COMPUTATIONAL STUDY AND EXPERIMENTAL VALIDATION OF A SOLAR PHOTOVOLTAICS AND THERMAL TECHNOLOGY

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ABSTRACT

The work presented in the paper provides a detailed TRaNsient System Simulation (TRNSYS) model that simulates the performance of a solar photovoltaic – thermal (PV/T) collector and examines its potential contribution for household heating applications in the UK. Based on this, a system is modelled to simulate the hot water demand of a house through connecting the solar – thermal panel with a thermal storage tank, a pump and a controller. The results obtained from the simulation indicated by how much the solar panel is able to convert solar energy into electrical power and heat over different seasons of the year and provide the hot water needs of the household. The model was validated based on the experimental configurations of a hybrid heat pipe based solar PV/T module and through applying cooling cycles, the thermal and electrical outputs and efficiencies of the system were indicated. Through this, it is investigated that the temperature of the solar panel can be reduced on average by almost 25%, which subsequently, will result in an increase of the electrical power output by nearly 15%. The simulation results also assisted in investigating and analysing aspects such as the effectiveness and efficiency of the panel over different times of the year and helped to optimise the performance of the system. For instance, it is simulated that the system can provide hot water for the household throughout all seasons of the year and under different solar radiation conditions. However, it is discovered that in order for the system to meet the required output demand, input from an auxiliary power unit may always be necessary.

Keywords: PV/T Solar Panels, TRNSYS Simulation, System Modelling, Efficiency

1 INTRODUCTION

With growing concern regarding global warming and rising energy prices throughout the world, numerous programs and targets have been developed and introduced by governments and organisations to encourage the public to use energy efficient technologies and cheap renewable energy sources. In this regard, the use of solar energy has been described as the most widely-available renewable energy source used worldwide to achieve global sustainability targets.

Indeed, solar energy is inexhaustible on a human scale and available everywhere, every day. At present, solar energy can be used in two different ways: either this energy can be collected and transformed to produce electricity thanks to photovoltaic cells or this energy can be recovered as thermal energy. In 2017, the worldwide solar PV capacity reached 402 GW while the solar thermal capacity was estimated at 480 GWth, which represents respectively about 15% and 18% of the total renewable energy production [1]. As its name indicates, a Photovoltaic (PV) solar panel uses the photovoltaic effect to turn solar radiation into electricity. As the solar radiation hits the silicon surface of the PV module, an electric charge is created inside the semiconductor. At the PN Junction (Positive/Negative), an electron-hole pair appears forcing the electron to go through the circuit to balance the potential difference. That way, a current is created in the PV module due to the solar excitation.

It is discovered that the PV solar panel efficiency varies in regard to the technology and materials used but the most widespread commercial ones have an efficiency between 8-25% [2]. The largest research challenge in this area is to use cost-saving materials that have low activation energy and increase the overall efficiency while reducing manufacturing costs. Unlike PV solar panels which focus on electrical energy, solar thermal technologies use collectors to recover heat energy from solar radiation. By the circulation of a working fluid such as air, water, oil, salts or carbon dioxide, solar energy can be used for space heating and cooling, to warm-up water, to participate into a pre-heating of a combustion chamber or to reduce the heating costs of a heat pump. Solar technology panels have an efficiency between 70% and 90% [3].

The main advantages of thermal solar technologies compared to PV solar panels is the simplicity of this technology as the solar heat energy is only recovered and not transformed to electricity. This also explains why the efficiency of solar thermal technologies is significantly higher than that of PV panels. The other main advantage of solar thermal is the storage capacity, as heat is easier to save than electricity, especially in a house. Most of the commercial solar thermal systems use water as a working fluid and can store warmed-up water in the house tank.

Nevertheless, novel technologies named PV-T (Photovoltaic/Thermal) panels have appeared and they combine the solar photovoltaic (PV) modules and solar thermal collectors. By using both photovoltaic and thermal recovery systems, PV-T panels produce electricity from solar radiation while recovering heat via a working fluid. Moreover, it has been shown that both effects are not simply summed. Indeed, cooling the PV module also increases its electrical generation. This makes PV-T panels a really promising combination of both electrical and thermal energy production. Their efficiencies evolve depending on the technology used, the materials of both PV module and thermal collector, the working temperature of the system, the working fluid used and the working conditions such as the inclination of the panel. Yet, PV/T efficiencies are more than 10% for the PV module and 40% for the thermal collector and can reach far higher ratios.

Globally, however, and despite the advances in producing high efficiency and low cost solar panels, the technology is yet to be adopted in large and commercial scale [4]. This study will therefore aim to illustrate in what manner by using PV/T modules, electricity and heating can be generated for a household and how temperature changes can affect the efficiency of modules. The work will be conducted through computational demonstrations using TRaNsient System Simulation (TRNSYS) software. This enables a computational model to be built that can be used without the need of experimental setups to investigate the behaviour of solar panels under different conditions and loads.

2 STATE OF THE ART TECHNOLOGIES

According to International Energy Agency statistics, Solar energies provided 303 TWh in 2016, which represents only 1.22% of the global power generation [5]. This, as *Peng et al.* [6] explain, is mainly due to some technical and economical limitations of current solar panels, such as having low commercial and economic module efficiencies. In this regard, several attempts have been made to study and investigate the reasons behind the factors that affect the solar module efficiencies and recommendations have been provided to improve the performance and functionality of solar cells.

For instance, *Stropnik and Stritih* [7] identified that one major reason which significantly influences Photovoltaic (PV) solar panel efficiency is the working or panel surface temperature. *Tan Jian Wei et al.* [8] in another study demonstrated that temperature has an adverse effect on the cell efficiency as, if the temperature of solar cells is increased, the energy conversion of the module is decreased. *Moharram et al.* [9] specifically mentions that the efficiency of the module drops with the rise in temperature with the rate of approximately 0.5%/°C. Several other studies such as [10-13] also came to the same conclusion, proving that an increase of the module temperature has a direct negative link to the efficacy of solar panel. This therefore indicates an important area of research which must be addressed in order to improve the usability of solar energy and the applications of solar panels.

Having mentioned this, several researchers and scientists have conducted projects to develop cooling techniques for solar modules, in order to increase the efficiency of the solar panels and tackle the problem indicated. There are several methods which have been tested experimentally to cool down solar cells for efficiency improvements and heat generation. As *Wu and Xiong* [14] explain, many cooling techniques which are mostly based on water and air cooling systems and other cooling techniques that include phase change and conductive cooling materials have been tested experimentally to try to increase the efficiency of the module. Each technique works in a distinct way and provides a different rise in overall efficiency. *Irwan et al.* [15] tried to cool down the surface of solar panels with the use of a fan and achieved an increase of 3.5% output voltage compared to when the panels are not cooled. *Nižetić et al.* [16] in an experiment developed a cooling system based on water spray to cool down solar panels and demonstrated that an effective output electrical efficiency of almost 6% can be achieved. In another study *Rajaram and Sivakumar* [17] showed that with the use of a phase change material at the back of a solar panel for cooling, the performance of the module can be increased by nearly 5%, with an increase of almost 8% for power production. *Radziemska* [13] explains, hybrid photovoltaic-thermal systems (PV/T), which combine PV and heat extraction modules together, have also been proven to improve the overall efficiency by almost 40% through stabilising the cells' temperature. PV/T hybrid modules collect the heat that is absorbed and dumped by the PV cells to the surrounding again after photovoltaic conversion and generate heat and electricity simultaneously. There are four main types of PV/T modules depending on the collector technology: PV/T air type collectors, PV/T liquid type collectors, concentrating PV/T water collectors and air/water combination type collectors [18]. In PV/T air collectors, air is used as a working fluid to recover the heat and it can be used for drying, space heating and ventilation. *Tiwari and Sodha* [19] investigated hybrid PV/thermal air collector performance studying the impact of glazing and of using a tedlar film over the module capacity. It was observed that a glazed PV/T air collector without tedlar reached the highest performance of an overall 40% efficiency. *Kumar and Rosen* [20] evaluated the performance of a double pass PV/T air collector with a special focus on the use of small fins to increase the heat transfer rate between the PV cell and the working fluid. By increasing the heat exchange surface with fins, the cell temperature was decreased from 82°C to 66°C which leads to a 15.5% and 10.5% gain of thermal and electrical efficiencies, respectively.

By means of an unglazed, single pass, open loop PV/T air system, *Bambrook and Sproul* [21] demonstrated that increasing the air mass flow rate will provide higher thermal and electrical efficiencies. Between a 0.05 kg/s m^2 and a 0.1 kg/s m^2 air flow rate, the relative electrical efficiency increase was 15% whilst the relative thermal one was 38%. *Kostic et al.* [22] tried to add reflectors to improve a PV/T air collector performance. Even if the energy-saving efficiency with a reflector decreased from 60.1% to 46.7%, the total generated electrical and thermal energies have respectively increased by 25% and 8% while using reflectors, they attest. After a PV-T modelling investigation, *Dupeyrat et al.* [23] designed and tested a single glazed PV/T liquid collector with water as a working fluid. Under optimum conditions, this system reached an unprecedented 79% thermal efficiency whilst the electrical efficiency was 8.7%. *Sakhr et al.* [24] proposed a PV/T system made of glass, air gap, PV panel, absorber plate layers and opted for a spiral flow design absorber. The maximum thermal efficiency observed rose to 61.3% on sunny days and the electrical efficiency was up to 12.8%. The highest combined efficiency is 74.1% for this prototype. *Nahar et al.* [25] introduced a novel thermal collector design excluding the absorber plate to improve the heat transfer. However, the overall efficiency decreased by 4.4% while removing the absorber plate. Yet, the global efficiency of the hybrid PV/T water system could reach 80%. The important effects of tilt angle and connection mode of PVT modules have been evaluated by *Sun et al.* [26] on a PV/T liquid collector using water as working fluid. It has been shown that the series connection can result in a 5.4% increase of energy benefits whilst improving thermal energy by 11.4%. *Tripathi and Tiwari* [27] experimentally evaluated the performance of a fully covered concentrated PV/T water collector. They showed that the manual maximum power point tracking technique was more efficient than a fixed position. To overcome working fluid freezing issues, heat pipes have been introduced as thermal collectors to work like a thermal diode, conveying the heat in only one direction. The heat pipe introduction in PV/T collectors has allowed secure PV/T systems whilst significantly decreasing the working fluid circuit resistance. *Tang and Zhao* [28] designed a novel micro heat pipe array and investigated both air and water cooling. The best results were obtained while using water as a working fluid. In that case, the PV cell temperature was reduced by 8% which led to a 3% increase of electrical efficiency.

Jouhara et al. [29] employed a novel flat heat pipe (heat mat) as a heat exchanger for homogenous cooling and proved experimentally that an efficiency increase of about 15% for the module can be provided. In this study, an innovative system for transferring the waste heat generated from the photovoltaic solar panels was developed and tested [30]. As can be seen from Figures 1 and 2 below, the heat mat comprises a cooling manifold that incorporates several heat pipes which are placed under the PV cell. In this system, the generated heat from the PV layer is simply transferred to the heat mat, and because of the specific characteristics of the heat pipes in conveying heat effectively, the PV panel is subsequently cooled.

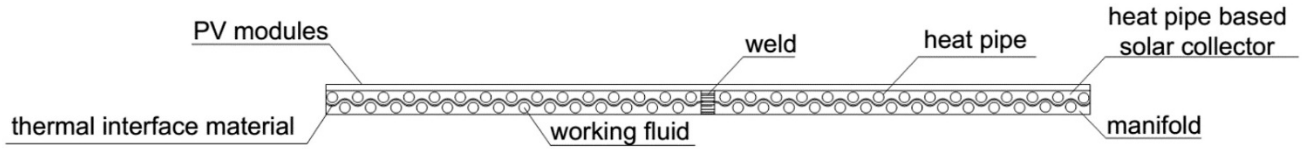

Figure 1: Cross Section of the Heat Pipe Based PV/T Panel [30]

Figure 2: Heat Mat Technology Set Up [29]

The technology, as shown in Figure 3, was examined in a set up that would represent a small family dwelling in Cardiff, UK. In this experiment, it was discovered that approximately 60% of the hot water demand of the household can be covered, even in the case of days with low levels of solar radiation [30]. The system thermal efficiency was reported to be around 50% while producing almost 55 W/m^2 of electricity.

Figure 3: Solar PV/T Experiment Installation Set Up [30]

Table 1 below shows other state of the art studies which have been conducted on different techniques and methods used for cooling of PV panels and indicates what results were achieved.

Table 1. State of the Art Studies

Reference	Title	Method	Results
[31]	Improved PV/T solar collectors with heat extraction by forced or natural air circulation	PV system was cooled through forced air circulation and by attaching a configuration of suspended metallic fins to the back surface of the panel.	The technique proved to achieve greater efficiency results when compared to the typical forced air cooling systems used in the study.
[32]	An Experimental Study of Combining a Photovoltaic System with a Heating System	Cooling was achieved by covering the top surface of a PV panel with a thin film of water and by using a heat exchanger to remove the waste heat.	Results of the experiment showed an increase of the total energy and electrical power output from the system, as the temperature of the panel was lowered.
[33]	Hybrid photovoltaic/thermal solar systems	A Hybrid PV/T solar system was built by combing forced water and air circulations techniques with additional surface glazing.	Results indicated that the water circulation cooling method was a better option in regards to efficiency increase. The use of glazing increased the thermal efficiency while reducing the electrical power output.
[34]	Electrical/thermal performance of hybrid PV/T system in Sharjah, UAE	A water based cooling system that is made of rectangular copper pipes is built and attached to the backside of a PV panel.	The prototype is experimentally tested in a hot location of the Middle East and it is investigated that through the proposed method, electrical power efficiency increase and hot water can be obtained.
[35]	Performance of PV panel coupled with geothermal air cooling system subjected to hot climatic	A geothermal cooling method was constructed by using a heat exchanger that includes several pipes, which were connected to a system of air blower and buried under the ground.	The experiment resulted in successfully cooling the temperature of the panel and increasing the power output from the panel. This method was proved to improve the PV module efficiency by pre-cooling the inlet (ambient) air.
[36]	Passive cooling technology for photovoltaic panels for domestic houses	A passive cooling method was designed that utilises rainwater as cooling fluid and a gas expansion device for water distribution. In this configuration, the gas that is stored in a chamber is thermally expanded by receiving solar	The system proved that through a fully passive system and with no energy input from any source, significant electricity output increase and efficiency improvements can be achieved.

		radiation and through that, water it pushes from a storage tank to flow over the PV panel.	
[37]	Performance study of solar photovoltaic thermal collector integrated with cooling system	Air and water was forced through a designed cooling heat exchanger that comprised specially made channels. The heat exchanger was then attached to the lower surface of a PV panel, absorbing and taking the waste heat from the panel.	Results from the experiment illustrated that a greater overall efficiency increase can be obtained through the waster based cooling method.

3 SYSTEM MODELLING

The TRNSYS simulation engine was employed to develop and analyse the performance of a photovoltaics-thermal system. The program enables the user to analyse and evaluate the functionality of a complex transient system through the use of a graphical interface front-end called Simulation Studio. In this environment, the system is split into several components or Types and is linked to inputs and outputs. In short, a Type is a component whose outputs can be calculated mathematically as a function of the input of time-dependent values [38]. The transient behaviour of the system is solved by discretising the time domain and iteratively solving for each variable at each time step [39]. Each Type requires a set of input parameters which are usually defined from other components or by specifying data files and a set of output parameters which can be treated as the input to other Types or be plotted and saved as the result of the simulation.

For instance, and as demonstrated by *Reddy et al.* [40] and *Huang and Huang* [41], output values from the simulation can be plotted through an online plotter (Type 65) or saved in the form of data (.out) by a printer (Type 25). Through Weather Generators (Type 15), the hourly weather data of a specific location is generated and with the use of Photovoltaic-Thermal Panels (Type 50), the electrical and thermal performance and functionality of a PV/T array can be defined. Other components such as a Thermal Storage Tank (Type 4), Differential Controller (Type 2), Pump (Type 3), Regulator and Inverter (Type 11) and a load profile can be also found from the extensive library of TRNSYS to complete and control the system and generate the output at a desired rate and value. This, for instance, was demonstrated through a simulation developed by *Wang et al.* [42]. In this study, a TRNSYS model of a solar collector hot water installation was created to examine the optimum installation angle and orientation of a solar panel to produce hot water for a severely cold area in China. Through simulation results, it was concluded that the best collector installation angle mainly depends on the local latitude and the collector orientation. In another investigation conducted by *Balasubramani and Vijayakumar* [43], the performance of a 1kWp grid containing a Photovoltaic System was modelled and analysed. It was demonstrated that through modelling with TRNSYS, the overall effect of meteorological conditions on the operational characteristic of a grid connected PV system can be determined. *Stropnik and Stritih* [7] also presented a work which illustrated how the efficiency of a PV panel can be increased with the use of phase change material (PCM). In this study, the performance and temperature of a PV panel model with and without PCM were examined and it was concluded that the temperature of the PV-PCM panel on average is less than the solo PV panel. Through TRNSYS, it was predicted that this will result in an average efficiency improvement of 7.3% over a year.

Bilbao and Sproul [44] used RC networks to build a PVT-water model for transient analysis. The main advantage of this was to directly simulate the PVT collector in an electronic circuit. Moreover, this RC model has proved more accurate compared to the steady state model regarding experimental data correlation. Thanks to this model, the collector's time constant and thermal capacitance have been determined. *Li and Jing* [45] studied and optimized the performance of a PV/T system thanks to coupled TRNSYS and CFD simulation. The optimum PV cell and best working conditions were also determined. The TRNSYS model should be able to evaluate and predict the performance of a PV/T system regarding different weather conditions over the desired period of time, authors attest. *Choi et al.* [46] attempt to couple TRNSYS with ArcGIS software in order to evidence the PV potential in urban areas. By direct access to the Geographic Information Systems (GIS), TRNSYS and PV analyst simulation could work simultaneously to assess yearly PV system performances on buildings. *Quesada et al.* [47] compared TRNSYS predictions with experimental results of a grid-connected photovoltaic system. Despite inaccurate input data and model uncertainties, the monthly error between TRNSYS estimations and experimental data was 2.2% on average. Thanks to TRNSYS, *Mohasseb and Kasaeian* [48] compared flat plate collector and evacuated tube collector performances. Their simulation revealed that the energy gain of an evacuated tube collector (ETC) is between 15% and 30% higher in a year than flat plate collectors, depending on the hot or cold climate.

Based on the above conducted literature review, a system was created to simulate and investigate the effect of cooling on the output and efficiency of PV solar panels. The model is designed by integrating a PV solar panel with a solar thermal collector into one component (PV/T). As *Good et al.* [49] explains, this system improves the electrical efficiencies of the solar PV by removing generated heat from the module and converting that to hot water. By looking at the simulations modelled by *Herrando and Markides* [50] and using the experiments conducted by *Jouhara et al.* [29] for the verification of the results, a system is modelled which can be used to demonstrate how a PV/T system can improve energy efficiencies of a household in London, UK.

The cooling system as can be seen from the flow chart shown in Figures 4, comprises a closed-loop configuration that takes the heat away from the panel and converts that into hot water, which is then stored in a thermal storage tank. Following this, a controller, gives orders to the pump to drain cold water from the tank and delivers that to the panel when temperature of water is at 20°C. This ensures that cold water is being circulated through the panel, absorbing the generated heat. Following this and by connecting Type 65, the performance of the panel based on electrical power output and efficiency can be monitored, with and without water circulation. This should give an indication of the behaviour of the panel to the solar radiance and temperature, which can then be combined with the produced heat and electrical power figures to point out the overall gain from the system.

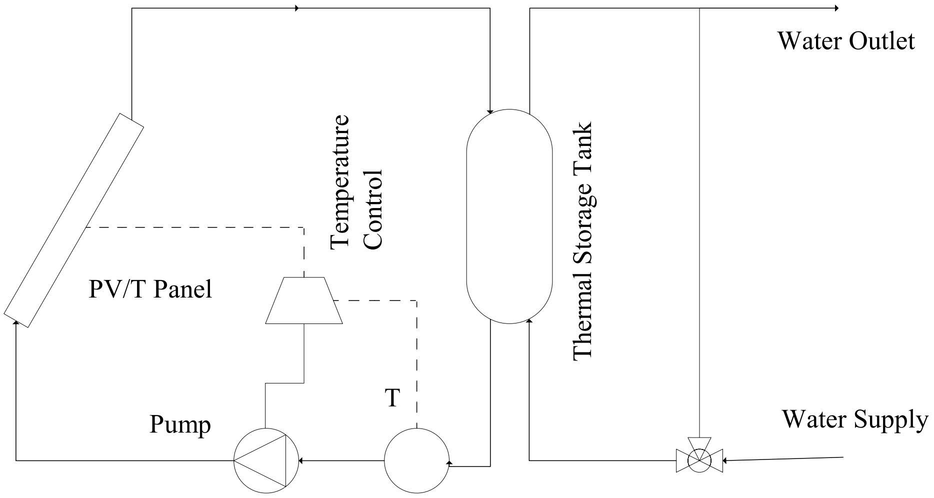

Figure 4: Schematic Diagram of the full PV/T System

4 ESTIMATIONS AND SYSTEM VALIDATION

As can be seen from Figure 5 below, the system is designed to illustrate the electricity and hot water outputs through connecting the module with a water supply, a hot water tank and a pump. The system is modelled so it provides hot water at 60°C throughout the year for a household with the use of the heat absorbed by the thermal collector that is passed through a tank with auxiliary heat unit (Type 4). It is estimated that a household of four occupants consume about 130 L of hot water through using showers 4 times per day and washbasins 20 times per day (for food preparation and washing). The hours when water is drawn from the system are set to be 7am to 8am for 2 showers and 4 uses of washbasins, 1pm to 3pm for 8 uses of washbasins, 7pm to 9pm for 1 showers and 8 uses of washbasins and 10pm to 11 pm for 1 showers. The estimated temperature and volume of the hot water demand in the model are based on the studies conducted by *Energy Saving Trust* [51], where it was revealed that the mean household hot water consumption in England is around 122 L~140 L/day. The World Health Organisation (WHO) recommends that hot water should be stored and supplied at a minimum temperature of about 60°C and in this regard therefore, the system must ensure the delivery of that [52].

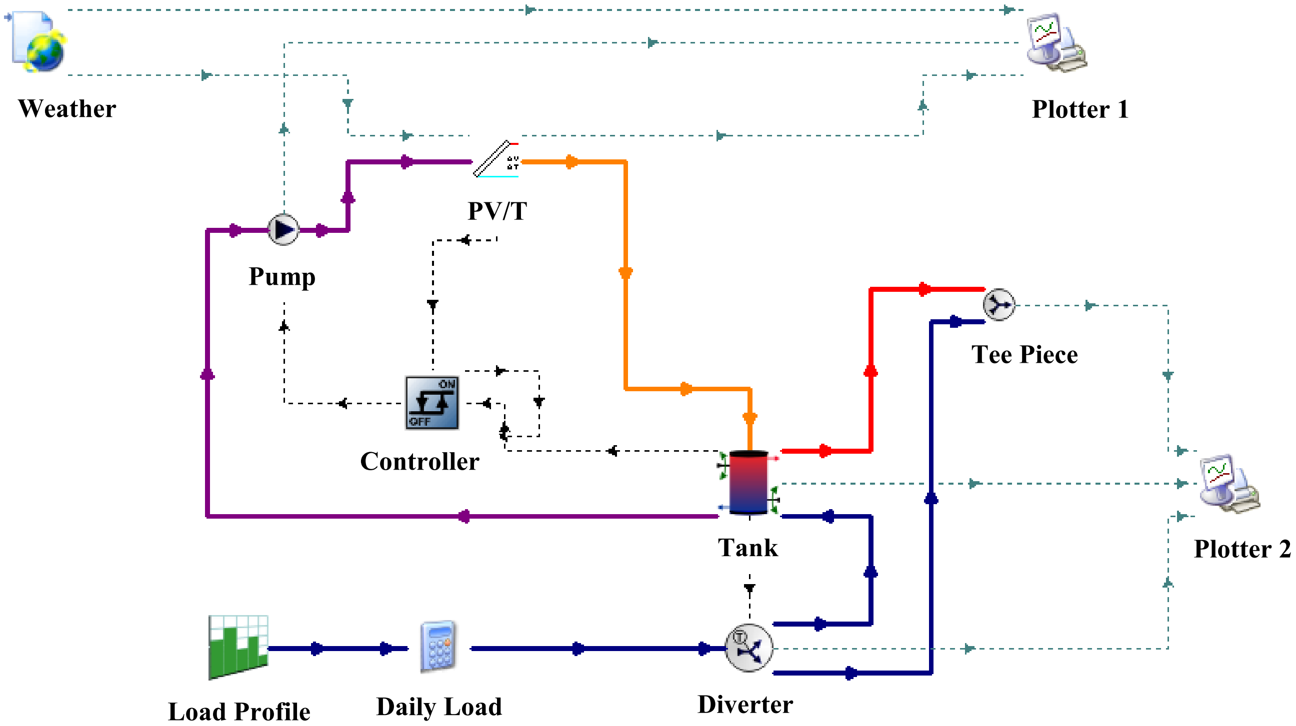

Figure 5: Schematic of the PV/T System in TRNSYS Simulation Platform

The system is controlled through a differential controller and a flow diverter which use a set point temperature and high limit condition to maintain the desired temperature. The controller (Type 2) works as an On/Off differential device, which can be used to control the difference between upper and lower temperatures and function based on the value of the pre-set control signal. The module includes a high limit cut-out and brings the control function to off mode if the high limit condition exceeded. On the other hand, the flow diverter works based on supplying and mixing cold water by sensing the temperature of the tank and by monitoring the inlet temperature of the controller. For instance, when the temperature of water exceeds the limit set by the flow diverter, the controller orders the pump to stop functioning and as a result the temperature of water in the tank is reduced and cooler water is mixed through the tee piece. The boundaries of the controller are set so that the pump stops and starts working when the temperature difference between the output of the collector and the storage tank is less than 5°C and 2°C respectively. The description of the key parameters of the system is given in Table 1 below.

Table 2: Design Parameters of the System in TRNSYS

Component	Type	Descriptions	Value
PV/T Module	50	Module Area	6.4 m^2

		Fluid Specific Heat	4.18 kJ/kg.K
		PV Reference Condition Efficiency	15 %
		PV Cell Reference Temperature	30°C
		Solar Cell Efficiency Temperature Coefficient	0.5 %/K
		Number of Glass Covers	1
		Packing Factor	1
		Inclination Angle	36°
		Facing Orientation	South
Pump	3	Maximum Flowrate	4 kg/hr
		Maximum Power	300 kJ/hr
Storage Tank	4	Tank Volume	150 l
		Maximum Heating Rate of Elements	10000 kJ/hr

Based on the study conducted by Jouhara et al. [29-30] and in order to validate the system, the parameters shown above were set for the PV/T model and the simulation was run for the duration of 7 hours in September or 6033-6040 hrs from the start of the year, using weather data from Cardiff, UK. As can be seen from Figure 6, the average cell temperature results were obtained from the simulation and compared to the experimental results. As it is indicated, the outcome of the model closely matched the results obtained through the study and therefore, it can be said that the model is validated by this mean.

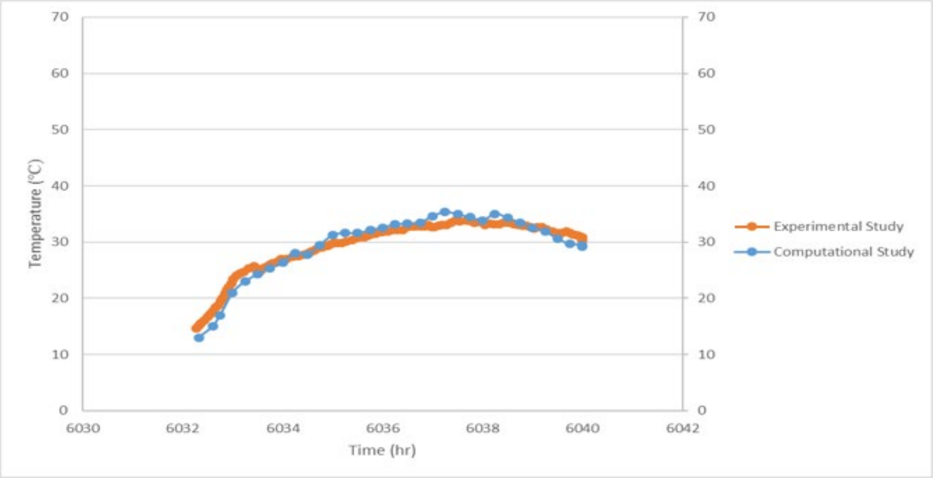

Figure 6: Comparison between Simulation and Experimental results for Model Validation

5 RESULTS AND DISCUSSION

The system performance is examined by comparing the electrical power output of the collector with and without water circulation around the module. As explained by *Jouhara et al.* [29], the thermal and electrical output of PV/T panels can be defined by using the mass flow rate of water entering the system ($\dot{m}$), the value of specific heat capacity of water (cp), the temperature difference between outlet and inlet of the collector (ΔT), the current (I) and voltage (V) generated by the PV module, the surface area of the module (A_{PV}) and through using Equations 1 and 2 shown below.

The amount of heat produced from PV panel is given as:

$$1) \quad Q_T = \dot{m} \,.\, cp \,.\, \Delta T$$

The PV electrical power can be given from:

$$2) \quad Q_{EL} = I.V/A_{PV}$$

The simulation was run for 8760 hours or 1 year to investigate the result of electrical and hot water generation under different solar radiation conditions throughout the year. Based on the above explanations and by using the plotter component, it is demonstrated that the temperature of the PV panel is much higher when it is not cooled. Following this, the system was examined by allowing water circulation from the tank to the panel and results were obtained for comparison. As can be seen from Figures 7 and 8, it can be indicated that the surface temperature of the solar panel has reduced by almost 25% on average when water circulation is applied. This as shown by Figure 9 indicates that the waste heat from the panel has been absorbed by the thermal collector and transferred to the water flow as hot water is produced and delivered to the tank. Having mentioned this, it is also shown that the amount of heat absorbed by the system fluctuates throughout the year, especially during winter and summer time. This is merely based on the fact that the solar radiation changes rapidly during different seasons, generating heat at various rates.

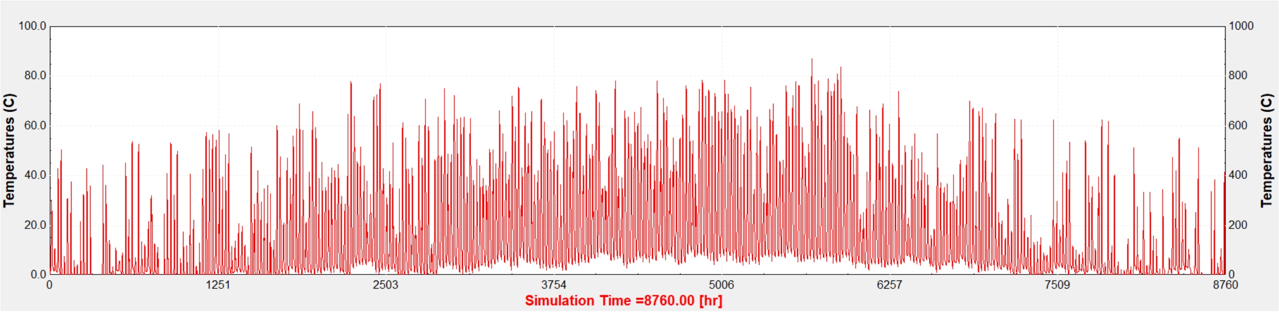

Figure 7: Temperature of Solar Cells without Cooling

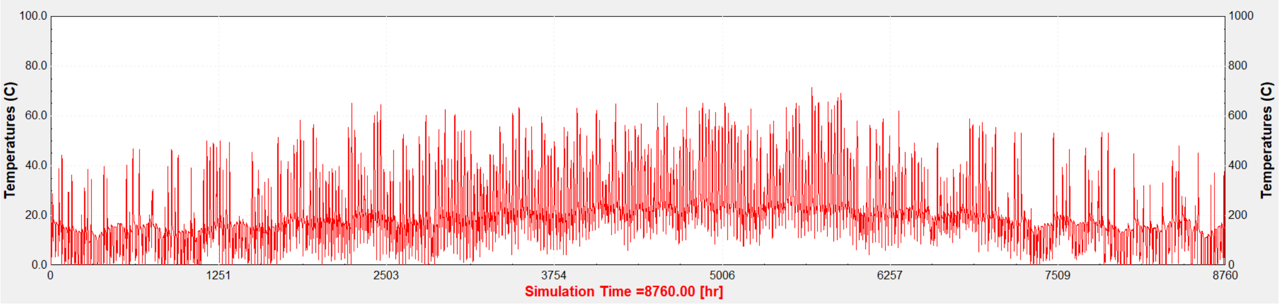

Figure 8: Temperature of Solar Cells with Cooling

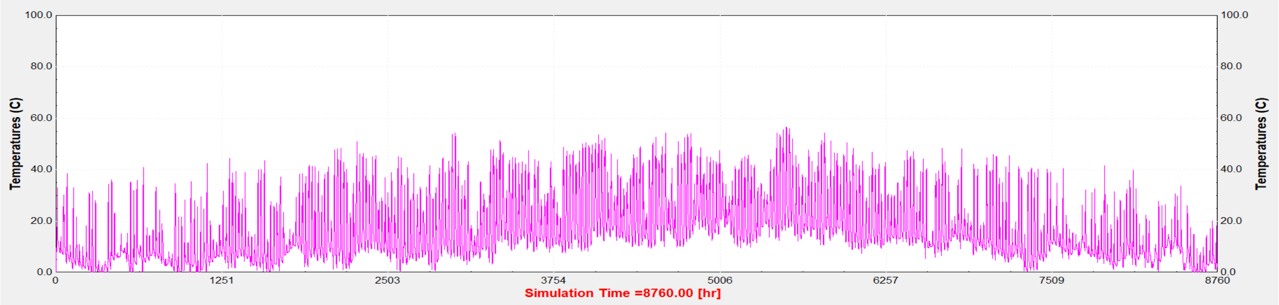

Figure 9: Outlet Temperature of Water

Furthermore and in order to investigate the effect of cooling of the panel on the PV power output, the results as shown in Figures 10 and 11 below were plotted for comparison. As it is illustrated, the effect of cooling of the panel has resulted in an increase of the electrical output power by nearly 15%. This verifies the investigated facts in the conduced literature review and demonstrates how an increase in the cell temperature can affect the efficiency and power output of the panel. As can be seen through this study, it is discovered and validated that the solar panel electrical power output is affected negatively throughout all seasons of the year, as the solar panel heats up. Nevertheless, it has been indicated that the effect also applies during winter time, when the ambient temperature and solar radiation is expected to be low. However, it is show that with the cooling of the panels, the efficiency and power output of the panel will increase.

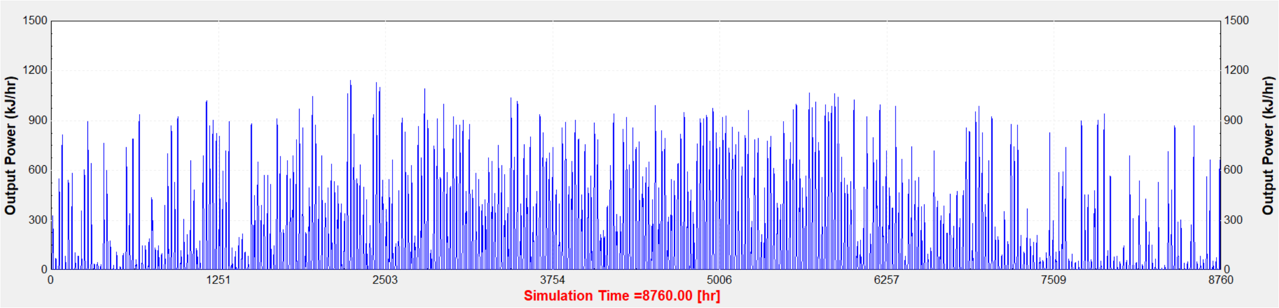

Figure 10: Electric Output Power of the Module without Cooling

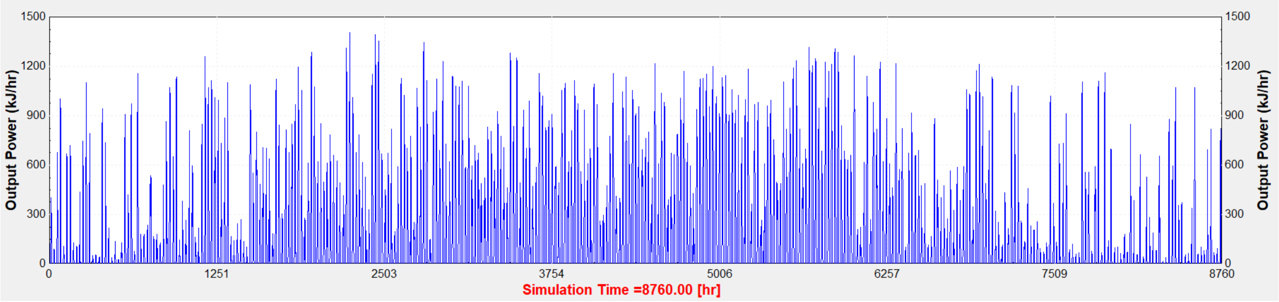

Figure 11: Electric Output Power of the Module with Cooling

As can be seen from Figure 12 below, the system is capable of providing hot water at 60°C through the year by employing the thermal collector and the auxiliary heat unit of the thermal storage tank. Having said that, it is calculated that in order to satisfy the pre-set value of hot water, heat at a rate of 2000 - 5000 kJ/hr may need to be supplied to the system. This is more pronounced especially during night and wintertime, when the solar radiation was not adequate for the panel to provide hot water. Nonetheless, this can also be explained by looking at Figure 9 where it was indicated that the amount of production of hot water varies throughout the year, indicating various amount of heat being absorbed by the PV/T panel. Having said that, this is found to only and roughly affect the production of hot water during the day time hours, however for night time, the input from the auxiliary power unit is nearly always necessary.

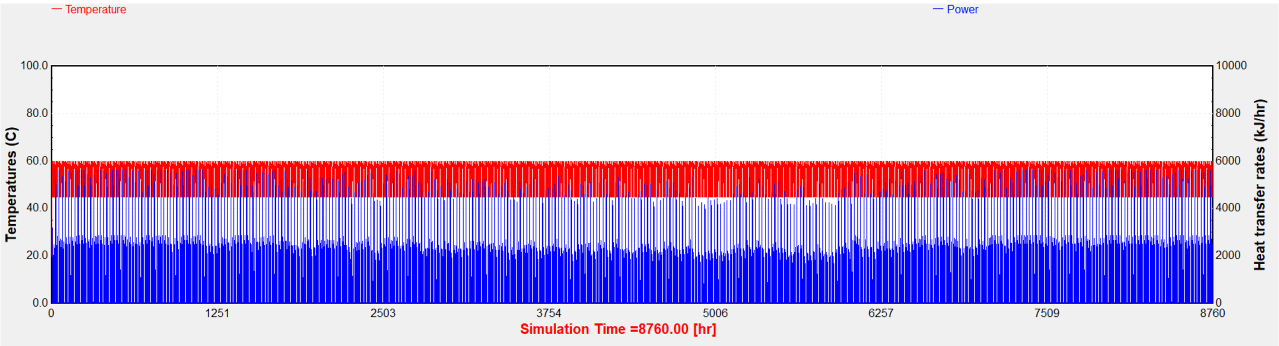

Figure 12: Hot Water Production Temperature (Red) and the Auxiliary Heating Rate (Blue)

6 CONCLUSION

In this study, it was discovered that, by using a hybrid photovoltaic-thermal module, an efficient energy system can be developed which could be used to provide heating and electricity to a household in London, UK. In this regard, a model was simulated in TRNSYS software which was used to evaluate the transient behaviour of the system. The simulation was configured and verified using previous work and literature on PV/T solar systems and modelling. The functionality of the solar module was analysed and it was shown that the electrical output from the panel decreases as the temperature of the cells increases. This was examined by preventing water circulation to the panel which as a result increased the module cells' temperature. Furthermore, it was discovered that the solar panel performance is affected negatively throughout all seasons of the year and also during winter time, when the ambient temperature and solar radiation is expected to be low. Nevertheless and by applying water circulation to the panel, the simulation showed that average the panel surface temperature can be reduced on almost by 25%, resulting in an increase of the electrical power output by nearly 15%. The simulation was then further studied to investigate if heating of a sufficient amount through the collector can be provided to the system. Based on this, it was demonstrated that an input from an auxiliary heating unit will be needed to satisfy the pre-set heating condition. This was mainly because, the amount of heat provided by the solar panel was not sufficient. Having said that, it was nevertheless indicated that the input from the auxiliary power unit is nearly always necessary throughout all seasons of the year. To follow this study, it is therefore of interest to investigate if a standalone PV/T system can be simulated to produce hot water throughout the year by feeding the auxiliary power unit with the electrical power generated by the panel. Such an off-grid system may be comprised with thermal and electrical storage system to produce hot water and heating throughout day and night and during all seasons of the year. In addition, by selecting different weather data, other studies can be conducted to discover the behaviour of the system and analyse if the demand of a household in a hot or cold location can also be met.

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