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Article

Heat Pipe PV/T System under Hot Climate Conditions-Experimental and Simulation Analysis of System Performance

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Abstract: With the rapid increase in energy demand, the limited availability of fossil fuel resources and the desire to reduce emissions of greenhouse gases, the importance of optimising PV installations is paramount. The objective and innovation of this paper is to examine the effect of a cooling system based on heat pipes on the performance of photovoltaic panels for a household in the hot climate of Kuwait for which the considered system has not been tested before. Experimental and simulation results show both the amount of heat and electrical power generated from the solar panels in two configurations with and without cooling, considering different seasonal cycles. The angles of the panels were located at their optimum position indicating an active tracking system. Numerical model of the system was developed in TRNSYS and validated based on the measurement data. Simulation results showed that the cooling effect of the panels significantly increases the electrical output by almost 6.25%. In addition, a reduction in solar cell temperature of around 8% was observed in the Kuwait climate. The proposed model supports the decision of implementing a PV/T system in hot climate areas where the effect of cooling will result in higher efficiencies for generating electricity.

Keywords: photovoltaic thermal system; heat pipes; thermal efficiency; electrical power output; TRNSYS simulation

1. Introduction

Due to limited amount of fossil fuels and the negative impacts they have on the environment, recent studies have stressed the need to minimize them as a world energy source [1,2]. Climate change is the source of various environmental problems in countries around the world, motivating scientists to conduct the research needed to help minimize energy use in the residential and commercial buildings, which accounts for roughly 40% of the total energy used [3]. Over the last decade, the demand for alternatives to fossil fuels has led to an enormous increase in renewable energy or clean energy, reflecting its benefits for both human life and the overall environment. Renewable energy derives from solar, wind, biomass, geothermal, and hydroelectric energy with each requiring different technologies to generate energy. Regarding solar energy in particular, it is relevant to the three pillars of sustainable development–social, economic and environment [4]. Solar energy, helps ensure sustainability and a clean environment, reduces the need for fossil fuels and associated costs, and promotes energy independence [5].

Photovoltaic (PV) technologies have an increasing share of total global renewable energy capacity [6]. The global PV base in 2022, reached 1185 GW (≈1.2 TW) of cumulative capacity [7]. In 2023 solar PV were responsible for three quarters of the increase in renewable energy capacity worldwide [8]. As highlighted by Kargaran et al. [9] and Hassaan et al. [10], photovoltaics are widely considered as one of the most promising, reliably, and efficient emerging technologies to convert solar energy into electricity and has a wide range of applications, including those related to domestic applications, transportation, street lighting, desalination and agriculture. Three generations of PV technology can be distinguished based on the manufacturing process, the material used, the temperature level as well as the performance of the photovoltaic cells [11]. The first generation includes silicon-based solar cells (monocrystalline and polycrystalline), the second thin-film cells, and the third generation includes technologies that are still under development: dye-sensitised, organic, and perovskite cells. Although Singh et al. [12] also identified the fourth generation to which "inorganics-in-organics" belongs [12] or as specified by Fazal and Rubaiee [13] to the fourth generation are tandem cell. PV efficiency depends on the type of technology used. Researchers are still working on their improvement. According to [14], the polycrystalline panels used in this study have an efficiency of 23%, while the highest confirmed conversion efficiencies for research cells is achieved by multijunction cells. As is well known, too high a PV temperature does not benefit its efficiency. As the operating temperature drops, the electrical output of the solar cell increases. Therefore, different cooling techniques are widely used and are particularly important in hot and humid climates. A distinction can be made between passive and active cooling systems. Active systems can include solutions based on water, air, nanofluids and phase-change materials However, the possibilities offered by thermoelectric cooling, heat sinks/fins/expanded surfaces, jet impingement, evaporation or heat pipe technology should not be overlooked.

The environment in which photovoltaic systems operate significantly affects their efficiency, and this is not only the effect of high temperatures but also of high relative humidity or sand/dust contamination [11]. In addition to the factors mentioned, solar irradiance, and wind speed, should also be noted [15].

Despite climate changes, the primary fuel used to meet Kuwait's rapidly growing electricity needs, is oil and related derivatives, as shown in Figure 1. Given this reality, the country releases an abundance of harmful green gas emissions into the atmosphere, demanding that the nation pursue a clean energy alternative. Complicating efforts, of course, is that oil and related derivatives provide Kuwait with its primary source of revenue, affording the country financial stability. Still, Kuwait would greatly benefit from turning to renewable energy sources like solar, which will help ensure that it meets energy demands and power its economy forward. In addition, since solar power does not produce greenhouse gases or harmful waste, it is an environmentally friendly alternative that promotes clean air and water. Furthermore, PV/T is more cost-effective than a system that separately utilises thermal and photovoltaic panels [16,17].

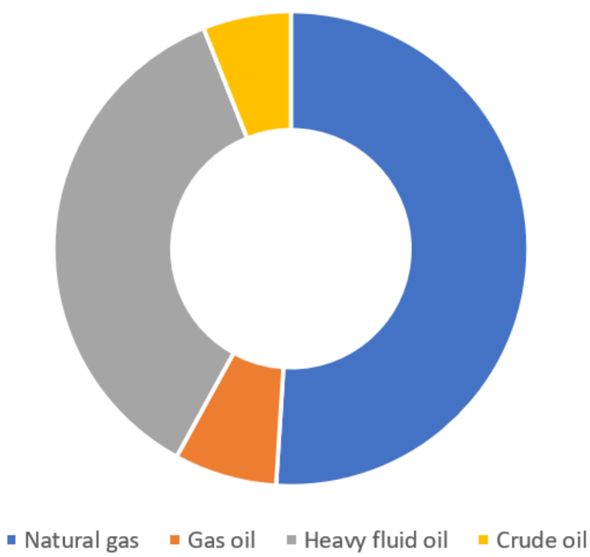

Figure 1. Hydrocarbon fuel usage by electrical power plants in Kuwait [16].

Al Enezi et al. [18] showed that the electrical load in Kuwait fluctuates between high and low levels depending on changes in temperature and relative humidity. Therefore, they concluded that the best way to generate electricity in Kuwait is through solar energy. Additionally, they stressed that the design and development of solar energy systems rely heavily on accurate solar radiation estimations. Kuwait, for its part, experiences solar radiation levels on horizontal surfaces that range from 500 W/m^2–1042 W/m^2 monthly average and clear skies. Solar energy as an alternative source of energy will likely benefit Kuwait's grid, making future research on this possibility worthwhile. Bunyan and Ali [19] investigated several photovoltaic tilt angle arrangements for Kuwait. When installed at the right tilt angle, photovoltaic panels can serve as both power generators and external shading devices. To maximize the sunlight at solar noon, mount the PV system due south. Throughout the year, at the solstices as well as equinoxes, the azimuth angle changes from 0° to 90° degrees to produce an optimal tilt angle greater than 30° degrees with optimal power output. At a tilt of 50°, the PV system's performance and output power are similar to those at a tilt of 30°, Kuwait's latitude. As the sun moves from 36° to the horizontal in December to 84° to the horizontal in June, the resulting output power shift is adequate but not optimal. Existing measurements showed that PV modules tilted at 50° can produce as much power as those tilted at a latitude-equal angle. Ghoneim [20] measured the performance of a combined photovoltaic-thermal collector's thermal and electrical output for the Kuwait climate at the collector test facility of the College of Technological Studies in Kuwait. To maximise the combined PV/T system's annual energy production, several photovoltaic-thermal collector slopes and azimuth angles were investigated. The tilt angle was 30°, and the combined photovoltaic and thermal collector faced due south. A numerical model was also used to simulate the combined collector's performance. The PV/T collector generated the most energy while facing south with a slope of 25° and an azimuth angle of 0°. The fact that Kuwait has more solar energy in the summer than in the winter coincides with the maximum energy output. PV cells convert some of the sun's rays into electricity, thereby reducing the amount of solar energy available for use in a thermal system. Thus, it is possible to utilise the PV/T collector in domestic hot water systems that require low temperatures, validating the positive environmental effects of the PV/T collector in Kuwait's climate and preventing roughly 1.4 tonnes of CO_2 emissions. Ramadhan and Naseeb [21] investigated the economic viability of the implementing PV systems compared to power plants that rely on fossil fuels, considering the levelized cost and efficiency of energy as well as CO_2 emissions generated from conventional energy. The levelized cost of electricity for a 1 MW PV station in Kuwait is approximated at $0.20/kWh for the current price of $5/W with 15% efficiency. Another issue influencing economic viability is the PV module's ability to generate electricity. Solar energy has become increasingly less expensive due to improved technology, the low cost of natural sources, their abundance, and other factors [4]. As such, Ramadhan and Naseeb advise that Kuwait should install PV solar systems in order to broaden its supply of electricity [21].

Kuwait holds great potential for the use of solar PV systems. To realize this potential, however, it is vital to know the impact that Kuwait's unique climatic conditions has on solar photovoltaic performance over the year, whether in relation to how hot panels become or how often sandstorms might occur. In addition, the hot, dry summers and bright, sunny days characteristic that characterize Kuwait's desert climate heavily impacts electricity use, as Kuwaitis are inclined to run the air conditioning, resulting in a seasonal spike in power consumption throughout the summer and diurnal surge from mid-afternoon to evening. Greater understanding, while critical to the study, will also strengthen the likelihood that power system designers take appropriate actions to successfully accommodate solar PV generation [16].

PV/T hybrid technology offers cooling techniques to reduce PV cell temperature and recover the waste heat that the panels for heating applications produce. Kargaran et al. [9] identified various methods of cooling photovoltaic panels, including heat pipes, air flow, nanofluid PCM, water, microchannel, liquid immersion, thermoelectric, jet impingement. Zhou J. et al. [22] have divided the PV/T modules according to the different cooling media: air-cooled, liquid-cooled, heat pipe-cooled and refrigerant-cooled. In addition, Osma-Pinto and Ordóñez-Plata [23] presented two thermal dynamic models for a non-irrigated and an irrigated PV panel. Abdo et al. [24] and Abdallah et al. [25] and Togun H. et al. [26] divided these methods into passive and active while Vassiliades et al. [27] who focused on a heat pipe PV/T system, demonstrated that PV/T panels integrated into a building can also follow an active or passive method. Gang et al. [28] presented design of a heat pipe-based PV/T system and introduced a numerical and experimental study to investigate output energy efficiency in comparison with a water-based PV/T system. The system produces electrical and thermal power with efficiency levels at around 9% and 42% respectively. Zhu et al. [29] demonstrated that novel flat copper tube loop heat pipe PV/T can achieve the highest overall efficiency of 59.3%, an electrical efficiency of 15.7%. A further article on the mathematical model concluded that the system under analysis can achieve electrical efficiency of 16.19%, thermal efficiency of 45.23% and overall efficiency of 61.42% with the specified design parameters. Ahmed B.O. et al. [30] focused on investigating the energy, exergy and power production of the tested PVT systems showing maximum electrical energy efficiency, thermal energy efficiency and total exergetic efficiency of 11.2%, 86.2% and 15.3% respectively. Moradgholi et al. [31] investigated an experimental test of PV/T in a hot location of the Middle East in both summer and spring seasons. They found that the system's electrical and thermal efficiency can be raised by almost 6% and 16% in the spring and by nearly 8% and 45% in the summer. Khordehgah et al. [32] analysed a heat pipe-based PV/T system using the TRNSYS transient system simulation software, and tested the technology's potential contribution to supplying electrical and thermal energy to a London household. They observed that the system's electrical efficiency can be increased by about 12% during the summer.

Heat pipe, is a device that uses the condensation and vaporisation of a working fluid to move heat from one location to another. It consists of a sealed container, a wick structure, and a tiny amount of working fluid such as water, acetone, methanol, or ammonia that is in equilibrium with its own vapour. Figure 2 shows a heat pipe schematic whereby the evaporator, the adiabatic transit phase, and the condenser, are three distinct divisions. Once heat is introduced into one end of the pipe, the working fluid inside evaporates since the heat in this case is transferred through the pipe wall and wick structure. Vapour pressure is then produced, sending the vapour to the pipe's opposite end through the adiabatic transition section. Next, the vapour condenses by transferring the latent heat of vaporisation to the heat sink through the wick structure and pipe wall. The wick structure subsequently absorbs the liquid portion of the vapour flow. In this paper, a wickless heat pipe is used in the heat mat. The main differences between heat pipe and thermosyphon is that thermosyphon has no wicking structure and uses gravitational forces to transfer the working fluid from the condenser to the evaporator section [33].

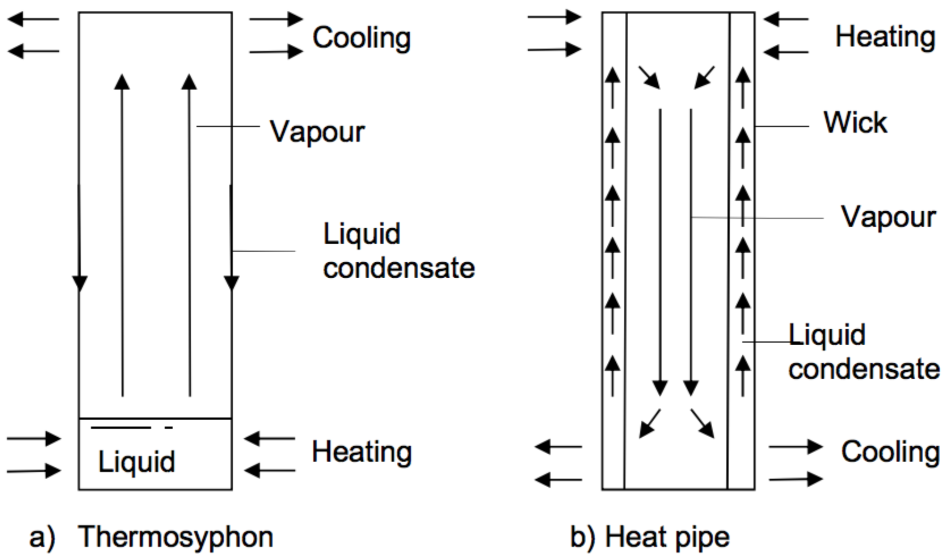

Figure 2. Thermosyphon and Heat Pipe [33].

The experiments described above show that using heat pipe technology in conjunction with solar panels can result in significant efficiency improvements. Heat pipe technology as a super-conductor may be applied to effectively and efficiently absorb and transmit waste energy to another forms, increasing an application's overall effectiveness [28,29]. In addition, improving heat pipe technology might increase heat transmission. The efficacy of a multichannel heat pipe flat heat mat and heat pipe can increased the total area of the absorbed heat during the heat transfer process. The type of technology used can improve the efficiency of photovoltaic solar panels. Finally, cooling PV panels can significantly increase the electrical energy output and produce waste heat, which can improve the overall efficiency of both the electrical and thermal outputs. The heat pipe PV/T panel shows that the heat mat is comprised of a manifold and several heat pipes shaped as tubes used to transfer the working fluid. To transfer the absorber and the heat produced to the heat pipe's working fluid, the PV panels must be positioned over the heat mat. Furthermore, thermal storage systems are crucial to support the increase in overall efficiency and lower system costs [28], although this is not the subject of this analysis.

This paper focuses on the performance analysis of a household PV/T system for Kuwait's climate. The system under consideration has not previously been tested for hot climate conditions. Therefore, the following sections present the innovative results of an examination detailing the effect of a cooling system based on heat pipes on the performance of photovoltaic panels (PV/T) in a year-round cycle. Section 2 briefly summarises heat pipe based PV/T system technologies. Section 3 describes the test bench in detail and the measurements performed for which an error analysis was carried out. Furthermore, the developed numerical model of the system under investigation in TRNSYS software is presented. In the following Section 4, the results of measurements and simulations are provided and discussed and the associated root-mean square error (RMSE) is determined. This paper examines the feasibility of PV/T systems under Kuwait's climatic conditions.

2. Methodology: PV/T System Examination

The analysis of the PV/T system which uses a heat pipe-based cooling system was divided into two stages. The first was an experimental analysis in the laboratory. In a second step, a numerical model was prepared in TRNSYS. This section presents the development of the test bench, the measurement methodology, uncertainty analysis and numerical model. The experiment and simulation was conducted to determine both the PV/T technology's electrical and thermal performance.

2.1. PV System's Electrical Power and Thermal Energy

To test the system and compare the electrical power output with and without the cooling technique, the following equations were used. The thermal and electrical output of the PV/T panels is shown in Equations (3), (4), (6) and (7) [34].

2.1.1. PV System's Electrical Power and Thermal Energy

The PV module's I-V characteristics defined using V_{OC}, the maximum voltage that the solar cells can reach in an open circuit, and I_{SC}, the maximum current that the module can reach in a closed circuit. In an open circuit, the maximum voltage is reached while the current is zero. In a short circuit, unlike in an open circuit, the voltage is zero and the current is at its highest. The electrical power, the product of the current and voltage, can be calculated using Equation (1):

$$P = IV \tag{1}$$

Another measure to analyse a solar cell is the characteristic resistance R_{SH}, defined as the solar cell's output resistance at its maximum power point (MPP). It is determined by Equation (2):

$$R_{SH} = \frac{V_{MP}}{I_{MP}} = \frac{V_{OC}}{I_{SC}} \tag{2}$$

The PV electrical power is then calculated using the following Equation (3), taking into consideration the PV panel's area [34]:

$$\dot{Q}_{el} = \frac{I_{SC}V_{OC}}{A_{PV}} \tag{3}$$

The PV's electrical efficiency is found using Equation (4), which provides ratio of the power that the solar cell delivers to that of the incident solar radiation [34]:

$$\eta_{el} = \frac{I_{SC}V_{OC}}{A_{PV} \times G} = \frac{\dot{Q}_{el}}{G} \tag{4}$$

The photovoltaic cells in an illuminated module operate at a temperature higher than the ambient surroundings. Therefore, the use of NOCT is important, as it is an indicator of the temperature differential under standard operating conditions (the ambient temperature is 20 °C, the solar irradiance is 800 W/m^2, and the wind velocity is equal to 1 m/s). The ambient temperature is collected from data based on Kuwait's climate conditions along with the solar irradiance for each month and considers wind velocity. To account for the Kuwait's ambient conditions, Equation (5) is needed to evaluate the PV cell temperature that is read by the data logger [16]:

$$T_C\ (°\mathrm{C}) = T_{amb} \left(\frac{NOCT - 20^{\circ}}{800}\right) G \tag{5}$$

The amount of heat produced from the PV panel is calculated using Equation (6):

$$\dot{Q}_{th} = \dot{m}cp\Delta T \tag{6}$$

where,

$\dot{m}$ is the mass flow rate of the water entering the system, measured manually;

the value of c_p of water is constant at 4182 J/kg °C;

ΔT is the temperature difference between the inlet and outlet of the collector.

Thermal efficiency is calculated using Equation (7), where A_c is the area of the collector [34]:

$$\eta_{th} = \frac{\dot{Q}_{th}}{A_c G} \tag{7}$$

2.1.2. PV/T System Energy Efficiency

Equation (8) reflects the project's main purpose, which is to determine the energy efficiency of the PV/T system for Kuwait's climate. Using an Excel spreadsheet, Equation (8) is used to calculate the system's performance, subsequently using graphical illustration to highlight the effect of cooling on the PV [34]:

$$\eta_{el+th} = \eta_{el} + \eta_{th} \tag{8}$$

2.2. Experimental Setup of the Heat Pipe PV/T System

The experiment was conducted to determine both the PV/T technology's electrical and thermal performance. Figure 3 shows the PV/T's test rig, which was examined in the laboratory. The solar chamber was designed to represent a household located in Kuwait. Fans were installed on the chamber's sides to protect and control the ambient temperature. The solar simulator was positioned at the top of the solar chamber and contains lamps, light filters, and fans. It is used to measure solar irradiance using lamp intensity and to control the chamber's ambient temperature by referring to the external environment. The source light was a halogen tungsten lamp and the light filter was adjusted to correct the light's wavelength spectrum to daylight temperature. Finally, the fans in the solar simulator were used to cool down the lamps. The system's main, located chamber's side, is the control unit, which is used to control both the solar simulator and solar chamber. It includes a variable controller, power meter, solar battery, temperature controller, solar charge controller, and PV power and energy logger which are detailed in Section 2.4.1.

The test rig's configuration for the heat pipe-based PV/T system was designed using a rotating mechanism adjustable to positions at different angles from the horizontal. The test rig includes the heat mat, cooling manifold, and PV panels. The heat mat was adjusted in the vertical position where different thermocouples were placed at the condenser, adiabatic, and evaporator sections. The working fluid in the heat mat was ammonia and, as shown in Figure 3, the cooling manifold includes inlets and outlet ports for the water and is positioned at the condenser section of the heat mat. Two inlets and two outlets were instrumented with thermocouples to measure the temperature and to have a backup for each port in order to give more precise outputs.

As previously noted in the literature review, different types of PV module perform differently in terms of power output and efficiency. The type of PV material used in the test rig was polycrystalline, which has advantages such as low cost, ease of fabrication and slightly higher heat tolerance than other types [35]. Two PV polycrystalline modules were attached at the evaporator section of the heat mat, each of which has a maximum power rating of 20 W.

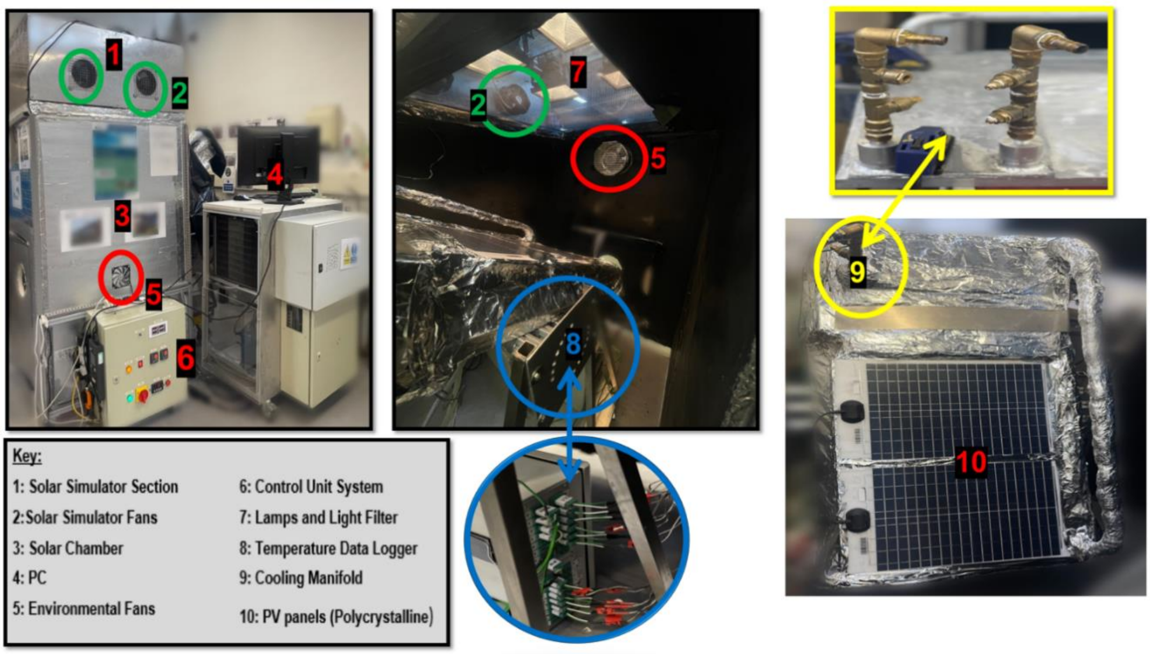

Figure 3. Configuration of the Experimental Set-up.

2.3. Parameters Used

To determine the thermal and electrical output of the PV/T-based system, several parameters related to Kuwait's climate were considered and are shown in Table 1. The data collected relates to monthly average values to provide a year-round analysis of the PV/T heat pipe system. Information for the average ambient temperature, daily radiation, and wind velocity was collected from NASA predictions of worldwide monthly energy resources [36]. The ambient temperature was converted into a PV cell temperature using the equation noted in Section 3.1 since the PV cell temperature depends on heat mat cooling. To this, daily radiation was measured at the start of each test by directing the lab's voltage controller to the desired radiation output. To meet the required output demand of an active solar tracking system, the angles of each month were positioned at their optimum location, tilted on a south-facing rack towards the sun. It was subjected according to Kuwait's location by considering a longitude of 48.25° and latitude of 29.25°. These angles were calculated using the Solar Panel Tilt Angle Calculator [37].

Table 1. Data used for the calculations.

Months	Ambient Temperature [°C]	Solar Angle	Daily Radiation $[\frac{\frac{KWH}{m^2}}{day}]$
January	14.15	36.3°	3.400
February	15.29	31.3°	4.370
March	18.89	26.3°	5.200
April	24.18	21.3°	5.920
May	30.14	16.3°	6.880
June	34.09	11.3°	7.960
July	35.95	16.3°	7.590
August	36.01	21.3°	7.260
September	33.15	26.3°	6.520
October	28.58	31.3°	5.070
November	21.98	36.3°	3.600
December	16.44	41.3°	3.070

2.4. Experimental Procedure

To determine the system's effective performance, the PV/T panels were tested under different values of ambient temperature, solar irradiance, water flow rate, and solar angle of orientation. Figure 4 shows all the parameters used to analyse the PV/T heat mat system's performance. The experiment was tested with and without the cooling manifold to investigate the effect of cooling on the system. The aim was to provide a yearly analysis of Kuwait's climate and conditions.

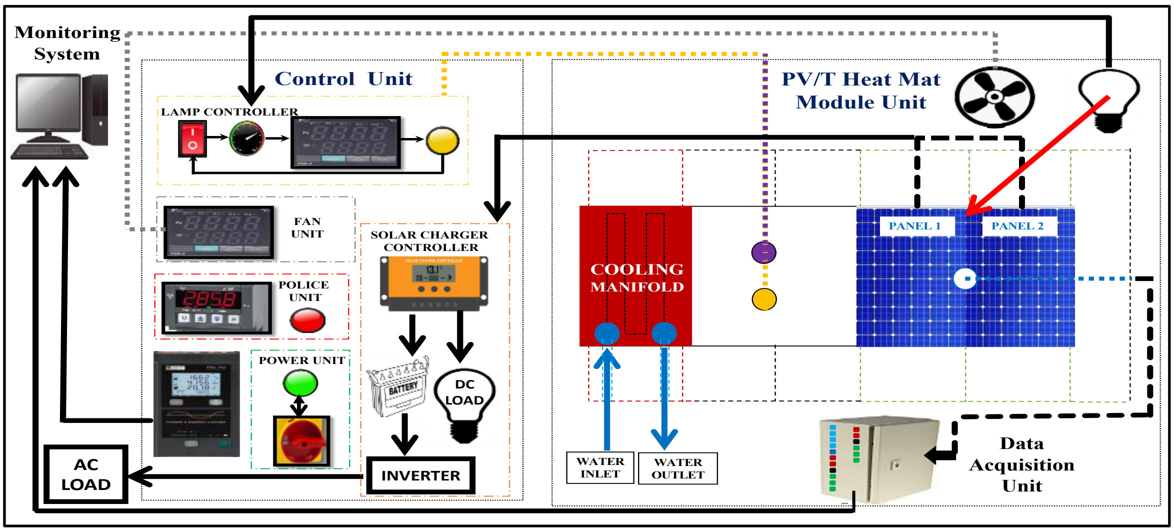

Figure 4. Pictorial Diagram of the PV/T Heat Mat System.

2.4.1. Electrical System

This subsection presents the specifications of the main test rig components used to measure the system's electrical output. As mentioned previously the PV module chosen for this experiment was a 20 W polycrystalline solar panel with dimensions 505 × 345 × 3 mm and open circuit voltage 21.6 V [38].

The solar charge controller was used to charge the electricity that the PV panels generated to send it to the battery bank [39] or LED lights. The solar charge controller chosen has a rated voltage of 12 V/24 V and a rated current at 20 A. The maximum PV input power at 12 V is 260 W and 24 V is 520 W. The maximum PV voltage is 50 V. The battery was located inside the control unit to store and distribute the electrical energy generated. The PV power and energy logger PEL 103 [40] was used to measure and record the performance of the electrical installations to improve the system's energy efficiency and reduce costs. The ISOM400 pyranometer measured the chamber's solar irradiance. The variable voltage in the control unit was adjusted to meet the required solar irradiance according to the data collected for the specified location. It measures a maximum light level of 2000 W/m^2 with an accuracy range of ±5 W/m^2 [41].

2.4.2. Thermal System

As mentioned in Section 3.1, the manifold was located in the condenser section positioned over the heat mat. It had inlet and outlet ports where water flow entered and exited the manifold with different temperature measurements. The heat mat configuration in Figure 5 presents the cooling manifold and its ports. The inlet water was set at an ambient temperature of 25 °C.

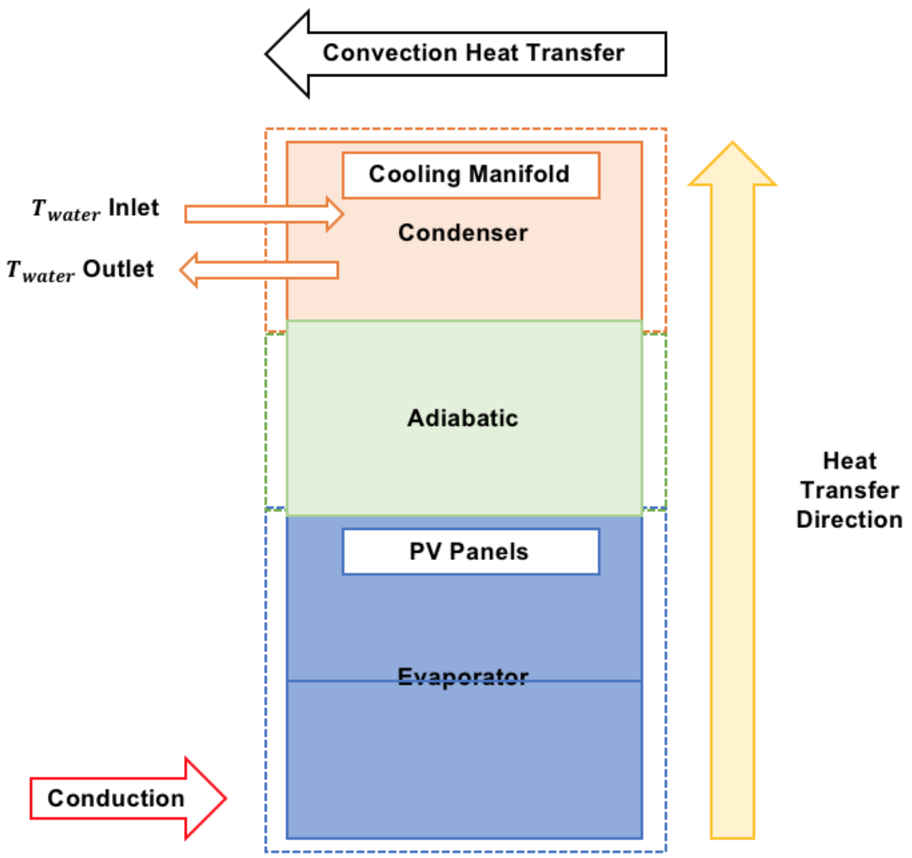

Figure 5. Heat Mat Test Rig Configuration.

The water flow entering the inlet port of the cooling manifold was measured by a flow rate meter, which includes a sensor and display. The sensor used was the Turbine Flow Sensor (FTB371-G), which has a range between 2 and 40 L/min with an accuracy range of ±1% [42]. The sensor was accompanied by a flow rate meter display to show the water flow's number scale [43]. The flow rate displayed by the meter varied. To check water flow and manually determine flow rate, a cylindrical measuring tube was used. The test rig's temperature was measured through the thermocouple, which was connected to the temperature data logging unit, from where it is sent to a PC. Lab View software was used to run the system and record the data sent from the temperature data logger.

Figure 6, prepared in AutoCAD, shows the placement of the thermocouples, either from the front side where the PV panels and cooling manifold are located, or from the surface of the heat mat at the back side. The thermocouple used was a K-type, and was suitable for temperature measurements in the range of −40 °C to 1110 °C with an estimated error of ±0.25 °C above the temperature range of interest. All of the thermocouples illustrated in Figure 6 were secured in the specified positions using thermal paste and covered with insulation material. This was done to ensure that the experiments ran on the same sequence and to give precise temperature readings.

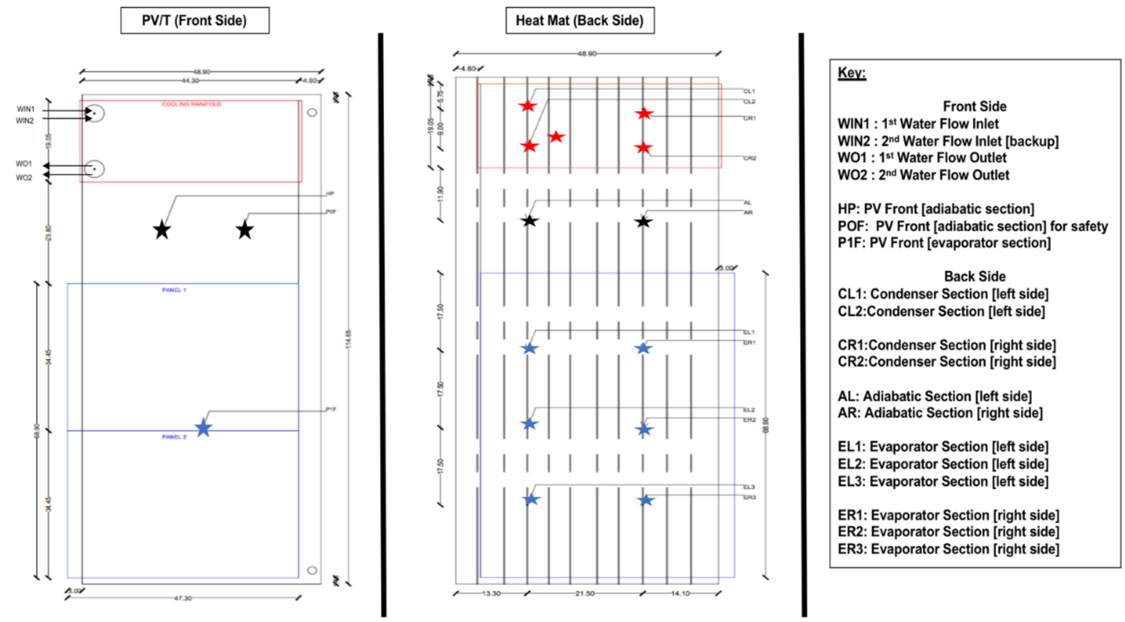

Figure 6. Schematic diagram of thermocouple locations.

2.5. Simulation of the Heat Pipe PV/T System

The second aim of this paper was to developed numerical model in Transient System Simulation Software (TRNSYS) and then compare the simulation results with the measurements. TRNSYS developed and used by the solar energy laboratory team at the University of Wisconsin, USA, in the 1960s enables the performance of the PV/T module system to be analysed [44]. It takes into account conditions in a typical meteorological year (TMY) for the specified location of Kuwait. This simulation program is widely used in the field of renewable energy engineering for the design of models of active or passive solar designs. With TRNSYS, users can model and simulate complex electrical and thermal systems, allowing them to create new interconnecting system components and solve differential equations by producing output results numerically or graphically. One program benefit is that it allows user to conduct a yearly analysis at time intervals for any desired weather conditions. In addition, TRNSYS can improve the system's performance and cost in an optimised design. Using the Simulation Studio in TRNSYS affords the user the ability to analyse and evaluate the functionality of complex algebraic and differential equations, representing a graphical interference. The system covers different components and types where input and output parameters are provided for component, like forcing functions, integration, printing plots, and data interpolation.

The modelled system includes a closed-loop configuration that combines both electrical and thermal systems. Figure 7 shows a schematic of the PV/T system in the TRNSYS simulation program designed to generate electricity and produce warm water as outputs. Plotting output values is possible with Type 65 Online Plotter or Type 26 Printer. Connecting Type 65 Printer enables monitoring of the panel performance based on electrical power output and efficiency, with and without water circulation. The system is controlled with a Type 2 differential device to control the upper and low temperatures to obtain the desired temperature output. Another controller unit is the flow diverter, which is used to sense the tank temperature and to control the controller's inlet temperature. Once complete, the Type 4 tank sends the controlled temperature to the Type 3 pump to deliver the flow to the Type 50 PV/T module, introduces PV/T array functionality and electrical and thermal performance. The system inputs and parameters correspond to Kuwait's climate conditions. To this end, TMY weather data from Kuwait were uploaded, including that related to dry bulb temperature, wind velocity, beam radiation at the surface, angle of incidence, and solar radiation. Finally, the system simulation was aligned according to the change of the PV panel's electrical efficiency. The simulated electrical efficiency depends on the flowrate, specific heat capacity, and the temperature variation between the inlet and outlet of the collector. Accordingly as introduced by Khordehgah et al. [45], the following Table 2 indicates the design parameters of the system in TRNSYS.

Table 2. Design parameters of the system in TRNSYS [45].

Component	Type	Descriptions	Value
PV/T Module	50	Module Area	6.4 m^2
		Fluid Specific Heat	4.18 kJ/kg °C
		PV Reference Condition Efficiency	15%
		PV Cell Reference Temperature	30 °C
		Solar Cell Efficiency Temperature Coefficient	0.5%/C
		Number of Glass Covers	1
		Packing Factor	1
		Inclination Angle	36°
		Facing Orientation	South
Pump	3	Maximum Flowrate	4 kg/h
		Maximum Power	300 kJ/h
Storage Tank	4	Tank Volume	150 L
		Maximum Heating Rate of Elements	10,000 kJ/h

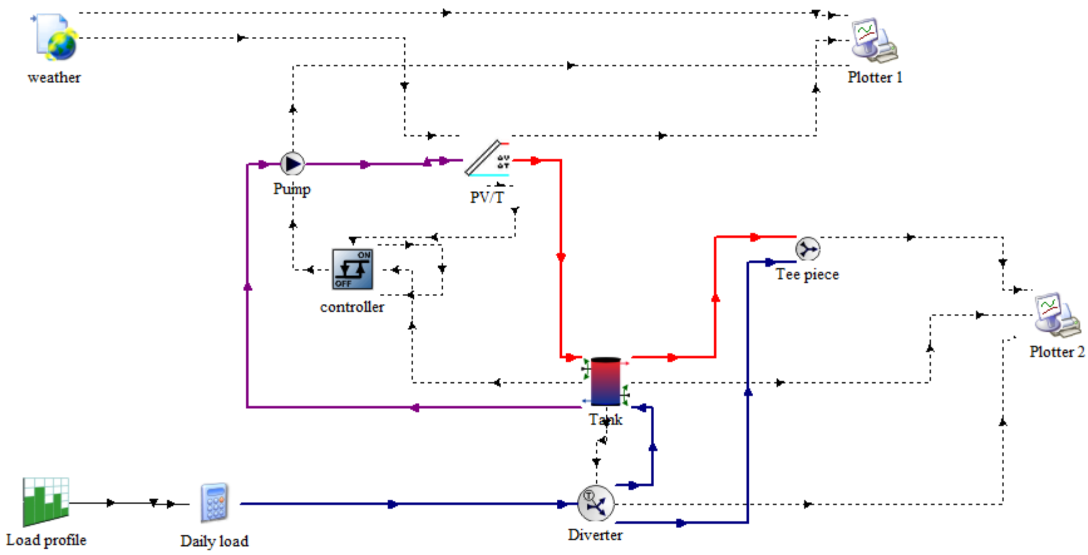

Figure 7. Schematic of the PV/T in TRNSYS Simulation.

3. Presentation of Analysis RESULTS and Discussion

The following section summarizes the main findings of the investigation into the performance of the PV/T technology, focusing on the system's electrical and thermal energy. In the following sections, the results of the experimental analysis and the results of the simulations are presented and discussed.

3.1. Presentation of Experimental Results for PV/T Performance

The experimental results were generated on an average monthly basis over one year to determine the PV/T systems's performance in Kuwait. Each month, tests were run once for cooled and once for uncooled systems, yielding 12 for each or 24 in total. Figure 8 shows the average daily irradiance for each month, demonstrating that the summer months have the highest irradiance. According to Kuwait's whether data, the lowest average irradiance in December, at about 128 W/m^2. Another important parameter, ambient temperature, Figure 9, shows that Kuwait's lowest average temperature is in January at about 14°, while the highest is between 35 and 40° during the summer season.

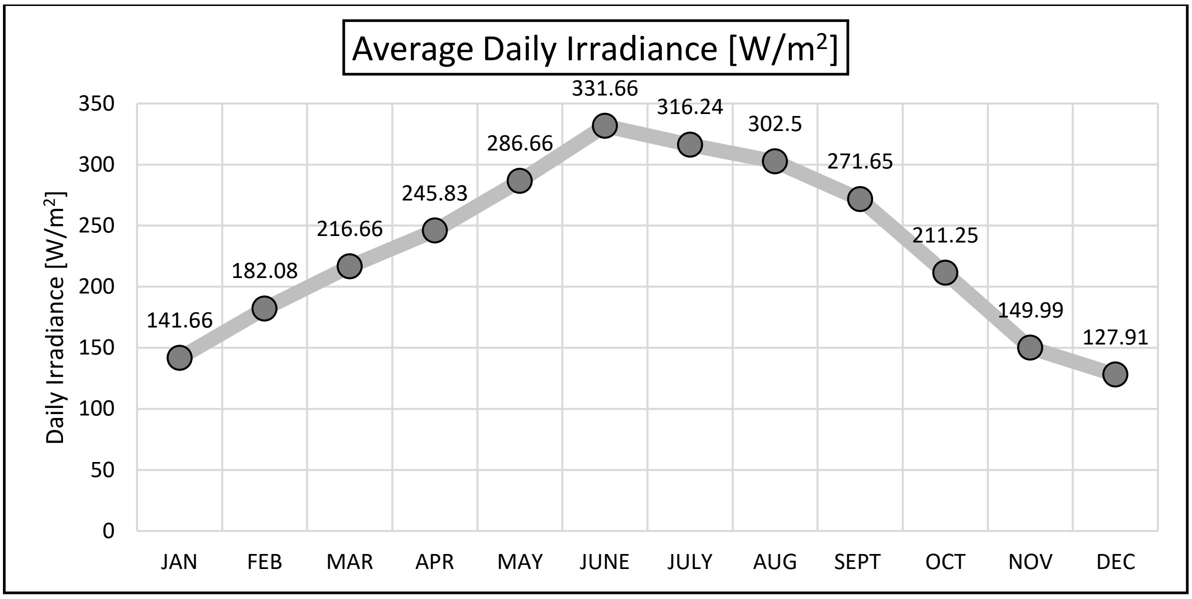

Figure 8. Average daily irradiance on a monthly basis.

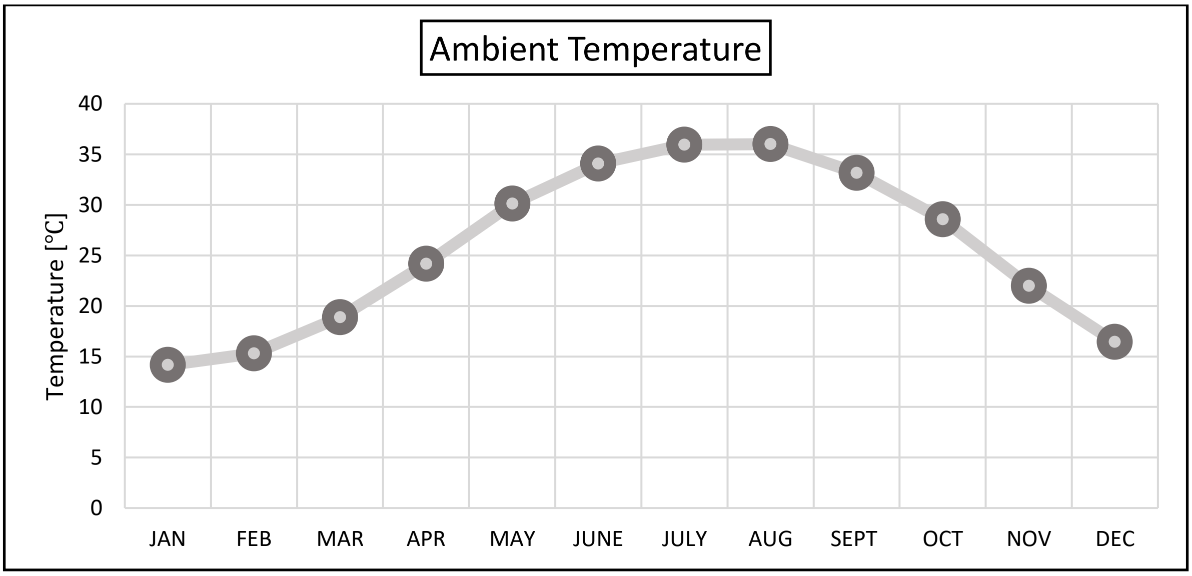

Figure 9. Average Ambient Temperature on a monthly basis.

3.1.1. Thermal Performance

The system's inlet and outlet water temperatures were recorded separately for each month. The systems' flow rate meter was set at the beginning of each test to between 1 and 2 L/min. To examine the system, the water circulation in the condenser section was allowed to reduce the amount of working fluid sent to the PV panel. As demonstrated in Figure 10, the thermal collector absorbed the panel's waste heat, the thermal collector delivering the water flow as heated water to the system. This suggests that the system delivers hot water back to the tank with an approximately 5% increase. Figure 11 indicates the variation in thermal output and efficiency. The standard deviation was determined for all measurements performed. Table 3 shows exemplary results: temperature for one of the thermocouples and flow rate.

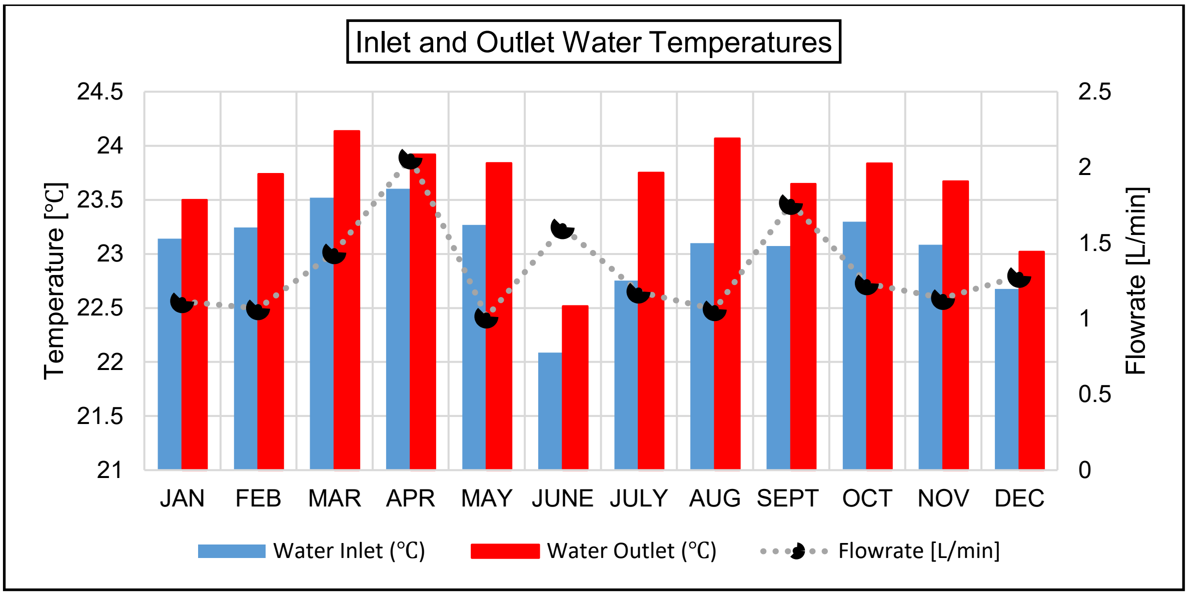

Figure 10. Inlet and Outlet Water Temperatures at different flowrate measurements.

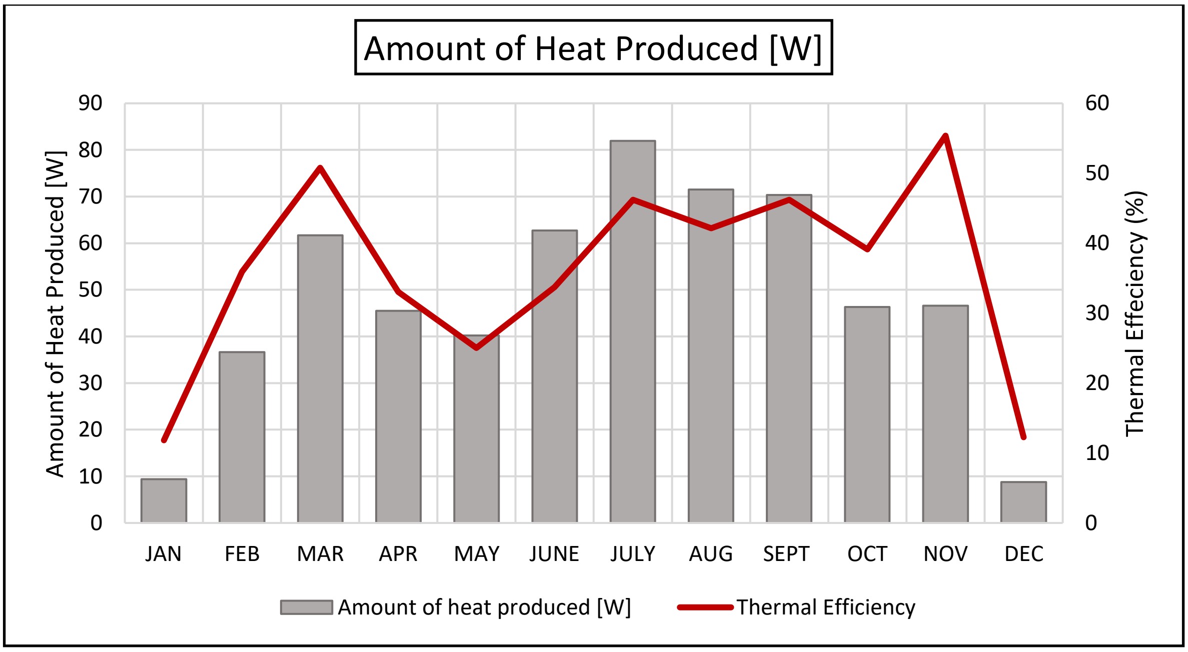

Figure 11. Amount of heat produced and thermal efficiency performance.

Table 3. Exemplary measurement results with standard deviation.

Month	Ambient Temperature °C	PV Cell Temperature °C (Calculated)	PV Cell Temperature °C (Measured)	Standard Deviation (for measured PV Cell Temperature)	Flowrate (L/min)	Standard Deviation (for Measured Flowrate)
January	14.15	18.75	24.42	0.19	1.12	0.01
February	15.29	21.21	24.49	0.49	1.07	0.01
March	18.89	25.93	23.52	1.09	1.44	0.02
April	24.18	32.17	34.72	1.95	2.06	0.05
May	30.14	39.46	33.44	0.85	1.01	0.01
June	34.09	44.87	34.46	1.84	2.10	0.09
July	35.95	46.23	32.67	0.62	1.18	0.02
August	36.01	45.84	26.20	3.20	1.06	0.01
September	33.15	41.98	28.40	1.99	1.76	0.03
October	28.58	35.45	24.29	1.82	1.23	0.02
November	21.98	26.85	24.60	0.17	1.14	0.01
December	16.44	20.60	23.38	1.09	1.28	0.01

3.1.2. PV Panel Performance

The effect of the panel's cooling on PV electrical power output was also investigated. Figure 12 illustrates the electrical power output when the system has no cooling system, while Figure 13, demonstrates the electrical power output when the system is cooled. A high cell temperature has a significant impact on the system's electrical power and the efficiency. When the system is cooled using water circulation, the electrical power output increases as presented in Figure 14. The measurement results showed an average increase in electrical output power of almost 3.62% and a reduction in the solar panel's cell temperature, depending on the month, between 3.02% in December and 36.22% in June.

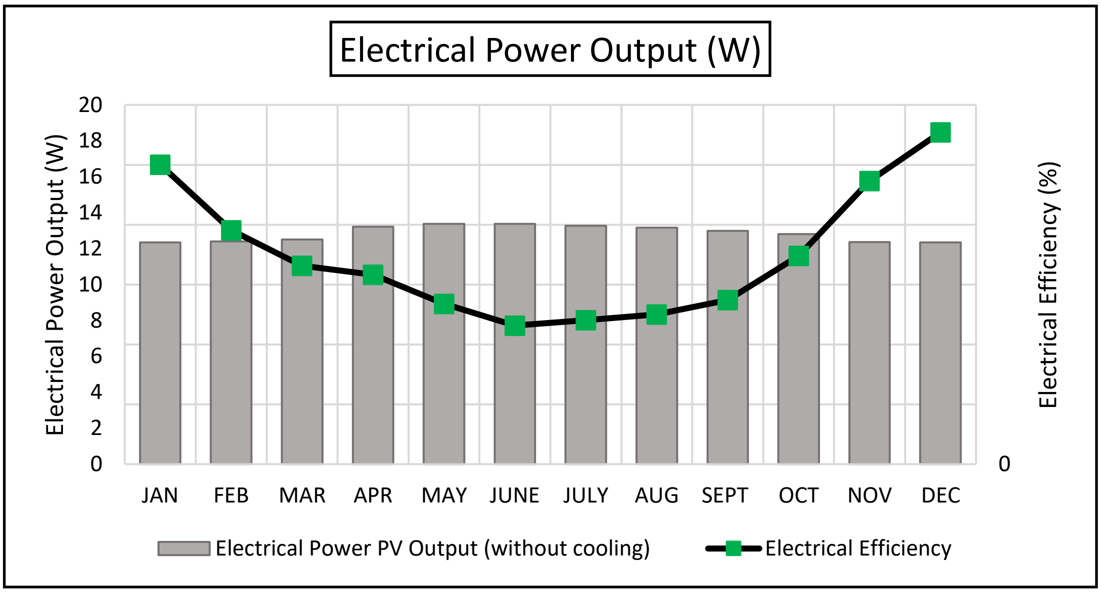

Figure 12. Electrical PV power output without cooling system.

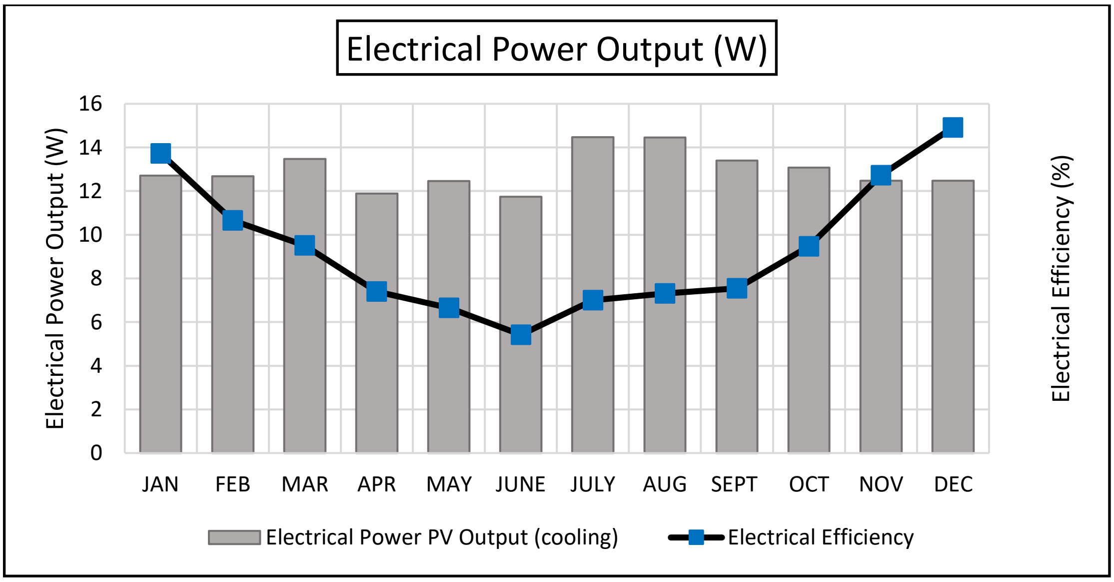

Figure 13. Electrical PV power output with cooling system.

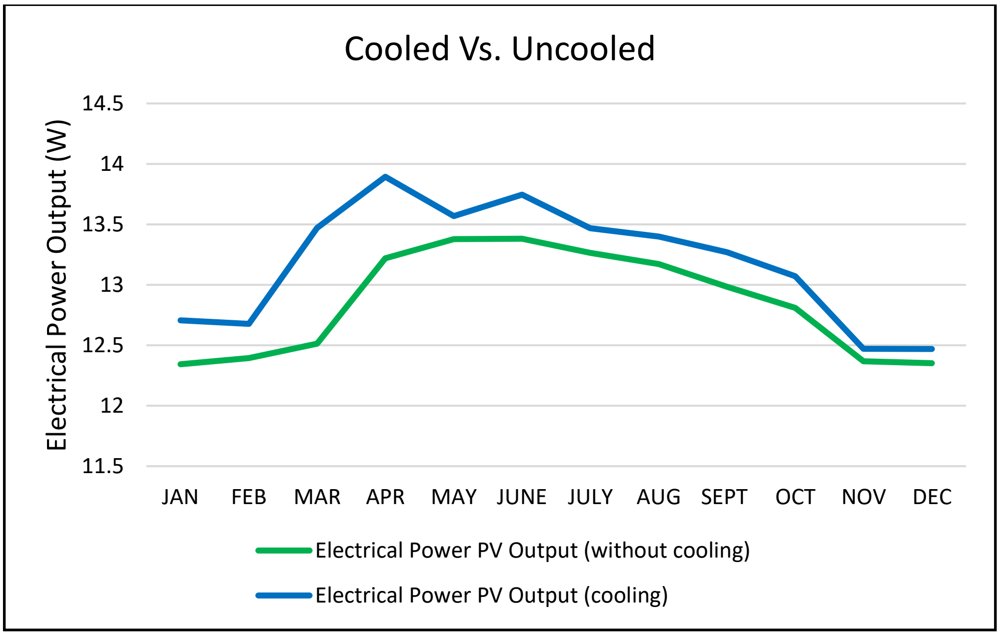

Figure 14. Effect of cooling on the PV system.

3.2. Presentation of Simulation Results

The simulation was performed for 8760 h using TRNSYS, its purpose to investigate the electrical power outcomes under Kuwait's solar radiation and temperature conditions. TRNSYS results indicate that the PV panel's temperature is significantly higher when it is not cooled. For this reason, the system with water circulation was tested. Figure 15 indicates an almost 8% a drop in the solar panel's cell temperature caused by the circulation of water. Consequently, the thermal collector has taken in the panels waste heat and transferred it to heat water, shown in Figure 16, and it is demonstrated that the system is able to produce heat throughout the year. It is based on the variation in solar irradiance and the production of levels of heat, which differ depending on the season.

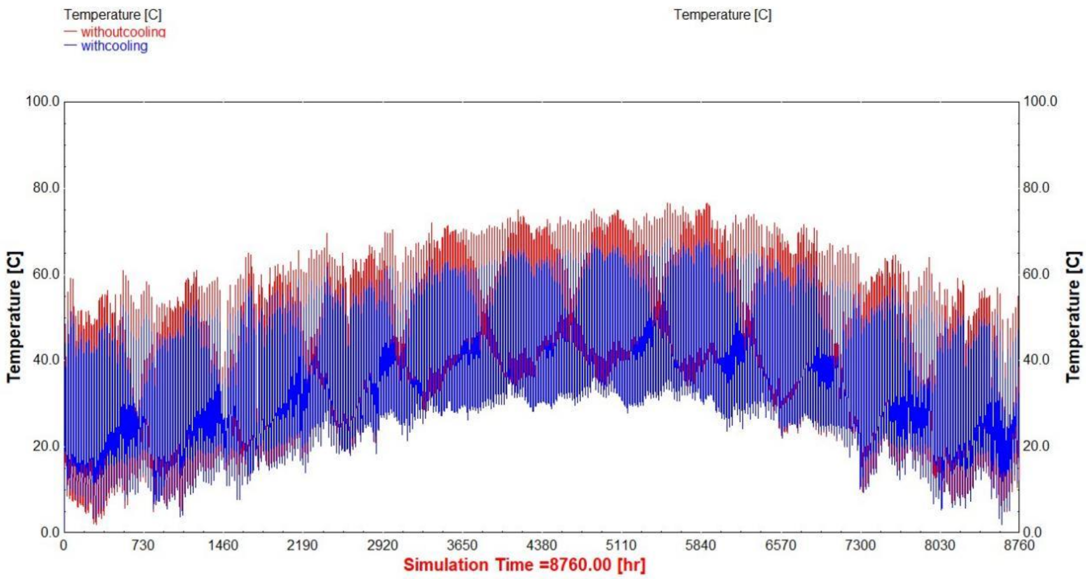

Figure 15. PV cell temperature (TRNSYS).

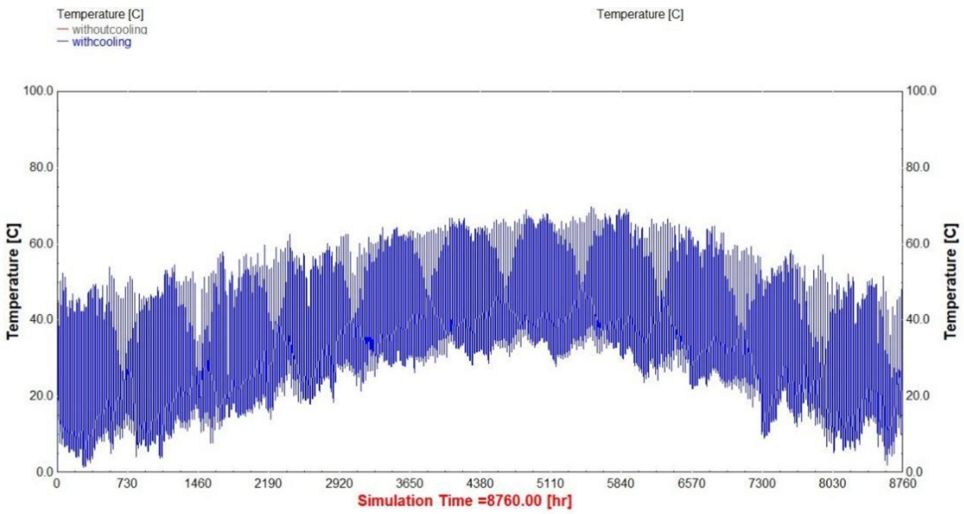

Figure 16. Outlet water temperature with cooling (TRNSYS).

Additionally, the data in Figures 17 and 18 show the needed comparison to study the cooled panel's performance on PV power output. The effect of cooling the panel has a significantly increases electrical output power by almost 6.25%. This indicates that, as the solar panel's temperature increases during the year, the ability to produce electrical power is adversely affected. Therefore, the graphic results from the TRNSYS simulation demonstrate that cooling the panels will increase the system's efficiency and its electrical power output.

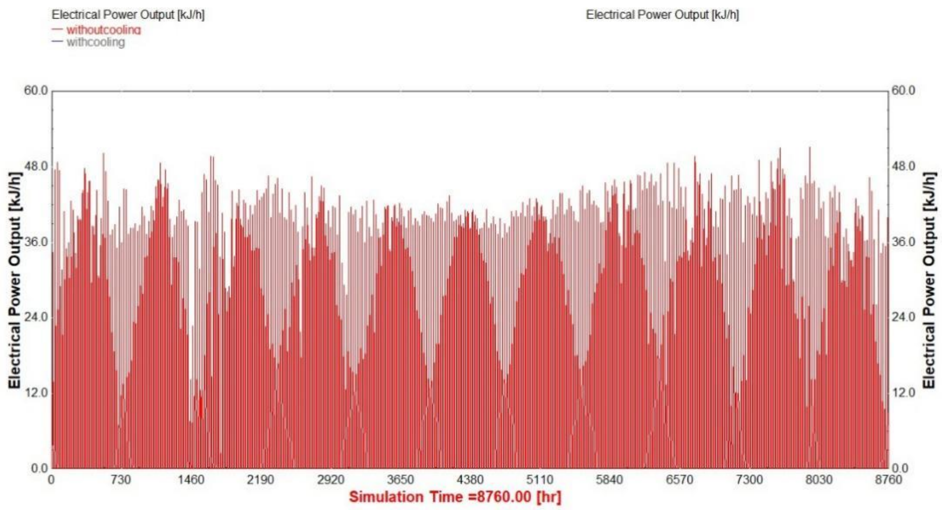

Figure 17. Electrical PV power output without cooling system (TRNSYS).

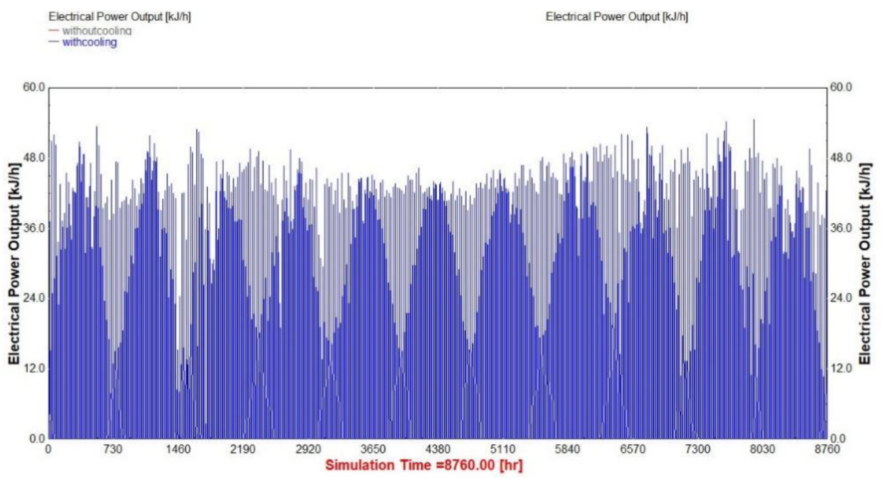

Figure 18. Electrical PV power output with cooling system (TRNSYS).

3.3. Discussion

The research outcome shows the effect of cooling on PV electrical power and efficiency. Khordehgah et al. [45] examined the performance of a solar photovoltaic thermal collector for a household in London, finding it possible to reduce the solar panels temperature by almost 25%, increasing electrical power output by nearly 15%. This approach was tested to investigate PV/T performance for a household under Kuwait hot climate conditions. Findings show that the electrical power increased and the PV cell temperature declined when the cooling system was implemented and examined experimentally and computationally using TRNSYS. Table 4 compares the experimental and TRNSYS results in terms of absolute error and accuracy percentage, showing that the results have acceptable margins of agreement and accuracy with the lowest percentage accuracy of 91% for individual months. Root-mean square error was determined to verify the experiment and was 0.69. Based on this, the proposed system results in an increase in electrical output power of almost 6.25% and a reduction in the solar panel's cell temperature by approximately 8%. The results obtained for the hot climate of Kuwait are not as promising as for London, which is in a temperate maritime climate. A significantly lower increase in electrical output can be observed, almost half that of the study [45]. In addition, a slight reduction in solar panel cell temperature of only 8% was observed compared to the same system for London (25%).

Table 4. Electrical Power Output Error Analysis.

Month	Electrical Power Output Experimentally [Watt]	Electrical Power Output Using TRNSYS [Watt]	Error	Accuracy [%]
January	12.71	12.8	0.72	99.28
February	12.68	12.22	3.74	96.26
March	13.47	13.05	3.22	96.78
April	13.9	13.1	6.06	93.94
May	13.57	12.77	6.25	93.75
June	13.75	12.9	6.57	93.43
July	13.47	12.7	6.05	93.95
August	13.40	12.5	7.20	92.80
September	13.27	12.3	7.88	92.12
October	13.07	12.1	8.03	91.97
November	12.47	12.7	1.81	98.19
December	12.47	12.7	1.82	98.18

The paper examines the performance of the system in an annual analysis both on a test bench for monthly values and in TRNSYS in hourly steps. The analyses carried out have their limitations. The impact of wind, which could significantly affect the results of the analysis, was not considered in this study. Further research into this issue is therefore required. In addition, different water flow rates through the heat exchanger should be analysed to find the most optimal value for the climate under consideration. The proposed PV module type was polycrystalline, which is relatively low in cost, withstand a wide range of weather conditions and more eco-friendly compared to monocrystalline panels. Two PV modules were used in the system, each generating a maximum 20 W. To improve the system, experimental findings suggest using another PV module to generate better power output and efficiency. In addition, parameters such as mentioned wind velocity and humidity associated with Kuwait's climate might affect output results. As such, these parameters, along with analysis of the heat pipe's thermal resistance, will be considered when improving the system in future analyses.

4. Conclusions

This paper analyses the effect of a cooling system based on heat pipes on the performance of photovoltaic panels (PV/T) with active tracking for a household under Kuwait hot climate conditions. The system was investigated experimentally in the laboratory and computationally using TRNSYS. The experiment used a specially designed chamber in which Kuwait weather data for ambient temperature, average solar irradiance and sun angles were integrated. Panel angles were tilted to face south at an optimum position indicated by an active tracking system. Having obtained the experimental results, the system was then modelled using TRNSYS in order to confirm the effect of cooling on the efficiency of the panel. The most important results are presented below:

- Measurement results in the laboratory showed an average increase in electrical output power of almost 3.62% and a reduction in the solar panel's cell temperature, depending on the month, between 3.02% in December and 36.22% in June.
- The simulation results showed that the use of a heat pipe-based cooling system increases the electrical output power by 6.25% and solar panel's cell temperature dropped by approximately 8%.

- Root-mean square error was determined to verify the experiment and was 0.69. The study demonstrates therefore the high agreement of the model with experimental data and confirm the feasibility of using simulation to assess system performance under different climatic conditions.
- The PV/T system should be adjusted each time according to the climatic conditions. By comparing the results of the analysed system at two different locations (UK and Kuwait), it is concluded that the system should be redesigned to take into account the speed of the water flow through the heat exchanger.
- The study should be extended to include the effect of wind speed on the PV/T system.
- The presented results, although not as promising as for the temperate maritime climate in which London is located, show that the application of the analysed system could be beneficial in hot climates. However, further analysis would need to consider the cost of implementing the cooling system in relation to the electricity gains obtained.

Author Contributions

A.A., A.Ż.-G., H.J.: conceptualization, methodology, A.A. software; A.A., A.Ż.-G.: data curation, writing—original draft preparation; A.A., A.Ż.-G.: visualization, investigation; H.J.: supervision; A.A., A.Ż.-G.: validation; A.A., A.Ż.-G., H.J.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

MPP	Maximum power point
PCM	Phase change material
PV	Photovoltaic
PV/T	Photovoltaic/Thermal
RMSE	Root-mean square error
TMY	Typical meteorological year

Nomenclatures

A	Surface Area $\mathrm{m^2}$
cp	Specific Heat Capacity $\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$
G	Solar Irradiation $\mathrm{W \cdot m^{-2}}$
I	Current A
L	Length m
$\dot{m}$	Mass Flowrate $\mathrm{kg \cdot s^{-1}}$
$NOCT$	Nominal Operating Cell Temperature ℃
P	Power W
Q	Heat Transfer Rate W
R	Resistance Ω

T	Temperature K
V	Voltage V
W	Width m

Greek Symbols

Δ	Difference
η	Efficiency %

Subscripts

amb	Ambient
c	Collector
C	Cell
ch	Characteristic
el	Electrical
MP	Maximum Power
oc	Open Circuit
PV	Photovoltaic
sc	Short Circuit
th	Thermal

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