse solar radiation have been recorded. Experimental Test- setup Schematic Diagram in Figure 2 and Field test arrangement in Figure 3.

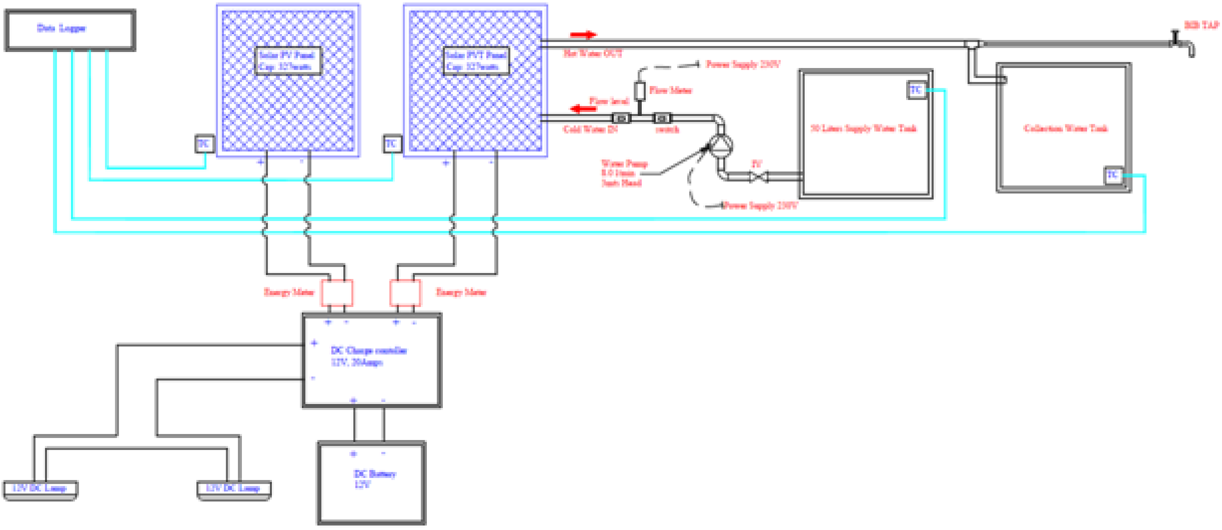


Figure 2: Experimental Test- setup Schematic Diagram

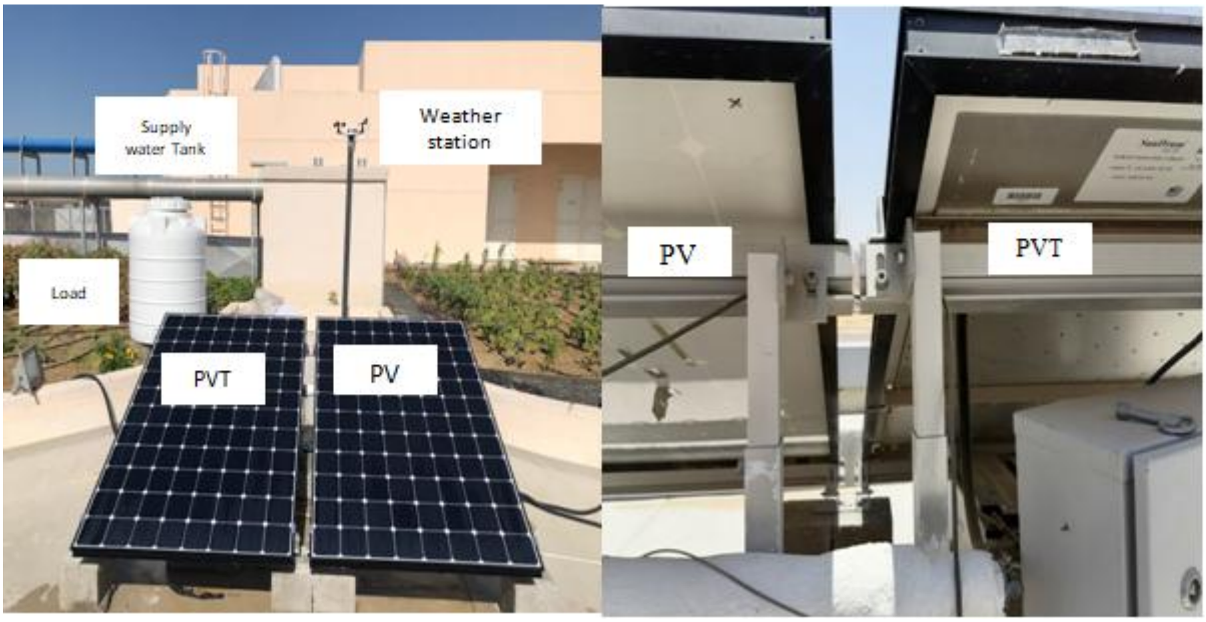


Figure 3: Field test arrangement

The actual useful power extracted from the solar collector is calculated from the following equation. The same equation was used to calculate the useful power generated from the PVT panel as per EN 12975-2:2006 (Kovacs, 2012):

$$\dot{Q} = \dot{m} c_f \Delta T \text{..}(1)$$

Where:

$\dot{Q}$ - useful power

c_f – Mean fluid temperature

$\dot{m}$ - Mass flow rate

ΔT - Difference between outlet temperature and inlet temperature

Output electrical power calculated by following equation.

$$P = V \times I \text{..............................}(2)$$

Where:
P - Electrical Power
I – current
V – Voltage.

2.3 Simulation Model

The second part of the methodology was the simulation phase. In the simulation part, the collected data from the experiment were used to develop a simulation model in TRNSYS 18. TRNSYS is a simulation tool that has powerful capabilities to mimic or simulate the behavior of both electrical and thermal performance of the PVT. In the current research, simulation model was developed. For PVT as shown in Figures 4. In this case, Type 560 was used to represent the PVT. Type 560 is the component that represents the unglazed type of PVT in TRNSYS. The reason for choosing the type PVT mentioned earlier in this research in the literature review. Additionally, a plotter of Type 65d is used to plot the results in comparison to input data. Type 25°C was used to print out the results file after running the simulation. The full model is shown in Figure 4.

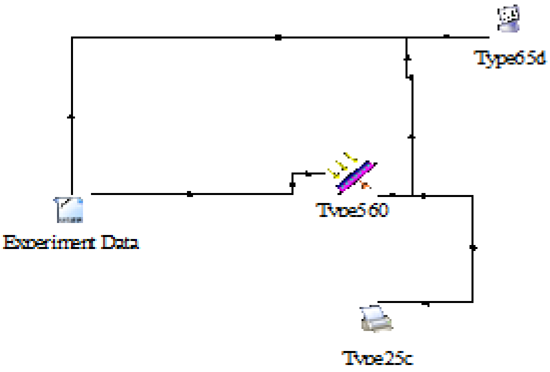


Figure 4: PVT system TRNSYS Model

3. Discussion of Results

3.1 Filed Experiment Results

The first objective of this research is to test and evaluate the electrical efficiency of PVT in comparison to standard PV during winter and summer. Table 1 and Table 2 show the results from the field experiment during summer and winter.

Table 1: Summary of experimental input data and output results for winter

	Parameters	Value	Unit
Input data	water flow rate	0.5	GPM
	Date of test	07-Feb-20	
	start time	06:00	AM
	End time	06:00	PM
	Test Duration	12	hr
	Sun rise	06:58	AM
	Sun Set	06:05	PM
	flow rate	0.031467	kg/s
	C_p	4179	J/kg·K
	Area	1.2	m^2
Output data (Results)	Maximum Electrical power PVT	119.196	W
	Electrical Efficiency PVT	14%	
	Maximum Thermal power PVT	494.2577	W
	Maximum Thermal Efficiency PVT	53.80%	
	Average Thermal Efficiency PVT	42.50%	
	Maximum Electrical power PV	115.5	W
	Average Electrical power PV	62.9	W
	Electrical Efficiency PV	13.30%	

Table 2: Summary of experimental input data and output results for summer

	Parameters	Value	Unit
Input data	water flow rate	0.5	GPM
	Date of test	24-August-20	
	start time	6:00	AM
	End time	6:55	PM
	Test Duration	12.00	hr
	Sun rise	6:00	AM
	Sun Set	6:05	PM
	C_p	4179	J/kg·K
	Area	1.2	m^2
Output data (Results)	Maximum Electrical power PVT	127.59	W
	Electrical Efficiency PVT	13.40%	
	Maximum Thermal power PVT	584.163	W
	Maximum Thermal Efficiency PVT	83.0%	
	Average Thermal Efficiency PVT	57.1%	
	Maximum Electrical power PV	120.375	W
	Average Electrical power PV	64.122	W
	Electrical Efficiency PV	12.2%	

3.2 Simulation Results

The simulation model results were compared with the data collected from the field experiment to investigate the accuracy of the simulation model. In the literature review, it has been mentioned the accurate simulation model must produce results within 5% error in comparison with the experimental results. The compatibility between the experiments results and simulation results is shown in Figures 5 and 6. The comparison has been conducted between experimental and simulation results of (T_{out}, output thermal power, and output electrical power).

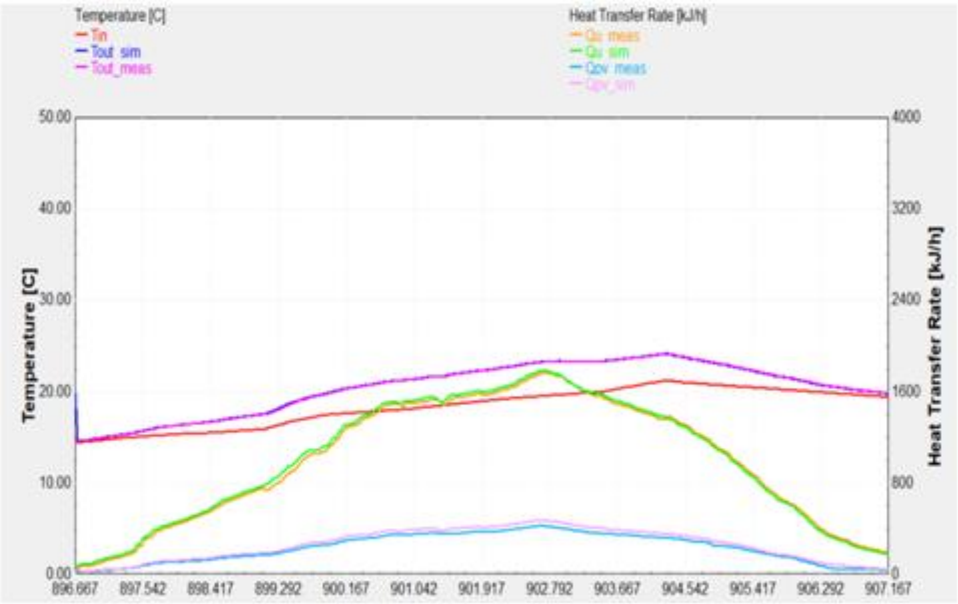


Figure 5: TRNSYS model results during winter in comparison with input data (Experimental results)

Where:

— T_{in} -Water Temperature inlet
— $T_{out\ Sim}$ -Water Temperature outlet simulation
— $T_{out\ meas}$-Water Temperature outlet simulation
— $Q_{u\ meas}$–Thermal power from experiment
— $Q_{u\ Sim}$ – Thermal power from Simulation
— $Q_{PV-meas}$–Electrical power from experiment
— Q_{PV-sim}–Electrical power from simulation

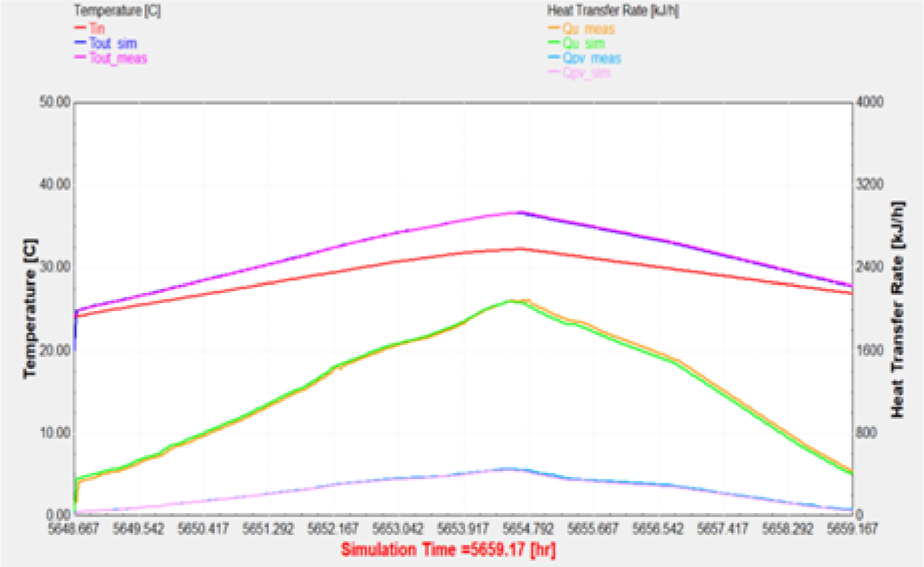


Figure 6: TRNSYS model results during summer in comparison with input data (Experimental results)

3.2.1 PVT Optimization Results

The optimization was done by changing each of the mentioned design parameters and assessing the impact of change on the (Electrical efficiency, Thermal Efficiency, and overall Efficiency). The selected design parameters to be checked were:

a) Number of water tubes. (Results shown in Figures 7&8)
b) Diameters of water tubes. (Results shown in Figures 9&10)
c) Water flow rate. (Results shown in Figures 11&12)
d) PVT panel Area.(Results shown in Figures 13&14)

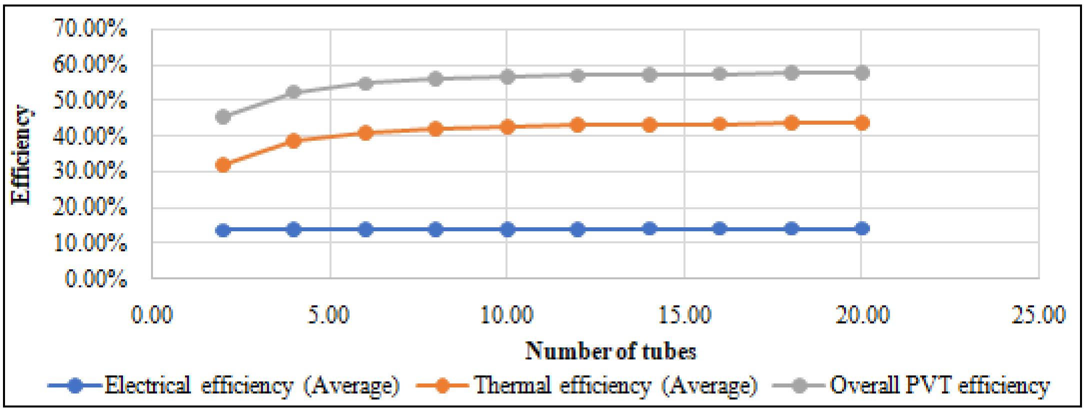


Figure 7: Effect of changing number of water tubes on overall PVT Efficiency in winter

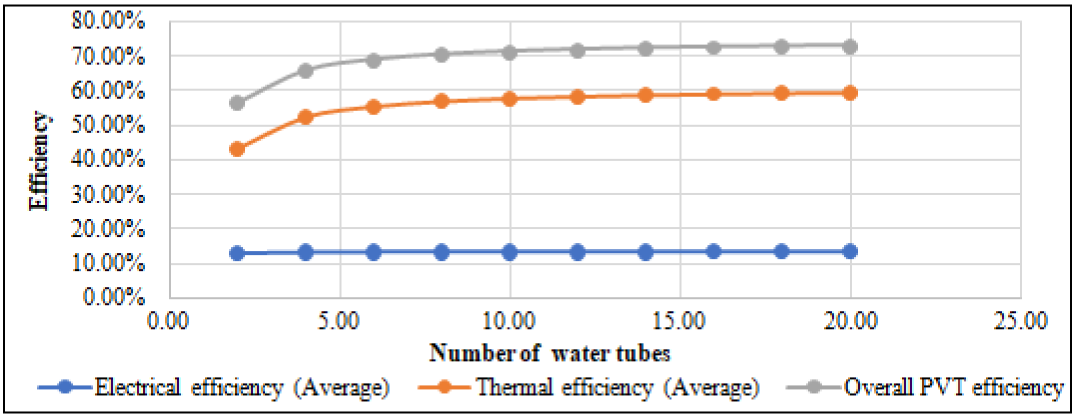


Figure 8: Effect of changing number of water tubes on overall PVT Efficiency in summer

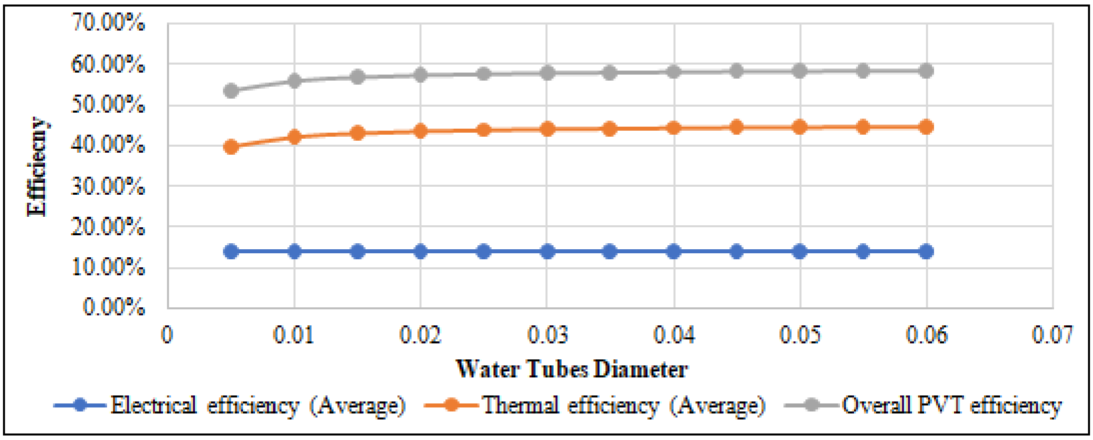


Figure 9: Effect of change in tubes diameter on overall PVT Efficiency during winter

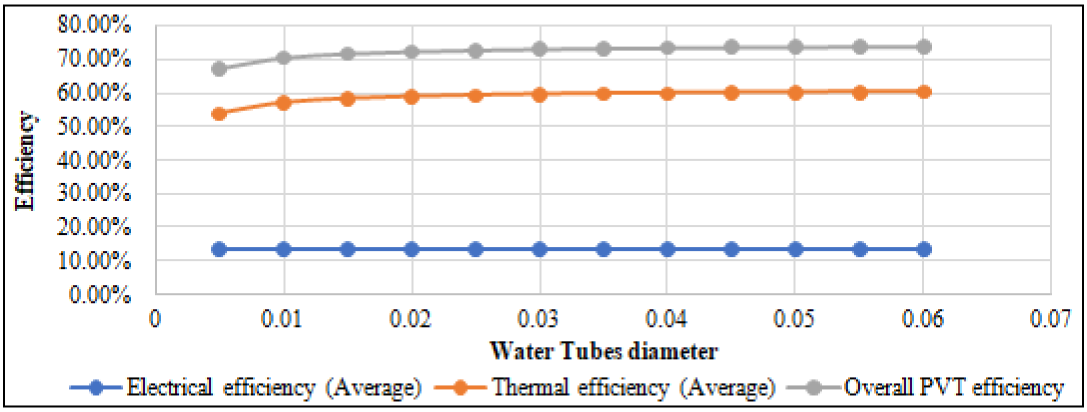
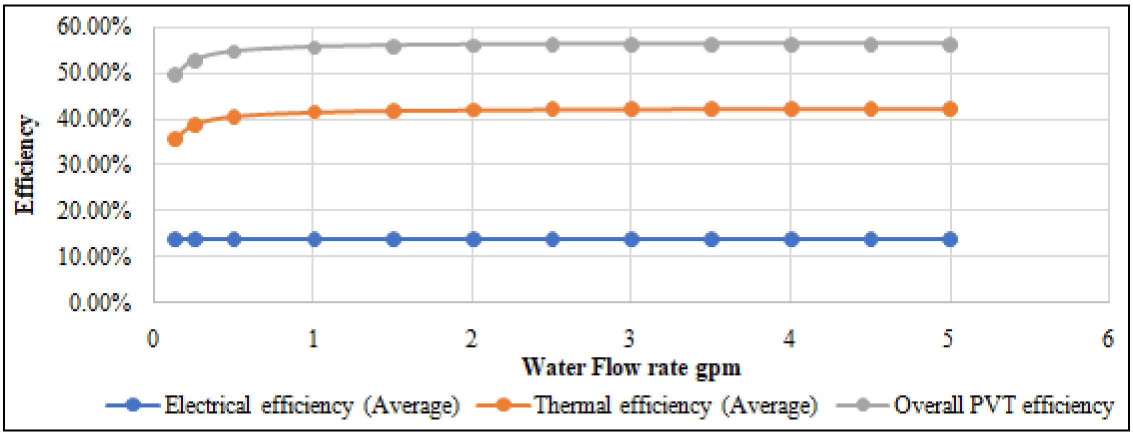


Figure 10: Effect of change in water tubes diameter on overall PVT Efficiency during summer



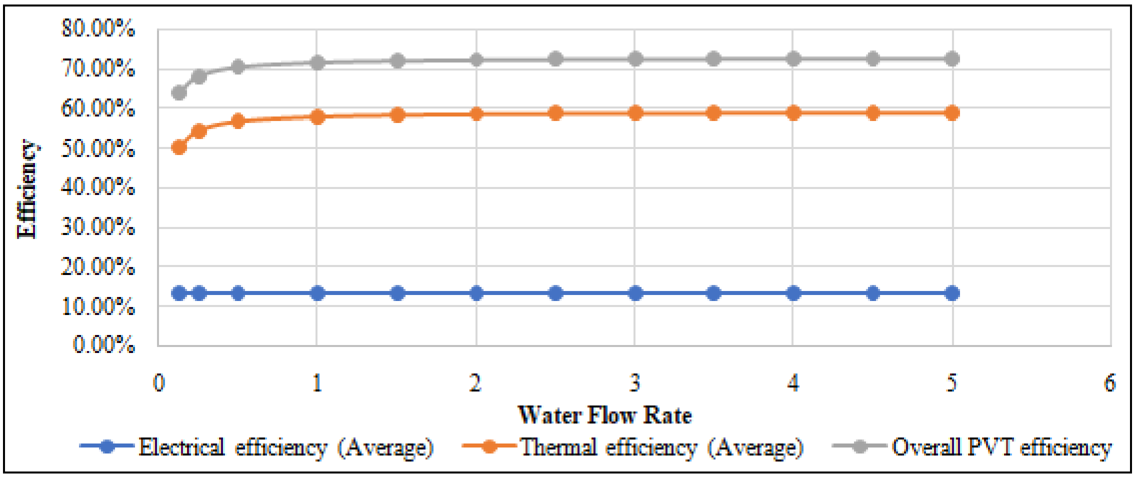
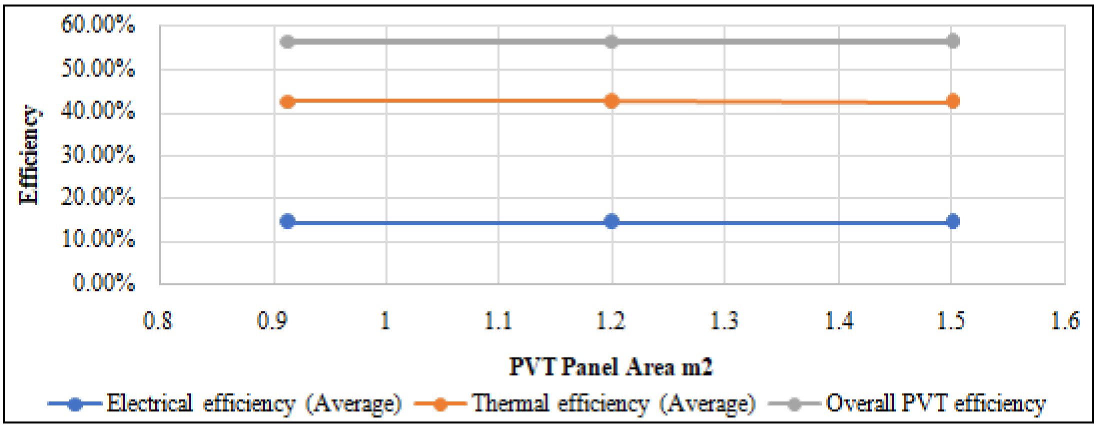
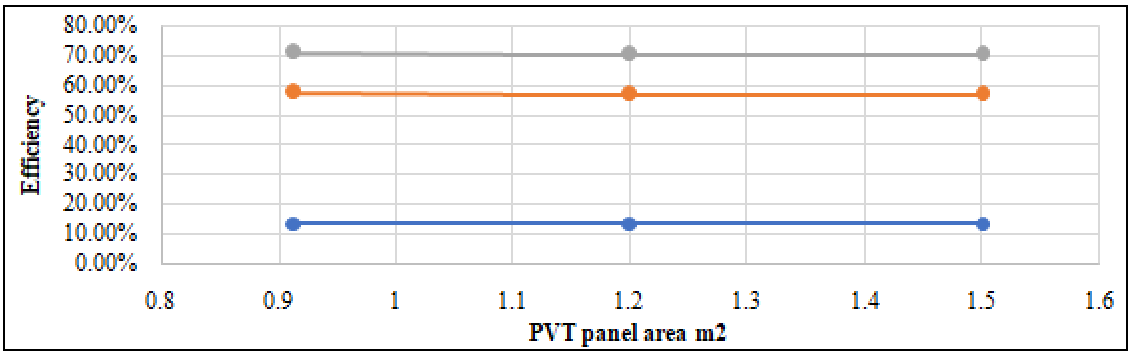


Figure 11: Effect of changing flow Rate on overall PVT Efficiency during winter





3.2.2 Complied Optimized Model

After identifying individual optimized parameter in the previous steps. Simulation for the optimized model has been tested compiling all the optimized values in one model. The optimized design parameters shown in below Table

Table 3: List of optimize design parameters

Parameters	Optimum value	Unit
Number of water tubes	12	Number
Diameters of water tubes	0.040	m
Water flow rate	2.5	GPM

Table 4: Comparison between the reference model and Optimized model during winter

Model	Electrical efficiency (Average)	Thermal efficiency (Average)	T cell Temperature Average C	T cell Temperature Maximum C	Overall PVT efficiency	Percentage of Enhancement in overall efficiency of PVT
Reference model	14.04%	42.11%	30.00	40.17	56.14%	7.2%
Optimized Model	14.15%	46.38%	28.50	37.50	60.53%	

Table 5: Comparison between the reference model and Optimized model during summer

Model	Electrical efficiency (Average)	Thermal efficiency (Average)	T cell Temperature Average C	T cell Temperature Maximum C	Overall PVT efficiency	Percentage of Enhancement in overall efficiency of PVT
Reference model	13.47%	57.10%	43.27	55	70.57%	7.5%
Optimized Model	13.57%	62.73%	41.41	52.55	76.29%	

Table 6: Compassion between PV panel Experimental results and Optimized model

	Optimized Model	PV	Enhancement in Electrical Efficiency
Electrical Efficiency in Winter	14.15%	13. 3%	6%
electrical Efficiency in Summer	13.57%	12.2%.	10%

4. Discussion

4.1 Experimental Results

Experimental results during winter gave a maximum electrical power generated from PVT of 119.2 W with a maximum electrical efficiency of 14% during the day. In comparison with the conventional PV panel, the maximum generated power was 115.5 W with a maximum electrical efficiency of 13.3%. Therefore, the enhancement of electrical efficiency in PVT was due to the cooling effect of water on the PVT cells (surface temperature). The cooling effect of water enhanced the output voltage from the PVT panel. Photovoltaic power output is affected mainly by two factors:

a) Weather conditions.
b) PV cell temperature.

The enhancement in the efficiency was equal to 0.7% between the PVT and the PV that is equal to 5%.

In addition to the electrical power, PVT generated thermal power of 494.25 W with a maximum thermal efficiency of 53.8% and average thermal efficiency of 42.5% during the test day; the test day was 7th Feb 2020. The maximum ambient temperature was around 24°C degrees during noontime and the highest global solar radiation was 1005 W/m^2. All the mentioned results are shown in Table 5.1.

During summer the test was conducted on 24th August 2020; the highest ambient temperature reached around 46°C degrees and the highest global solar radiation was 1014 W/ m^2.

The maximum electrical power generated from the PVT was 127.59 W and the maximum electrical efficiency was 13.40%. The maximum power generated from the PV panel was 120.375 W and the highest electrical efficiency was 12.2%. Accordingly, the enhancement in the electrical efficiency of PVT in comparison to PV and due to the effect of water cooling during summer was 1.2% that is equal to 8.9%. The PV's electrical efficiency has an inverse relationship with increase PV cell temperature.

The generated thermal power was 584.163 W with a maximum thermal efficiency of 83% and Average thermal efficiency of 57.1 %. Thermal efficiency, in general, depends on several factors as inlet water temperature, ambient temperature, and global solar radiation. All of the above results are summarized in Table 5.2.

From the results, PVT thermal performance was higher during summer more than in winter due to two reasons:

a) High ambient temperature.
b) Higher solar radiation.

On the other hand, the electrical efficiency of PVT during summer was less than the electrical efficiency during winter due to an increase in PVT cell temperature which resulted in decreasing the electrical efficiency.

However, the enhancement of the PVT electrical efficiency during summer was 1.2% more than in winter at 0.7%.

4.2 Simulation Results

4.2.1 Changing number of PVT collector tubes

Simulation results showed that increasing the number of tubes resulted in enhancing both the electrical and thermal efficiency of the PVT. This was due to an increase in the area of contact between the collector tubes and the working fluid. Accordingly, heat transfer enhanced and the PVT overall performance improved. The optimum number of tubes was 12 tubes as per the setup criterion. The electrical efficiency was enhanced from 13.24 % for 2 tubes to 13.49% due to water cooling effect the PVT cell temperature from 47.73°C to 42.80°C on average and 62.82°C to 54.84°C in maximum PV cell Temperature.

In addition, increasing the number of tubes from 2 to 12 results in thermal efficiency enhancement from 31.82% for 2 tubes to 43.18% for 12 tubes. The overall efficiency increased from 45.59% to 57.25%.

For summer results, the optimum number of tubes was 12. The electrical efficiency was enhanced from 13.24 % for 2 tubes to 13.49% due to water cooling effect the PVT cell temperature. The thermal efficiency was enhanced from 43.35% for 2 tubes to 58.53% for 12 tubes. Accordingly, the overall efficiency was enhanced by almost 15.18 % for an increasing number of tubes.

4.2.2 PVT Collector Tubes Diameter Changes

By increasing the diameter of the tubes, the area of contact with working fluid increases. As a result, the heat transferred between the collector and the working fluid is enhanced.

The optimum tube diameter in both winter and summer was found to be 0.04 m. In winter, electrical efficiency was 14.09%, Thermal efficiency was 44.32%, and the overall PVT efficiency was 58.42%.

During summer, the thermal performance was better. However, the electrical performance was less during winter due to an increase in PV cell temperature. Electrical efficiency was 13.52%, thermal efficiency 60.04% and, overall PV thermal efficiency was 73.56%.

4.2.3 Water Flow Rate Changes

The water flow rate was changed to a range of values: 0.125, 0.25, 0.5, 1, 1.5, 2, 2.5,….. and 5. According to the simulation model results, the optimum flow rate for winter and summer was 2.5 GPM. The efficiency kept increasing with increasing the water flow rate due to the decreasing the temperature of PV surface.

During winter, electrical efficiency was 13.94%, thermal efficiency was 35.82%, and overall efficiency was 49.76% at a water flow rate of 0.125 GPM. The efficiency was enhanced at the optimum flow rate of 2.5 GPM as electrical efficiency reached 14.10%, Thermal efficiency reached 42.29%, and overall efficiency 56.39%.

In summer analysis, with a water flow rate of 0.125 GPM, electrical efficiency was 13.36%, thermal efficiency 50.53%, and overall efficiency 63.89%. In optimum water flow rate 2.5 GPM, electrical efficiency was 13.50%, thermal efficiency was 59.03%, and the overall PVT efficiency was 72.54%.

4.2.4 PVT Panel Area Changes

PVT panel gross area was changed with a range of 0.914, 1.2, and 1.5 m^2. The results showed that the electrical and thermal efficiency both slightly decreased when the PVT area increased. In winter, the PVT panel area increase from 0.914m2 to 1.5 m^2. The electrical efficiency kept constant at 14.10%. The main reason was that the PV surface temperature changed slightly from 29.14°C to 29.19°C on average. However, thermal efficiency decreased slightly from 42.4% to 42.27%. In summer, electrical efficiency slightly decreased from 13.48% to 13.46% with increasing the PVTarea. This is due to an increase in PV surface temperature from 43.05°C to 43.45°C on average. Thermal efficiency as well decreased slightly from 57.65% to 57.10%. Accordingly, the overall efficiency slightly decreased from 71.13% to 70.56%. By increasing the panel area, the instance solar energy falling on the PVT panel increase that led to decrease in efficiencies. In addition, electrical and thermal efficiency have an inverse relation with the area.

4.2.5 Optimized Model

In the optimized model where all the optimum parameters were compiled the results are shown in Tables 4 and 5. Winter results showed that the optimized model has a 7.2% increase in overall efficiency than the reference model, the electrical efficiency increased from 14.04% to 14.14%, and thermal efficiency enhanced from 56.14% to 60.53%.

Summer results showed that the optimized model has a 7.5% increase in overall efficiency than the reference model. The electrical efficiency increased from 13.47% to 13.57%, and the thermal efficiency increased from 57.10% to 62.73%.

In addition, the enhancement in the electrical efficiency between conventional PV panels and the optimized model in the winter was 6% and in summer was 10% as shown in Table 6.

5. Conclusions

In the current research, the study has been carried out through two main parts (experimental part and simulation part) in order to achieve the study objectives. The first objective was to test and evaluate the electrical efficiency of PVT in comparison to standard PV during winter and summer. Hence, in the experimental part PVT panel and PV panel have been tested under the same weather conditions to study the performance. The experiment was conducted twice during winter and summer. In winter, the enhancement in the PVT electrical efficiency was 5% (as the increase was 0.7%) compared with the PV panel. In summer, the enhancement in electrical efficiency was 8.9% (as the increase was 1.2 %) compared to the PV panel of the identical electrical specification. On the other hand, thermal performance in both winter and summer was acceptable as in winter was 53.8% and in summer 57.1%. Since there was a tangible improvement in the electrical efficiency, PVT consider being a feasible system being used under UAE climate conditions.

In the second part of the research, the experimental data was utilized to develop a simulation model. The software which was used to develop the model was TRNSYS. The TRNSYS component used to represent PVT was Type 560.

The optimization of PVT performance was done by changing selected parameters such as (number of tubes, diameters of tubes, PVT panel area, and water flow rate) in winter and summer.

The results showed that an increasing number of tubes enhanced both the electrical and thermal efficiency of the PVT. The optimum number of tubes was found to be 12 number with overall PVT efficiency of 57.25% during winter and 72.02% during summer.

The second parameter was the diameter of the tubes. The optimum size of collector tubes was 0.04 m. The optimum size of tubes resulted in 58.42% of overall PVT efficiency during winter and 73.56% during summer.

The third selected parameter was the PVT panel area, the results showed that increasing the gross area decreases both thermal and electrical efficiency. The overall efficiency in winter decreased from 56.53% to 56.37% with increasing the PVT areas from 0.941 m2 to 1.5 m2. In summer, the overall efficiency decreased from 71.13% to 70.56%. Therefore, increasing the panel is not a feasible option.

For the change in flow rate, the optimum flow rate was 2.5 GPM. The overall PVT efficiency during winter was 56.39% and during summer was 72.54%.

Lastly, all the optimized parameters were combined and used in one model. In the optimized model, the overall efficiency in winter was 60.53%, and in summer, the overall efficiency was 76.29%.

In comparing PV electrical efficiency resulting from the experiment with the electrical efficiency of the optimized model, the results that the electrical efficiency of the PVT optimized model was better than PV by 6% more during winter and 10% more during summer.

In addition, it can be concluded that PVT performance was higher during summer than winter. The most influenced parameter among the studied ones was water flow rate. From mentioned results, it can be concluded that PVT is considered a feasible system in countries with the same weather conditions as the UAE.

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