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# INTEGRATION OF SOLAR HYBRID PHOTOVOLTAIC/THERMAL SYSTEMS WITH PHASE CHANGE MATERIALS

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## 1. ABSTRACT

Solar hybrid photovoltaic/thermal (PV/T) panels can be a very effective renewable energy system (RES) to supply domestic energy demand since they produce both electrical power and heat simultaneously. Thus, it can be the most suitable RES for buildings due to the space limitations since it uses the same aperture area instead of two separate systems. PV cells have a low efficiency of around 15 to 22% and the rest irradiation is converted to heat that increases the PV cells temperature and decreases electrical conversion efficiency. PV/T panel can be considered as a cooling system for PV as heat is absorbed by working fluid that passes through the back of the PV. This increases PV electrical conversion efficiency. The heat absorbed from the PV/T panel can be stored to better match demand considering intermittency of solar energy that is only available on daytime and sunny days yet heat demand can be at night or cloudy days. Phase change materials (PCM) could play an important role as a Latent Heat Thermal Energy Storage (LHTES) unit in the PV/T system to increase the overall solar fraction of RES. Apart from the high energy density and lower volume of a PCM over sensible heat thermal storage, the phase transition temperature can also help to thermally regulate the PV/T panel temperature during its operation. PV/T systems are not a mature technology on the market thus, operating conditions are not established in practice. Therefore, more research on the sensitivity analysis of a PV/T system and integration of PV/T with a PCM storage system is needed to achieve higher yields and solar fractions. In this study, a comprehensive test rig was installed to characterise and evaluate PV/T and in Edinburgh Campus, Heriot-Watt University. Maximum Electrical Power (149.6 W) and efficiency (10.84%) was obtained at the mean PV/T temperature of 27°C that is the lowest temperature in scope. Minimum Electrical Power (114.13 W) and efficiency (8.55%) was measured at the highest mean panel temperature (83°C). The temperature coefficient of PV was found at 0.40%/ °C. The highest efficiency(61.50%) was found at the lowest inlet temperature(21°C) whilst the lowest efficiency (19.74%) was measured at the highest inlet temperature(77°C). Integration of a PV/T with LHTES, 24 MJ of total heat from 63°C to 18°C, 19 MJ heat from 63°C to 49.5 °C and most importantly 15 MJ of heat content at the phase transition temperature around 58°C was obtained.

## 2. INTRODUCTION

Energy consumption has increased for the last decades with a growing population and developing technology and it is predicted that energy demand will increase by more than 30% by 2035 [1]. Conventional energy sources mostly rely on fossil fuels that release a great amount of greenhouse gases contributing a significant impact on global warming. More than half (51%) of total energy was consumed by heating and cooling sector whilst only 10% was supplied by renewable sources[2]. The importance of renewable sources to provide heating and cooling sector is clear therefore to mitigate the global warming effect. Solar energy is one of the most widely used RES owing to have advantages such as accessibility, applicability and low cost. Photovoltaic cells are one of the solar energy conversion methods that can convert sunlight directly to electricity[3]. Although the first functional silicon cell was developed by Chapin in the Bell Laboratories in 1954 with an efficiency of 6% [4], the electrical conversion efficiency of PV cells are still quite low having a range between 10% and 45%; typical commercial domestic PV conversion efficiency ranges from 15% to 22% [5].

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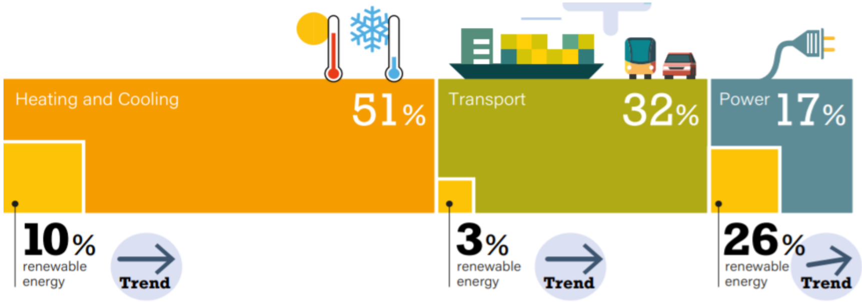


Figure 1. The ratio of renewable in the total energy by sector [2].

The reason behind the low efficiency is losses such as optic and electrical. Optic losses are mostly related to unabsorbed radiation that reflection may cause up to 30% loss if pure Si is used as the semiconductor material of cell [6], recombination is one of the electrical losses that is an adverse process of electricity generation that free electron and hole recombine and release the energy as light or heat[6]. These losses cause an increase in temperature of PV cells that have a temperature coefficient around 0.5%/K [7], [8],[9] meaning higher operating temperature PV cell leads to a decrease in PV cell efficiency.

Another Solar energy conversion method is solar thermal system(STS) which has a great impact on the global energy market as 51% of total energy consumption is a form of heat [2]. Solar thermal collectors are acting as heat absorbers and exchangers by converting solar irradiation into heat to produce hot water[10].

Photovoltaic -Thermal (PV/T) panels are devices to convert solar irradiation into both heat and electricity simultaneously by using the same aperture area [11]. The excess heat from PV cells can be extracted by STS allowing hot water production and also can be considered a cooling system to increase PV cells efficiency.

Although energy efficiency and production are important for RES, energy demand is also needed to take into account since produced energy needs to meet with energy requirements. Volumetric hot water consumption is the most important parameter for calculating the domestic hot water (DHW) energy requirement that depends on how many households live in the home [12]. In addition to the volume, there are other significant factors such as time and temperature range for hot water demand that need to be specified concisely to analyse overall system performance. The mean volumetric DHW consumption is around 122 lt/day with a mean energy content of about16.8 MJ/day based on data collection from 112 houses in the UK [12].

Although solar energy has many advantages such as availability and accessibility, it has drawbacks similar to all other renewable energy sources that are intermittent and unpredictable. Furthermore, solar sources are available in day time yet demand is in the morning and at night. Therefore, STS needs storage to better match demand and increase solar fraction.

LHTES is able to store the same amount of thermal energy with a smaller volume that could be seven times lower than sensible heat storage by taking advantage of the phase transition energy in nearly constant temperature [13]. PCMs can be used as part of STS to store thermal energy at times of high solar irradiance with low demand and discharge when there is not adequate irradiation with high demand. Furthermore, it can be also be considered as a thermal regulation for PV/T panels. Phase transition temperature and latent heat content are the most significant parameters for PCM since most of the thermal energy is stored and released at the phase transition temperature.

There is a need for an experiment to analyse PV/T performance and the integration of LHTES under real environmental conditions (outdoor).

## 3. METHODOLOGY

An experimental test rig was installed for testing PV/T performance and characterisation and the integration with LHTES under real environmental conditions (outdoor) at Heriot-Watt University (Edinburgh, Scotland).

There is no established international standards for testing the performance of PV/T panels and characterisation of them [14]. However, PV/T is a combination of two systems PV and thermal, standard testing method for PV (IEC 61215) and thermal (EN 12975) could be used separately [15].

The system was designed as a close loop, a Grant LTC4 thermal bath provides constant water inlet temperature that needs to be controlled to characterise the performance of solar collectors[16]. The flow rate should be controlled as the heat rejected from the panel is calculated with the formula Q= m*c ($T_{outlet}$-$T_{inlet}$). A Wilo-Yonos PICO-STG model pump was used to circulate water and control the flow rate by Pulse width modulation (PWM). The actual flow rate was also measured by the Cynergy UF08B model ultrasonic flow meter. Thermosense APB3-0010 pressure sensors were used to measure the pressure drop for one panel.

A weather station is the most important part in testing STS as the irradiation, wind speed and ambient temperatures are the key value for calculating the efficiency. Kipp&Zonnen CMP10 model Pyrometer was used for irradiation measurement and DF Robot anemometer was used for wind speed. Furthermore, in order to calculate solar thermal efficiency the inlet, outlet and ambient temperatures are needed to be measured according to the EN 12975-2 standards [16], RS PRO K type thermocouples were used for all temperatures measurements.

Electrical measurement of PV/T was obtained by Seaward PV200 Complete Kit that provides IV Curves which is the main measurement for characterisation of PV panels.

Four glazed PV/T(Solimpeks PowerTherm) panel was used that has an aperture area of 1.427 $m^2$ with 828x1640x90 mm dimensions. It has a 180Wp nominal power with 35.15 V nominal voltage and 5.12 A nominal current. The PV material is Monocrystalline with 72 cells which are 125x125 mm each [17].

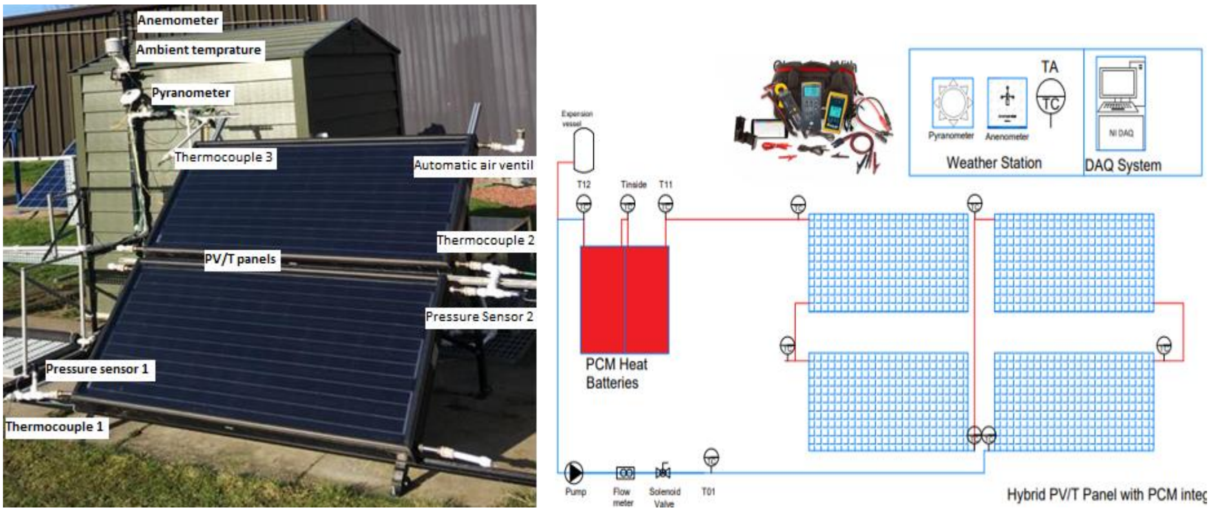


Figure 2. Experimental test rig for PV/T characterisation and hydraulic drawing for integrated LTHES.

For LTHES, a heat battery from Sunamp Ltd. with 58 °C phase transition temperature Sodium acetate trihydrate PCM was used in the experiment. The heat of fusion for PCM is 226 kJ/kg[18].

National Instrument (NI) Data Acquisition System (DAQ) system were used for data collection and NI cDAQ 9174 chassis with appropriate modules (NI 9213, NI 9402, NI 9203, NI 9219, NI 9481) connected to the Labview software to control, collect and store the data with 1-sec frequency.

## 4. RESULTS/DISCUSSION

As it was mentioned in the methodology part, the performance of PV and thermal side of PV/T was analysed separately. Different inlet temperature ranging from 20 °C to 80 °C with a flow rate of 1 lpm was circulated to the PV/T panels to analyse the effect of temperature on electrical and thermal performance of PV/T panel. Ambient temperature was measured in between 24 °C and 26 °C under the measured irradiance that varied from 935 to 985 W/m$^2$ during the test period under real environmental conditions (outdoor) at Heriot-Watt University in Edinburgh, Scotland.

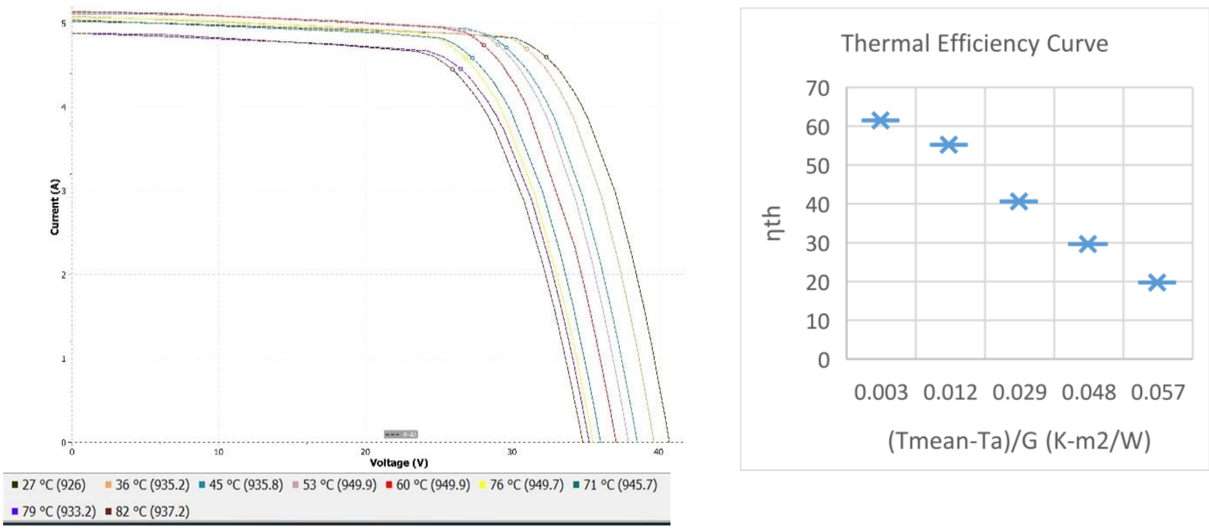


Figure 3. IV and Thermal curves for different inlet temperatures of PV/T.(Mean water temperature ranges from 27°C to 82°C)

Before analysing overall system (PV/T with PCM storage) performance, PV/T panel was characterised thermally and electrically with a measurement of IV curves that shows short circuit current ($I_{sc}$), open-circuit voltage ($V_{oc}$) and maximum power point (MPP) in the same graph. MPP is the point where $V_{mpp}$ and $I_{mpp}$ provide the maximum power that is used for calculating the electrical efficiency ($\eta_{elc}$) of PV cells and fill factor(FF) listed in Table 1.

| Tmean | I (W/m2) | Voc (VDC) | Isc (ADC) | FF | Vmpp (V) | Impp(A) | Pmax W) | ηel |
|---|---|---|---|---|---|---|---|---|
| **27** | 966 | 40.7 | 5.023 | 72.65 | 31.84 | 4.7 | 149.648 | 10.84477 |
| **36** | 976 | 39.7 | 5.083 | 72.16 | 31.05 | 4.7 | 145.935 | 10.47818 |
| **46** | 976 | 38.6 | 5.121 | 70.82 | 29.68 | 4.7 | 139.496 | 10.01585 |
| **53** | 984 | 37.9 | 5.14 | 70.63 | 29.05 | 4.7 | 136.535 | 9.71368 |
| **60** | 984 | 37.1 | 5.145 | 69.55 | 28.01 | 4.7 | 131.647 | 9.365927 |
| **71** | 962 | 36.1 | 5.05 | 68.99 | 27.36 | 4.6 | 125.856 | 9.168006 |
| **76** | 962 | 35.5 | 5.067 | 68.25 | 26.82 | 4.6 | 123.372 | 8.987058 |
| **79** | 933 | 35.3 | 4.881 | 68.58 | 26.5 | 4.5 | 119.25 | 8.937639 |
| **82** | 933 | 34.8 | 4.881 | 67.88 | 25.94 | 4.4 | 114.136 | 8.554351 |

Table 1. Electrical performance of PV/T under different mean fluid temperatures.

It was found that the maximum power (149.6 W) and efficiency (10.84%) was obtained at the mean PV/T temperature of 27°C which is the lowest temperature in scope. At the same time, minimum Power (114.13 W) and efficiency (8.55%) was measured at the highest temperature (82°C). The temperature coefficient of PV was found 0.40%/°C which was given in the manufacturer datasheet as 0.45%/°C. This difference might be caused by the PV temperature measurement that was taken the mean temperature of fluid since it was not possible to measure PV temperature directly. Thermal performance of PV/T was also measured and similar results with PV were obtained under open-circuit mode. The highest efficiency(61.50%) was found at the lowest inlet temperature(21°C) whilst the lowest efficiency (19.74%) was measured at the highest inlet temperature(77°C).

The performance of integration PV/T panels with a LHTES unit (hydraulic schematic can be seen in Figure 2) experimented on a sunny day(09/08/2021) started at 11.00 pm and finished at 17:30. The measured Irradiance was 215 W/m$^2$ lowest at the beginning, peak at solar noon with around 930 W/m$^2$, there was a cloud around 12.00 which effects the PV/T outlet temperature can be seen in the graph. The outlet temperature of PV/T which is the inlet temperature of LHTES marked as $T_{in}$, at the same time inlet temperature of PV/T is the outlet temperature of LHTES marked as $T_{out}$.

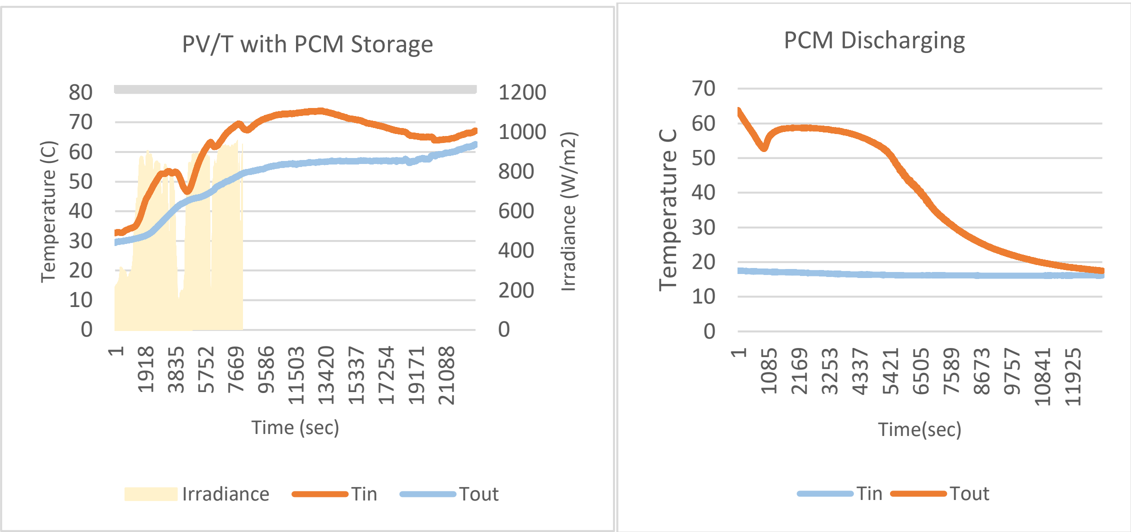


Figure 4. Integration of PV/T and LTHES system performance. ($T_{in}$, $T_{out}$ inlet and outlet temperature of LTHES )

The outlet temperature of LHTES increased linearly similar to a sensible thermal storage system(STSS) until the melting point of PCM which is 58°C. The outlet temperature of LHTES is a plateau at 58°C until PCM is melted completely then start acting as STSS. The process is the same for discharging. The outlet temperature reached over 63°C, PCM was melted completely at the end of test.

1 lpm main water supply with the temperature of 16-17 °C was sent to LHTES for discharging that can be considered as hot water supply to the user. The demand for hot water was found at 16.8 ± 2.2 MJ/day with a mean hot water temperature around 51.9°C[12]. A nearly constant water outlet temperature (58°C) was supplied to the user during the melting period for 70 minutes that counts 15 MJ energy content. In addition, including the starting experiment (63.5 °C) until the desired temperature for the combi boiler (49.5°C) [12], the LTHES system could supply 110 minutes of hot water to the end-user with19 MJ energy content. A total of 24 MJ was measured during the whole discharging period at a temperature range from 63.5 to 17 °C.

## 5. CONCLUSION

In this study, PV/T characterisation, performance and integration of LTHES experimented under outdoor conditions. The electrical efficiency of PV was decreased with a 0.40%/°C temperature coefficient. Thermal efficiency was also decreased with increasing inlet temperature. Integration PV/T with LTHES, 15 MJ of heat at 58°C or 19 MJ of heat over 49.5 °C could be supplied to the user that the average daily consumption is 16.8MJ/day.

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