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Energy Performance Analysis of a PV/T System Coupled with Domestic Hot Water System

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Abstract: In this paper, a standalone photovoltaics-thermal solar panel is modelled using the TRNSYS simulation engine. Based on this, it is explored how such a system can be comprised with thermal and electrical storage components to provide electricity and hot water for a dwelling in a warm location in Europe. Furthermore, it is investigated how by cooling the temperature of the solar cells, the electrical power output and efficiency of the panel is improved. The performance of the system has also been studied and it is investigated by what amount the solar panel is able to convert the solar energy into electricity. Through this, it is discovered that when the temperature of the panel is reduced on average by 20%, the electrical power output is increased by nearly 12%. Moreover, it is demonstrated that the modelled system can provide hot water under different solar radiation conditions and during all seasons of the year.

Keywords: PV/T solar panels, TRNSYS simulation, System modelling, Efficiency

1. Introduction

With the ever rising concerns regarding the environmental impacts related to greenhouse gas emissions of energy production as well as the growing trend of increase in energy prices, the engineering industry is eager to find more sustainable and cheaper sources of energy. In this aspect, the focus on developing technologies that can harness and store renewable energy sources has been set as one of the most important areas of investment and research. In this regard, the use of solar energy, as being the most available renewable energy resource, has received a very special attention during recent years.

Solar energy can be captured to produce thermal or electrical energy through either photovoltaics or thermal solar panels. Having said that, the systems can also be combined together to generate both heat and electricity [1]. These technologies which are mainly passive and require no power input from any source, can produce energy pollution and noise free. Nonetheless and in spite of extensive developments of solar panels, the technology however is found to have a very low module efficiency and because of that, is yet to be implemented in global scale [2]. For instance, one of the major factors that prevents photovoltaics solar panels to generate electricity and lose efficiency is temperature [3]. According to Tan et al. [4], once the surface temperature of the solar panels hits 25°C, the efficiency of the panel drops by nearly 0.5% for every degree of temperature increase.

This has followed several studies that have been conducted to look into the cause of this issue and accordingly investigated that employing cooling techniques is crucial to obtain valuable efficiency outputs from PV systems. Although there are various types of proposed cooling systems for PV systems, they can be categorised into two major types: active cooling, and passive cooling [5]. Active cooling in simple terms consumes energy to operate, while passive cooling does not require externally supplied energy. Instead, passive cooling employs natural conduction or convection to enable the extraction of heat.

Active cooling on the other hand, draw energy from external sources to cool down the solar panel. Most of the methods employed in active cooling can be either be based on air or water cooling [6]. The extracted energy can then therefore be use used for another purpose, hence, improving the overall efficiency of the whole system. This means that the active cooling methods often leads to more power being produced, as well as more accessible energy.

Based on above findings, it is of interest that in this paper, a comprehensive state of the art literature review to be conducted. Furthermore, several comparisons will be made and a system of photovoltaics solar panel will be modelled by using TRNSYS simulation software. From this and through comparing the model with investigated studies, the model will be validated and based on this it will be discovered how the efficiency of a photovoltaics panel can be improved when an efficient thermal absorption system is in use. Moreover, it will be explored if the demand of a household in a hot environment through days and night over a year can be supplied using a standalone photovoltaics-thermal panel that can incorporate external electrical and thermal storage systems.

2. State of the Art Study

Figure 1 shows the main cooling methods employed for PV panels. As can be seen, it is discovered that cooling techniques of PV panels can be mainly divided into three major types: conductive, air, and water cooling.

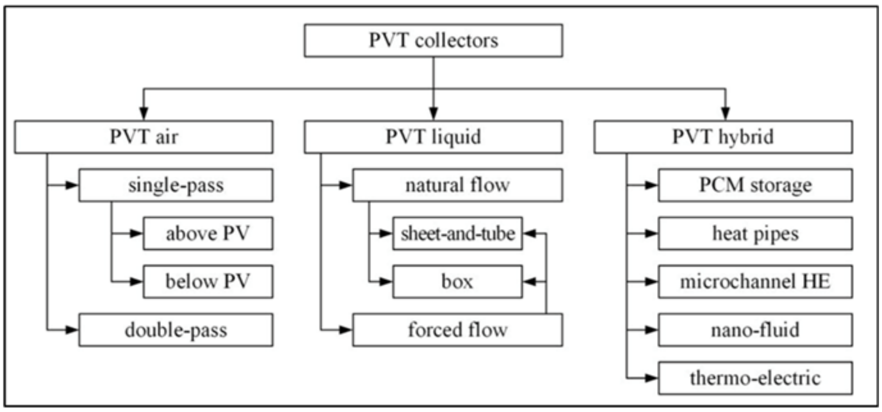

Figure 1. Cooling Methods of PV Collectors [7]

It should be noted that these technologies mostly function based on conductive cooling techniques. In conductive cooling, the principal component of heat transfer from the PV system is conducted through conduction to a coolant fluid such as air or water. This for example has been demonstrated by Popovici et al [8], where a PV system that incorporates an air cooled heat sink has been used. Experimental studies summarised that there can be about a 9% increase in electrical efficiency when a PV system with the heat sink is employed, as compared to case without a heat sink [9].

The water based cooling methods however are also found to be comparatively efficient cooling techniques since water has a high thermal capacity. In one study carried out on the cooling of a PV panel, it was shown that the method helped not only achieving a stable temperature of 30ºC, but also an increase in the overall efficiency of about 20% [9]. Further modification of the water cooling system has been made by incorporating a water trickling configuration. Observations made suggested that it was possible to achieve an increase in the relative output efficiency of about 15% [10].

Fakouriyan et al. [11] developed a model of a water-cooled PV/T system and illustrated that how by passing water underneath the surface of the solar panel, both hot water and cooling effect can be obtained. This model proved to improve the electrical efficiency of the panel by around 12%, significantly reducing the payback period of the system.

Kazem et al. [12] on the other hand conducted a deep study into a water-based PV/T collector and reported that the electrical power performance of the solar panel can be improved by around 8% when water is circulated through a manifold under surface of the panel. This study which was conducted in one of the hottest regions of the Middle East, suggested a massive potential for the use of PV/T panels in a hot area and concluded that thermal characteristics and heat exchanger coefficient are important factors when looking into the design of such a system.

The use of phase change material on the other hand (PCM) for cooling has also been identified as an effective type of passive conductive cooling. The use of such a passive technology means that the heat is dissipated through the process of conduction without no additional work involved [13,14]. It is discovered that with the appropriate type of PCM material, electrical efficiency increase of as high as 5% can be achieved [15].

Following above findings, Peng et al. [16] in an experiment used ice to cool down the surface temperature of a PV panel and examined how this method can affect the overall electrical output. Through this study and by examining the performance of the panel, it was demonstrated that by using the cooling method, an overall efficiency increase of almost 7% can be achieved. Furthermore, a life cycle assessment for the cooled and non-cooled panels was conducted and it was explored that in comparison, cooling of solar panels can lower cost and the payback period to 12.1 years, compared to 15 years while increasing the operation and lifetime of the system.

Having shown that, Elminshawy et al. [17] managed to come up with a novel cooling system which took advantage of using geothermal cooling to control PV cells temperature. In this experiment, a PV cooling system was constructed by using a heat exchanger that comprised several pipes, which were connected to a system of air blower and buried under the ground. The heat exchanger was then connected to a channel that was placed under the panel surface. The configuration was designed in a way so that it can pass and generate cool air by using a centrifugal fan that draws air from outside and sends it through the cold soil where the heat exchanger is placed. This resulted in successfully cooling the temperature of the panel by up to 13%, resulting in enhancing and increasing the power output of by nearly 14%.

Rajput et al. [18] came up with an innovative idea and designed a cylindrical pin fin heat sink to study the effect of cooling on a photovoltaic panel. In this study, a high intensity halogen lamp was employed to increase the surface temperature of a polycrystalline panel to an average of 85°C. Through this method and by attaching the heat sink to the back surface of the panel, the overall surface temperature was significantly dropped and the power output was increased by nearly 10%.

Furthermore, Herrando et al. [19] built a numerical model of such a PV/T system and discovered that with a completely covered collector and a flow-rate of 20 L/h, 51% of the total electricity demand and 36% of the total hot water demand over a year can be covered by a hybrid PVT system The PV/T technology proved to save 35% higher amount of CO_2 over a lifetime of 20 years when compared to PV-only systems.

Table 1 shows the summary of other studies which were conducted in regards to PV cooling, indicating the advantages and disadvantages of each method.

Table 1. Summary of PV Cooling Methods

Reference	Description	Method	Advantages	Disadvantages
Saikrishnan et al. [20]	Experimental Investigation of Solar Paraffin Wax Melting Unit Integrated with Phase Change Heat Energy Storage by Using Phase Change Material.	PCM was used as a type of heat storage material which was attached to the back of the PV panels. When the PV was subjected to solar radiation, the PCM material underwent a phase change from a solid to a liquid condition, along with heat absorption.	Ability to store large amounts of energy in the daytime (during melting process) and releasing it at night. Increases the performance of the system around 5% along with a rising electrical power production to 8%.	Low phase- change enthalpy, low thermal conductivity and possible risk of flammability. Over time the material adsorptive capabilities degrade. The system cannot achieves the same performance during season change especially during winter and summer
Mehrotra et al. [21]	Performance of a Solar Panel with the Water Immersion Cooling Technique.	Submerging the solar panel into the water to sustain their temperature, especially in peak solar radiation hours and hot climate.	Reduced PV module temperature. Effective increased efficiency when the accurate submersion depth is reached.	The nature of the technique used can affect the electrical efficiency after a period of time
Irwan et al. [22]	Comparison of a Solar Panel Cooling System by Using a Dc Brushless Fan and Dc Water.	Used a DC brushless fan and water pump with an inlet and outlet manifold to obtain a steady movement of fresh air and circulation of water at both sides of the PV module.	Feasible technique which can increase the electrical output power significantly. The payback period of the investment can be reduced.	The technique consumes electricity and there can be a risk of break down Might require maintenance.
Borkar et al. [23]	Performance Evaluation of Photovoltaic Solar Panel Using Thermoelectric Cooling.	Thermoelectric cooling was used to increase the efficiency of the overall power output from the system by taking advantage of thermoelectric effect.	The technique used the waste heat from the panels to promote higher overall output efficiency. No direct contact with the PV module	The development of the technology is slow and can be expensive. Low conversion efficiency rate are obtained.
Nižetić et al. [24]	Water Spray Cooling Technique Applied on A Photovoltaic Panel: The Performance Response.	In order to get the maximum cooling effect, water was sprayed over both sides of the panel simultaneously. It was tested at the highest solar radiation hours. The Monocrystalline type of PV was used and the panel temperature was significantly reduced.	The electrical output efficiency was increased by approximately 6%. The technology is found to offer self-cleaning effect and can be hugely effective for small scale PV arrays.	The amount of water combustion can be significant and may not be very effective for large scale PV arrays.

The use of heat pipe based cooling systems is also found to be another effective method of cooling PV panels which has been the focus of several studies [25]. A cooling system that incorporates heat pipes takes advantage of both the convection and phase change phenomena of a cooling device at once, hence improving the overall heat absorption and transfer from the PV cells. In this technology, the hot PV panel that is facing the sun can be placed directly on a surface of several heat pipes. The heat from the PV is then absorbed and transferred onto a working fluid which is inside the heat pipe. This will then make the working fluid to expand and evaporate, thus taking up the heat from the panel. Next, the vapour which has been created due to the evaporation of the working fluid, travels and releases the latent heat to a cooler section where the heat sink or the condenser of the heat pipe is located. The heat sink can include a manifold to cool the heat pipe through air, water or other cooling mediums [26]. The working fluid then completes the cycle by travelling back as a liquid through a capillary action to the evaporator or the hot PV cells to repeat the process again. Heat pipe based cooling systems can be used to achieve a more stable and rather uniform PV-T panel temperature [27].

Jouhara et al. [28] performed further investigations into this matter, took advantage of the heat pipe technology, and built a novel heat mat that can effectively take the waste heat away from the solar panel. In this study and can be seen from Figure 2, a multi-channel flat heat pipe (heat mat) was connected to a cooling manifold and placed under the surface of a photovoltaics panel. In this configuration, the heat was absorbed by the heat mat and transferred through the heat pipe working fluid to the condenser section, which cooled down the whole system. This experiment managed to bring the surface temperature of the PV panel down by an average of nearly 30°C, resulting in an increase of the electrical output efficiency by almost 15%. The technology was then implemented to a building which simulated a family house in Cardiff, UK and it was illustrated that nearly 60% of the hot water demand of the dwelling can be produced, even during the days when the level of solar radiation was low. Furthermore, the system managed to supply about 55 W/m2 of electricity while providing a thermal efficiency of almost 50%.

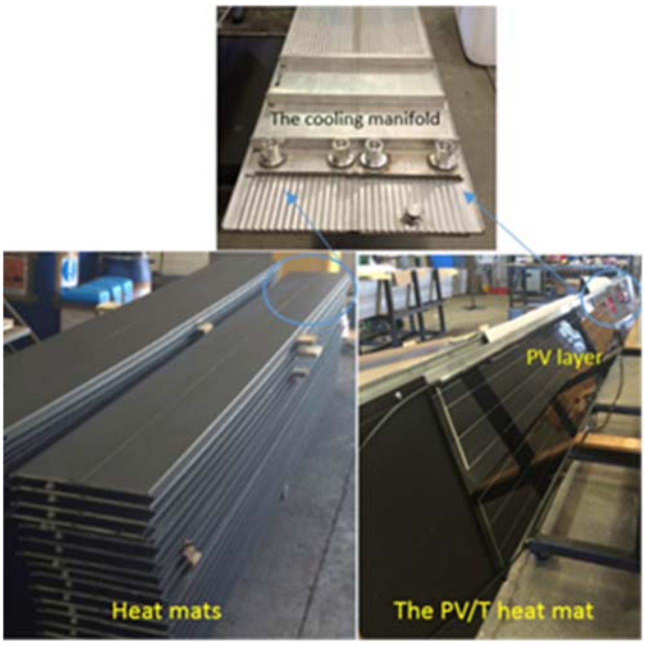

Figure 2. Heat Mat Heat Exchanger Configuration [27].

3. System Modelling

In this study and to follow above investigations, TRaNsient SYstem Simulation (TRNSYS) software has been employed to develop and model a photovoltaics-thermal system. As Beckman et al. [29] explains, TRNSYS has been identified as one of the most important and complete solar energy system modelling and simulation software. The software includes several components or Types that can be connected to each other to develop a system. In this aspect, the output of a Type can be calculated and can be used as a function of the input to another component or be illustrated as the result of the simulation.

The principle behind TRNSYS is employing algebraic and first order differential equations to represent the physical mechanisms into software subroutines or Types along with a combined interface. The interface has two essential parts quantities which are input and output. Output quantities can describe physical measurement, or first order derivatives varies with time related to the physical measurement. Each subroutine have a function relationship combining the input and output as shown in Figure 3 [30].

The system module can be created by connecting the input and output components with each other without concerning about the connection complexity as this program is designed for solving the relative equations. Each physical component has a target to represent, attached to the input that has been connected to a data file allowing to provide forcing function, printing plots, integrating or interpolating data.

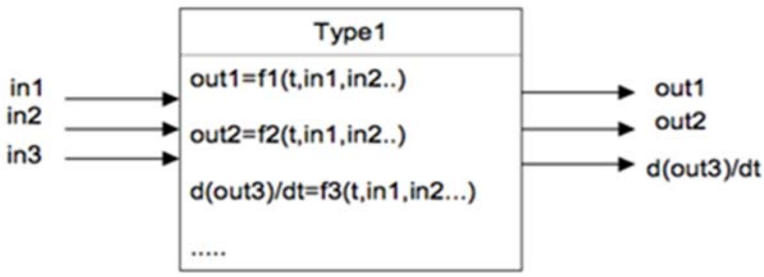

Figure 3. Principle of a TRNSYS component subroutine

For this study as shown in the Table 2 therefore, several Types were used to build and model the system. These Types were connected in a configuration so that the effect of cooling of the panel through water circulation can be indicated. As can be seen from Figure 4, the solar panel collects several data from Type 15 and Type 14, before producing electrical power and hot water outputs. The produced electricity from the panel is then guided to an inverter, which works as an electrical current convertor to and from Type 47. The hot water in this setup is instructed towards a hot water storage tank, which comprises an internal auxiliary power unit (Type 4) and works by delivering cool water to the pump and hot water to a tee piece. A tempering valve (diverter) has also been implemented and placed after Type 14, to ensure a constant delivery of output temperature to Type 11.

Table 2. Components Used for the System.

Type	Name
15	Weather Data Processor
50	PV-Thermal Module
4	Storage Tank
3	Pump
47	Electrical Storage Battery
48	Inverter
11	Diverter/Tee Piece
12	Tempering Valve
14	Time Dependent Forcing Function (Load Profile)
2	Differential Controller
46	Integrator Printer
65	Online graphical plotter

As can be seen from Figure 5, the system is modelled in a way so that the generated heat can be taken away and be stored in a thermal storage tank when cold water is passed through the panel. Following this, a controller is put in place to give order to the pump to deliver cold water from the tank to the panel with water at 20°C temperature. This is to ensure that cold water is passed through the panel to absorb the waste heat.

The electrical power input to Type 48 is monitored to investigate if the produced electricity is sufficient to be directed to the auxiliary power unit to supply constant hot water from the tank. The examination will be conducted thorough day and night and in all seasons of the year for a household of 3 in a hot location in Europe. The results of the simulation in terms of the electrical and thermal performance will be indicted by using Type 65.

In this regard, the installation will be simulated and tested in Madrid, Spain, using the Metronome weather data provided for this location. The reason for this selection was taken entirely on bases that as investigated, high temperature can negatively affect the performance of the solar panel and therefore, the choice of this location will allow to investigate the effectiveness and performance of the technology and the system.

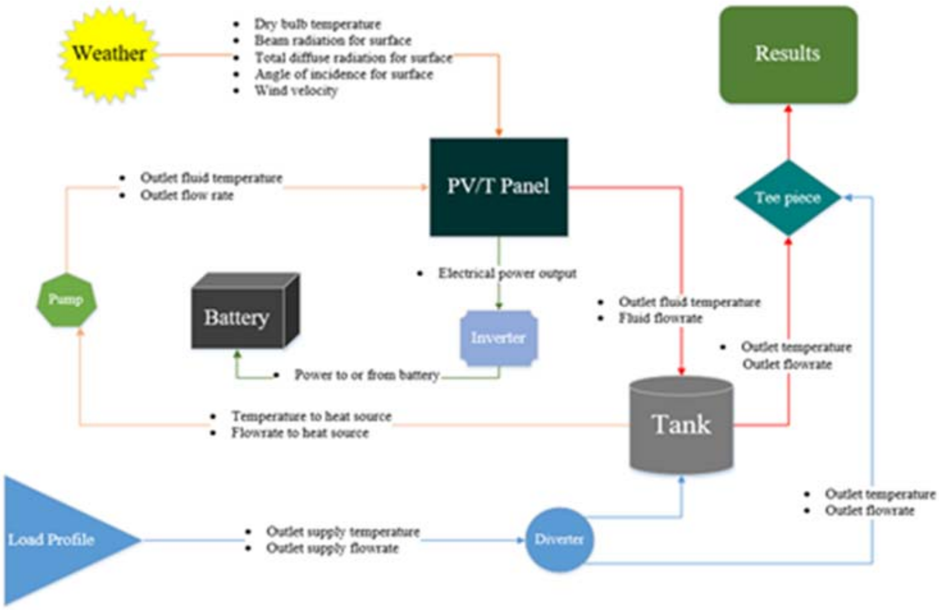

Figure 4. Flowchart of the Model.

4. Estimations and Model Validation

It is estimated that the hot water demand of a family of 3 is about 200 litres per day. This value is calculated by the amount of time each person takes shower and uses washbasins, which are assumed to be 1 time and 4 times per day respectively. The hours at which water is consumed are indicated to be between 6am to 7am for 2 showers and 3 washbasin uses, between 2-4pm for 6 uses of washbasin. 8pm to 10pm for 1 shower and 3 uses of washbasin. The output temperature and demand unit of hot water is taken from the study performed by Castillo et al. [30], where it was indicated that the average household in Spain consumes around 144 litres of water per person each day for shower and washing. 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 [31].

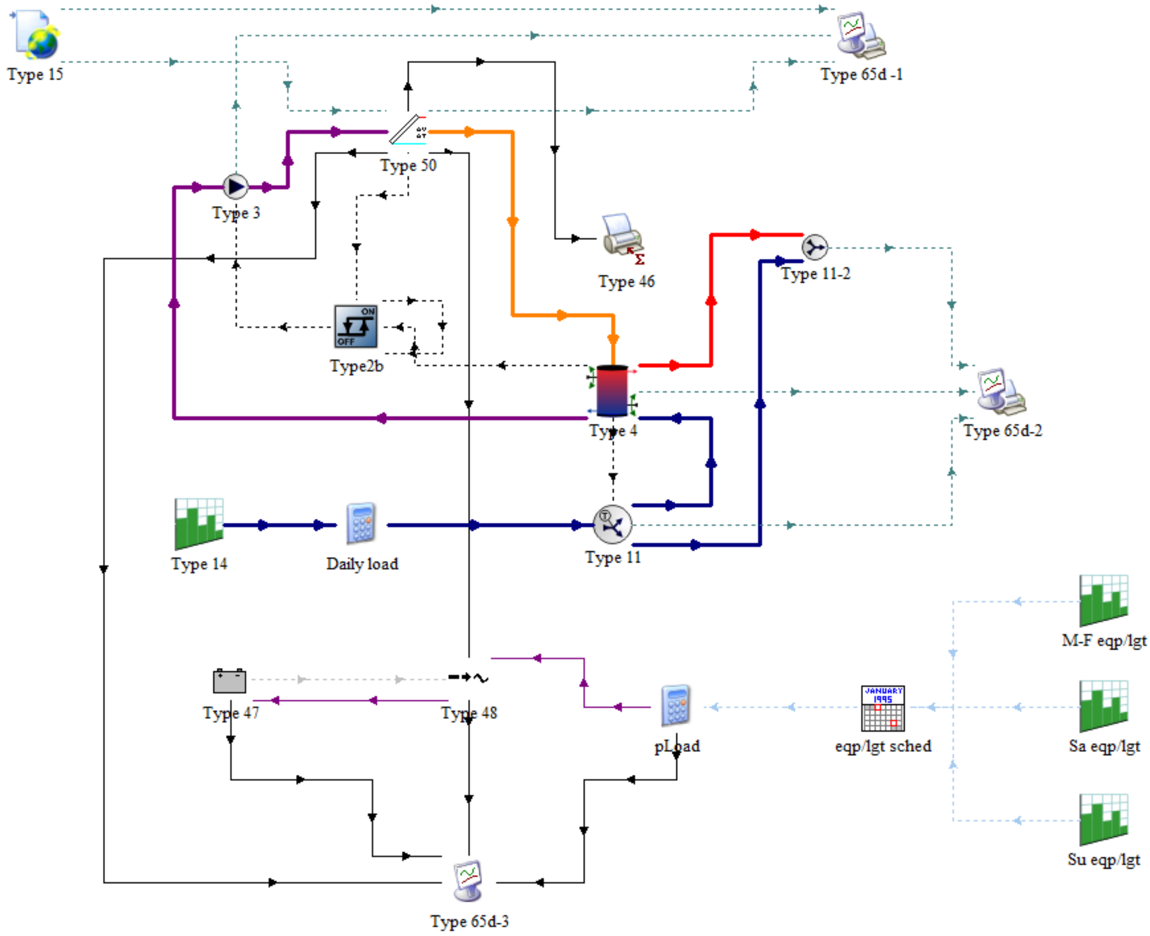

Figure 5. Schematic of the System in TRNSYS Platform.

The performance of the system was tested under different solar radiation for a duration of a year (8760 hours) and the transient behaviour of the electrical output of the module was monitored. As explained by *Khordehgah et al.* [25], the electrical power output, thermal average output and cooling effect of the panel can be defined as follow:

$$E_{EL} = I.U/A_{PV} \tag{1}$$

$$Q_T = \dot{m}\, Cp\, \Delta T \tag{2}$$

Where, EL is the electrical output (E), I is the current, U is the voltage generated by the PV module and A is the area of the panel (A_{PV}). Q_T is the amount of heat produced by the PV panel, $\dot{m}$ is the coolant mass flow rate entering the system (water), C_p represents the specific heat capacity of water, and ΔT is the temperature difference of water between the collector inlet and outlet.

The PV cell temperature, Tc, is influenced by various factors such as solar radiation, ambient conditions, and wind speed. It is well known that the cell temperature impacts the PV output current, performance and its time-variation can be determined. The PV cell temperature as well as whole PV solar panel temperature can be computed from the following heat balance [32]:

$$mCp_{module}\frac{dT_C}{dt} = Q_{in} - Q_{conv} - Q_{elect} \tag{3}$$

where:

T_C: PV cell temperature

Cp_{module}: Thermal capacity of the PV module

t: time

Q_{in}: Energy received due to solar irradiation,

Q_{conv}: Energy loss due to convection

Q_{elect}: Electrical power generated

The thermal energy transferred from the PV cell to the heat transfer fluid (HTF) is determined from the heat balance across the PV cell and HTF in terms of the heat transfer mechanisms; conduction, convection and radiation as follows.

The heat transfer by conduction is:

$$Q_{conduction} = (K_{pv} * \Delta T(T_c - T_m))/L_{cell} \quad (4)$$

where:

T_m: Module back-surface temperature

K_{Pv}: Thermal conductivity of PV cell

L_{cell}: Length of a PV cell

ΔT: the temperature difference T_c - T_m

The heat transfer by convection is determined from

$$Q_{convection} = h_{water} * \Delta T(T_m - T_f) \quad (5)$$

where:

$Q_{convection}$: Energy due to convection

h_{water}: Heat transfer coefficient

T_f: Fluid temperature

ΔT: the temperature difference T_m - T_f

The heat transfer by radiation is:

$$Q_{radition} = \varepsilon * \sigma(T_m^4 - T_f^4) \quad (6)$$

where:

ε: Emissivity PV cell

σ: Stefan-Boltzmann constant

Equation (5) can be rewritten as follows:

$$Q_{convection} = m_w * C_{p_{water}} * T_{fHx}/Area_{pipe} \quad (7)$$

where:

m_w: Water mass flow (HTF)

$C_{p\text{-}water}$: Specific heat of water

T_{fHx}: Maximum temperature difference at the Heat Exchanger heat tubes.

The finite difference formulation is used to determine the heat transfer fluid temperatures at each element where the heat transfer fluid tube is divided into a number of thermal elements:

$$T_f = T_{f\_in} + \frac{\delta Q}{m_{water}Cp} * t \quad (8)$$

where:

t: time

δQ: the heat transfer per element
T_{f_in}: Fluid temperature at inlet
C_p: is the water specific heat

The thermal energy transferred from the PV cell to the heat transfer fluid (HTF) is obtained by:

$$Q_{thermal} = m * C_{p_{water}} * \Delta T(T_{fHx+1} - T_{f\_in}) \quad (9)$$

where:
$Q_{Thermal}$: Energy from thermal process
T_{fHx+1}: Fluid temperature at thermal element 1
ΔT: Temperature difference T_{fH+1} - $T_{f\,in}$
The energy transferred to the heat transfer fluid is calculated from the integration of Equations (3)–(9) written for each element, dx, along the length of each tube.
It is worthwhile mentioning that the PV cell and panel temperature is influenced by different factors and in particular, the ambient conditions such as the temperature, humidity and wind speed among other parameters. The back temperature T_m of the PV cell and PV panel can be calculated from the heat balance across the PV cell as follows :

$$Q_{in} = mC_{p\_module}\,\Delta T = mC_{p\_module}\,(T_C - T_m) \quad (10)$$

where T_m is the module back-surface temperature and T_C is the PV cell temperature.
It is assumed that T_m is equal to the surface temperature of the heat exchanger tubes welded to the solar PV cell/panel in close contact to the back surface of each of the PV cells.

The water is then passed onto a thermal storage tank for heat storage. The total heat capacity of the medium at uniform temperature during a cycle with a temperature range difference (Δt) in the storage can be defined as:

$$\dot{Q}_C = \dot{m} * C_p * \Delta t \quad (11)$$

Where, $m^{\cdot}$ and C_p are the mass flowrate and the specific heat of water in this case.
In order to validate the system, the parameters in Table 3 are indicated and the water output temperature from the simulation is compared with the mathematical results [19] and based on the model developed by Khordehgah et al. [25]. As shown in Figure 6, it is investigated that the simulation results which is run for a weekday in July, closely match the model data.

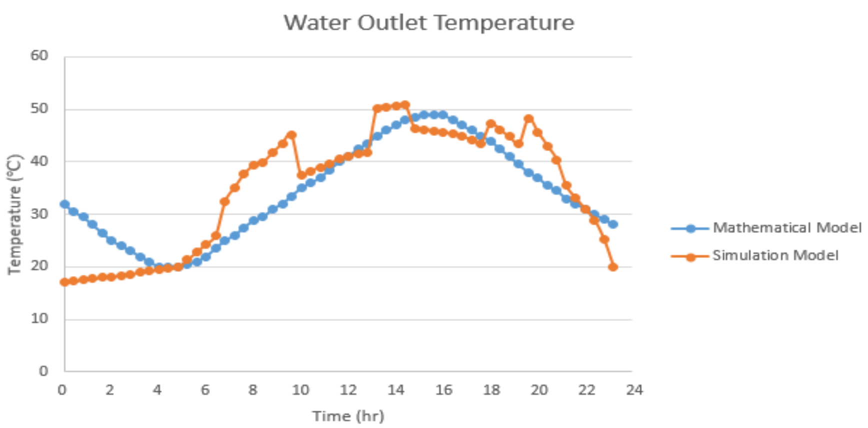

Figure 6. Comparison between Mathematical and Simulations Models

Table 3. System Parameters.

Component	Descriptions	Value
PV/T Module	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
	Packing Factor (ratio of PV cell area to absorber area)	1
	Inclination Angle	36°
	Facing Orientation	South
Pump	Maximum Flowrate	60 kg/hr
	Maximum Power	200 kJ/hr (0.056 kW)
Storage Tank	Tank Volume	250 l
	Maximum Heating Rate of Elements	5000 kJ/hr (1.39 kW)
Battery Bank	Energy Capacity	15kWh

5. Results and Discussion

By comparing Figures 7 and 8, it can be indicated that the surface temperature of the solar panel has reduced by about 20% on average when water is passed through the panel. Following this and as illustrated by Figures 9 and 10, this has resulted in an increase of the electrical output power by nearly 12%. 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.

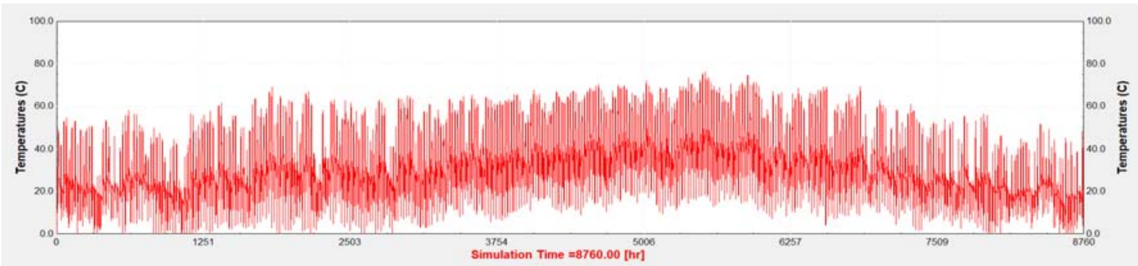

Figure 7. Average Temperature of the Module without Cooling.

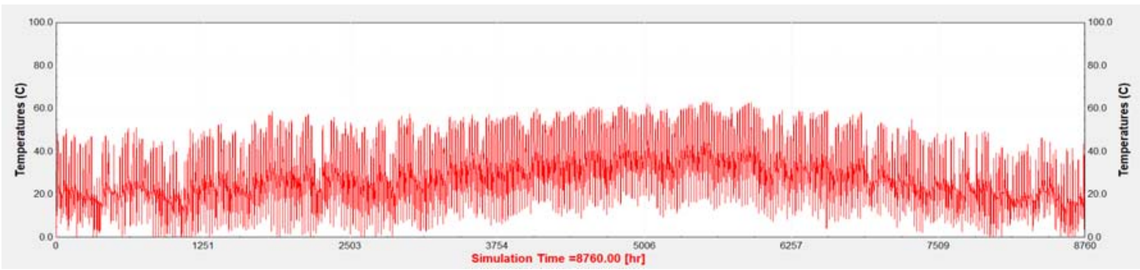

Figure 8. Average Temperature of the Module with Cooling.

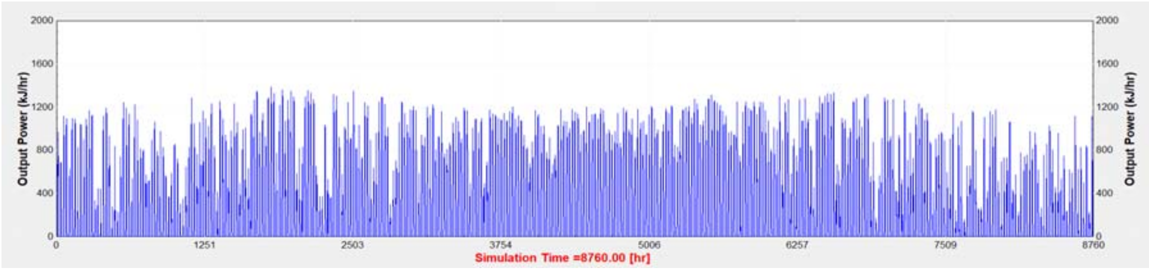

Figure 9. Electrical Output Power of the Module without Cooling.

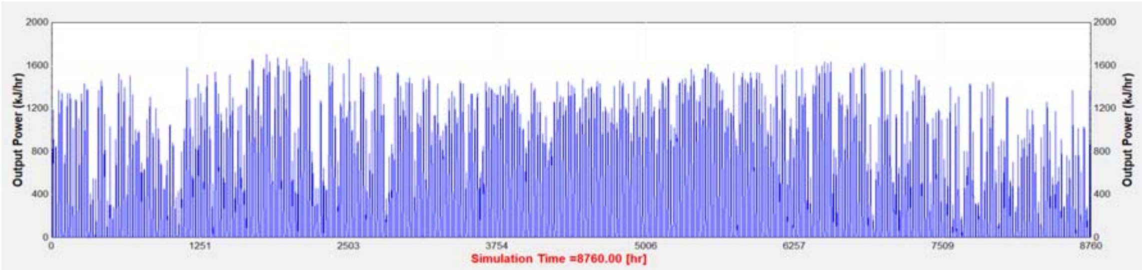

Figure 10. Electrical Output Power of the Module with Cooling.

As shown by Figure 11, it is further investigated that the system can supply the required demand of hot water (red) to the dwelling; however, the auxiliary unit in the storage tank may be required to supply heat at a rate of 1500 kJ/hr to keep the water temperature at 60°C throughout the year. Having said that it has also been illustrated that the electrical power from the battery bank (purple) may be adequate enough to feed the auxiliary heating unit (heating the water in the storage tank to the set value), especially during night and winter time, when the solar radiation is not sufficiently high enough.

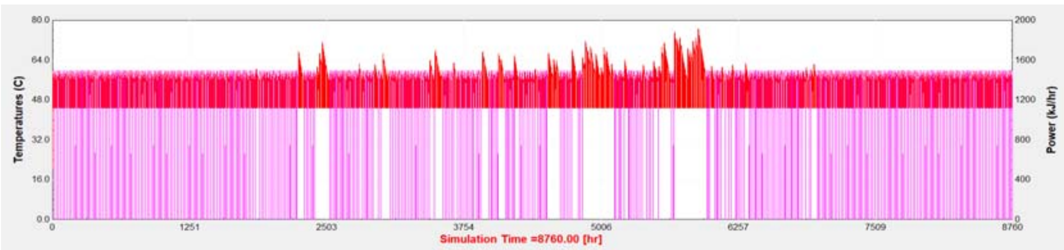

Figure 11. Water Temperature Output and Power to Load.

6. Conclusion

In conclusion, a system of a PV/T solar panel that can be used to produce electricity and hot water for a household in Spain was modelled using TRNSYS software. It was investigated how by cooling down the temperature of the PV cells, the electrical power output and efficiency of the panel can be improved. By looking at the current state of the technologies used for cooling of photovoltaics solar panels, it was demonstrated that several technologies have been developed and experimentally tested that provide different efficiency increase. Through this and by comparing the results obtained from the simulation and experimental data, a system was modelled and verified to investigate and examine the effect of cooling on efficiency of the panel.

This was conducted by allowing water circulation to the panel and comparing the result of that to the case when this was not applied. The simulation results showed that when the temperature of the panel is reduced on average by 20%, the electrical power output is increased by nearly 12%, confirming the findings in the literature review. Furthermore, it was indicated that the system is capable of providing hot water at the required amount throughout the year, however, an input from an auxiliary power unit may be required to heat up the water at the optimum temperature.

This was more pronounced especially during night and winter time, when the solar radiation was not adequate for the panel to provide hot water. Having said that, it was discovered the electrical power stored in the battery pack may be sufficient enough to feed the auxiliary power unit, developing a standalone system.

7. Acknowledgement

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