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Research Article

Development and performance analysis of hybrid photovoltaic/thermal (PV/T) system

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ABSTRACT

Increase in the surface temperature of Photovoltaic (PV) module affects its efficiency and life adversely. This relationship between efficiency and surface temperature of a PV module is defined as the temperature coefficient. Since solar parks are long-life projects, a small drop in efficiency of modules might result in a significant reduction in overall power output for large projects making this option unfeasible, for both economical and energy yield perspectives. This loss in power can be reduced by cooling of PV modules. A hybrid Photovoltaic and Thermal system (PV/T) was developed in this study to investigate the impact of this system on overall efficiency. In addition to producing electrical energy, the heat gained by the circulating fluid was utilized for domestic usage. A critical temperature of the PV module was identified in this study beyond which the drop in efficiency was higher than the temperature coefficient. This critical temperature was noted to be a function of radiation intensity and decreased with decreasing intensity. Incorporation of the cooling system resulted in a decrease in surface temperature of the module by 20% with an increase in electrical efficiency of up to 2.3%. The overall efficiency of the PV/T system of at least 70%, with a maximum overall efficiency of 85% was observed at different radiation intensities, making this system a viable alternative to the conventional PV or thermal systems being used currently.

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INTRODUCTION

The world is shifting towards renewable resources due to rapid depletion and global warming hazards of fossil fuels. Solar energy is a renewable energy source which is abundant and freely available [1,2]. Photovoltaic (PV) is the most widely used system for harnessing solar energy [3] providing 1.7% of the gross electricity production

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worldwide. International Energy Agency has identified photovoltaic (PV) as the fastest growing energy technology and rightly predicted its global installation to exceed 600 GW by 2019 (actual installation by the end of 2019 was noted to be 627 GW). Although PV technology is divided into three generations, the silicon based solar cells (mono and poly-crystalline silicon) cover over 80% of the current world installed capacity [4]. A PV module comprises of stacks of solar cells known as solar arrays that are made of silicon to convert incident sunlight into electricity by the photovoltaic effect [5]. Photons emerging from the sun when incident on a module produce excitation in valence electrons of silicon forcing them to jump towards conduction band, hence producing electricity [6]. Sunlight consists of photons of different wavelengths; however, only a small fraction of their energy is converted into electrical energy by the PV module, whereas the remaining energy is dissipated as heat energy, or stored as internal energy increasing the temperature of PV module [7,8]. The efficiency of PV module varies between 10-20% [6], depending upon three prime factors: irradiance flux (W/m^2), type of semiconductor, and the temperature of PV module [9]. Although the solar radiation intensity affects the power output from a PV module favorably, it also causes an increase in temperature of the module, hence decreasing the efficiency of the system. Since PV projects are long-life projects, even a small drop in efficiency might result in a significant reduction in overall produced power for large projects making this option unfeasible both from economical and energy yield perspectives. The surface temperature of a PV module not only affects the efficiency but also limits the lifespan of the conversion system. Effective cooling can improve the electrical efficiency of the system as well as decrease the rate of cell degradation with time, resulting in maximization of the life span of photovoltaic modules [10]. The surface temperature of PV module is influenced by climatic parameters such as wind speed, ambient temperature, relative humidity, accumulated dust and solar irradiation [11,12]. High ambient temperatures and high PV module surface temperatures cause overheating of the PV module, which reduces the efficiency radically. It has been estimated that every 1°C rise in the surface temperature of the PV module causes a reduction in efficiency of 0.25-.5% [9,13,14]. This relationship is termed as the temperature coefficient of the PV module. The quoted values of temperature coefficients are measured in controlled laboratory conditions. However, Kamkird et al. [15] noted that the experimental value for temperature coefficient is different from the values defined in the laboratory.

Many researchers have explored different methods aimed at maintaining the PV module efficiencies under high irradiation conditions. A recent overview of work in this area has been provided by Siecker et al. [10]. The cooling methods employed can be broadly classified as passive and active. Passive methods are permanently deployed and cannot be controlled during operation. Active methods, on the other hand, consume power while operational, but can be turned off when not required [16]. Cooling by water [17], air [5], heat pipes [18], phase change materials (PCM) [19] and combination of heat pipes with PCM [20] are some of the methods reported in the literature. Cuce et al. [21] used fins as heat sinks on the back of a small PV strip and found them to be effective in cooling the cells. Both water and air have been explored as coolants [14] in these systems. However, cooling through water has been more effective compared to air [13]. Popovici et al. [5] claimed that an increase in efficiency up to 6% is possible by flowing air across a PV module. Odeh et al. [17] sprayed water on the upper surface of a PV module noting a maximum efficiency improvement of 8%. Nizetic et al. [22] sprayed water on the front and backside of a PV module reporting an efficiency increase of 14%. However, both studies [17,22] reported contaminations as well as the loss of water which limited its reuse. Incorporation of PCM in solar cooling systems has also attracted interest of the research community recently [23,24]. The effectiveness of PCM based cooling has been reported to be lower than conventional systems [24]. Other systems, albeit complicated that have been investigated and found effective in increasing the power output include use of condenser evaporator heat pipe system [18,25,26], and thermoelectric cooling consisting of N and P-type semiconductors [10]. Innovative ideas, such as spectral splitting of the solar energy into photo and thermal components are also being explored. In this method, the spectrum is divided into two parts using absorptive, reflective and refractive filters. The spectrum capable of exciting the valence electrons is used to generate electricity while the remaining energy is converted to thermal energy without affecting the output electrical power. The high capital cost of such systems is a shortcoming that has to be overcome to achieve improved overall efficiency from such systems [27,28].

Another concept that has gained popularity recently for PV cooling is the utilization of thermal energy extracted from PV module i.e. a hybrid photovoltaic/thermal (PV/T) system which generates electrical and thermal energy simultaneously [29]. The system consists of a PV module and thermal collecting pipes mounted on the module. The circulating fluid (water) flowing through the pipes collects heat from the module, reducing the surface temperature of the PV cells. The heated water flows back to a storage tank and can be used for domestic, commercial or other applications. These systems are more popular due to their low costs compared with other methods.

Kalogirou [30] modelled and simulated a system based on the PV/T concept and reported an increase in electric efficiency from 2.8% to 7.7%, with an overall efficiency of 31.7%. A similar design proposed by Amna et al. [31] constituted a PV module incorporated with rectangular copper pipes that acted as thermal collectors with water flowing across them. The thermal efficiency of the system was measured to be between 60-70% while the electrical efficiency was observed to be in the range of 15-20%. Recently, Boumaaraf et al. [32] compared simulated results from MATLAB with those measured experimentally. Although the authors claimed agreement between the simulations and experiments, the comparison showed considerable variations amongst the results. They reported 7% electrical efficiency for the PV/T system compared to 6.78% for the PV system. Rawat et al. [33] used a copper sheet as an absorber alongside copper pipes as the thermal collector and noted a thermal efficiency of 50.1%. Santbergen et al. [34] developed a numerical model to compare the thermal yield of solar domestic hot water systems with one cover sheet and tube PVT collectors. Rejeb et al. [35] also developed a model for PV/T sheet and tube collector to study the effect of solar radiations and inlet water temperature on the efficiency of the collector. They observed that the thermal efficiency of the collector increases with an increase in solar radiation and decreases with increasing inlet temperature of the water.

It is evident from the above discussion that cooling the operating surface helps in achieving efficient PV systems. The thermal energy gained from the solar module can be utilized if the cooling system is properly designed. Although some studies have been carried out to gauge the potential of hybrid systems using solar simulators, testing of these systems under real conditions, and at high temperatures has scarcely been reported. The paper reports the findings from a comprehensive investigation on the effect of introduction of a cooling system on the electrical efficiency of a PV module, as well as the overall efficiency of the hybrid system. The study was conducted at various irradiation intensities. A control system allowed the cooling water to flow across the module multiple times till the desired temperature of water was achieved providing active control.

METHODOLOGY

A 150 W monocrystalline PV module was used for all tests reported in this manuscript (Table 1). Power output of the PV module was determined at different irradiance levels, initially without cooling to identify the effect of increasing surface temperatures on power output. These tests served as the baseline case for comparison of the efficiency of the PV module after installation of the hybrid cooling system. The experimental investigation reported was performed outdoors under real conditions in Peshawar, Pakistan (34°N, 71.5°E). The ambient temperature for all experiments reported was 41°C ± 2°C.

The active cooling system used in this research comprised of two technologies: Photovoltaic and thermal system for generation of electrical and thermal energy. Schematic of the complete system is shown in Fig. 1. The thermal system comprised of two water storage tanks, a pump and copper tubes mounted at the rear surface of the PV module (Figs. 1, 2). The back end of the copper pipes was insulated to avoid any heat loss to the environment. The first tank containing cold water acted as a sump tank from which water was circulated across the PV module. Water after absorbing heat from the module was stored in the second tank. Hot water from the second tank was recirculated back to the sump tank if its temperature was lower than the set temperature. The mass flow rate of water to the module was fixed at 10 kg/hr.

Table 1. Rated specifications of the module tested

Company	Ever exceed
Type	Monocrystalline
Module type	EX150–36M
Maximum Power	150W
Open circuit voltage	22.3 V
Short circuit current	8.91A
Weight	11.2 Kg
Dimensions	1.4 × 0.03 × 0.6 m

An 8W submersible pump, powered by a lithium-polymer (LiPo) battery, operated by an Arduino driven system controlled the water circulation (Fig.3). The input signal to this Arduino system was provided by a thermocouple measuring the temperature of water in the tank. The temperature on the front surface of the PV module was also measured using a surface type temperature sensor having an accuracy of ± 0.5°C over a working range of 55 to 125°C.

Details of the piping used for the cooling system are listed in Table 2 below:

Electrical efficiency (η_{El}) of the system was calculated using the following equation [36]:

$$\eta_{El} = \frac{I * V}{A * G} \tag{1}$$

Where I and V are the output current and voltage while A and G represent the area of solar module and solar intensity respectively. The thermal efficiency (η_{Th}) and the overall efficiency (η_{OA}) of the panel were determined using equations 2 and 3 [36]:

$$\eta_{Th} = \frac{\dot{m} C p \Delta T}{A * G} \tag{2}$$

$$\eta_{OA} = \eta_{El} + \eta_{Th} \tag{3}$$

RESULTS AND DISCUSSION

As discussed above, initially the thermal response of the PV module was measured at different intensities without the cooling system. Afterwards, the thermal collector was

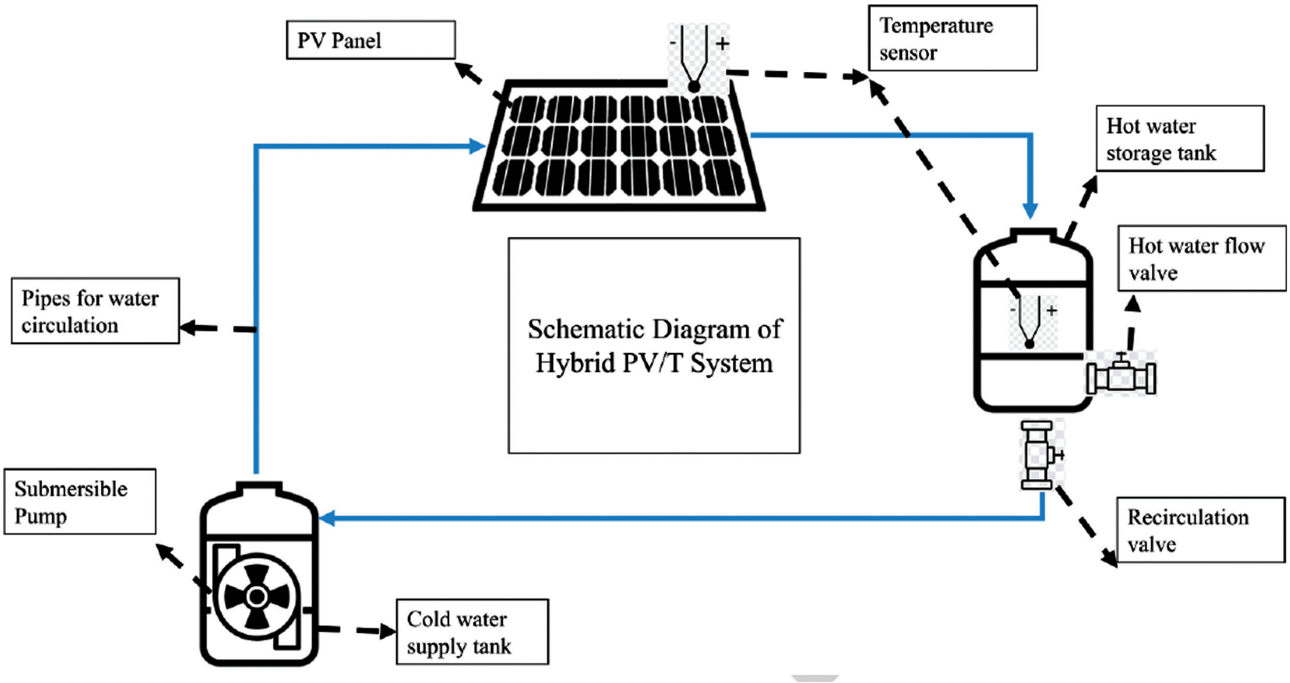

Figure 1. Schematic of the hybrid PV/T system.

Figure 2. CAD model of the thermal collector.

Table 2. Characteristics of pipe used for the cooling system

Material	Thermal Conductivity	Outer radius	Inner radius	Total length
Copper	400W/mK	0.003 m	0.0027 m	12.2 m

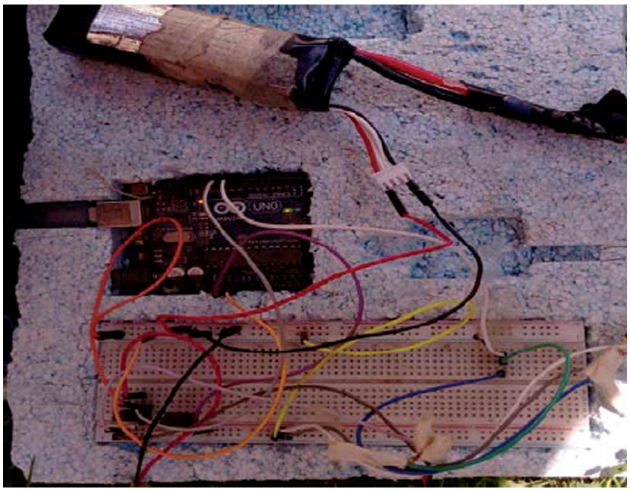

Figure 3. Electronic circuitry used to control circulation of water.

mounted on the PV module and its effect on electrical efficiency was noted.

As expected, a drop in efficiency of the module was noted with a rise in surface temperature at all radiation intensities. Similar to Kamkird et al. [15], this study also revealed that the power drop with temperature does not strictly follow the theoretical temperature coefficient but remains close to it. Fig. 4 shows the effect of temperature on the power output of the module at a solar intensity of 800W/m^2 and an ambient temperature of 39°C. A slight variation in radiation intensity and ambient temperature

Table 3. Target intensities (±3%)

Radiation Intensity (W/m^2)	950	800	750	650

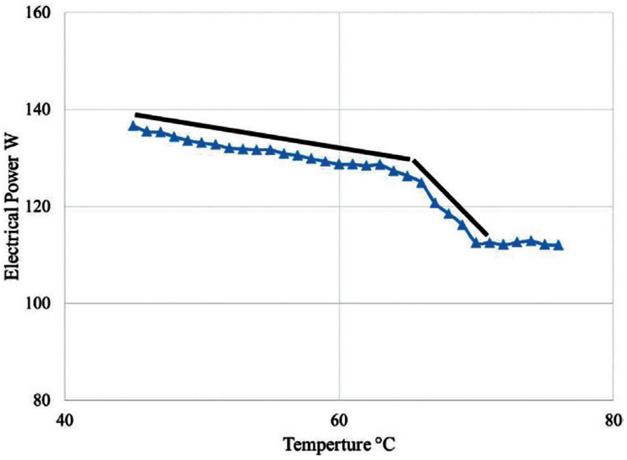

Figure 4. Effect of surface temperature on output power of the PV module at 800W/m^2.

was noted during the experiment. Three distinct regions can clearly be identified in Fig. 4.

1) In region 1, the power curve followed the documented 0.5% /°C drop per degree rise in temperature up to a temperature of 66°C.
2) Increase in surface temperature beyond 66°C lead to a sharp decline in power output of the module up to 70°C. The temperature marking the start of region 2 will be referred to as the critical temperature. This phenomenon has not been reported in the available literature. A possible reason for this can be that those studies were performed at relatively lower ambient temperatures. Measurement of the thermal response of the PV module at different intensities showed that the critical temperature was a function of radiation intensity; the dependence is listed in Table 4. The sharp decline in PV power in this range makes the cooling of PV modules inevitable for warm regions.
3) Fig. 4 also highlights the asymptotic behavior of power with temperature beyond 70°C, exhibiting that output power is no longer a function of module temperature.

Similar effect of temperature on power was observed at all the intensities tested. The power variation at intensities of 650, 750 and 950 W/m^2 shown in Fig. 5 clearly shows the three regions identified above. Also noticeable is the variation of the critical temperature with radiation intensity.

After characterizing the response of the module to temperature changes for different radiation intensities, the following methodology for cooling of the module was employed.

Table 4. Critical Temperature at different intensities

Radiation Intensity (W/m^2)	Critical Temperature (°C)
950	75
800	66
750	63
650	53

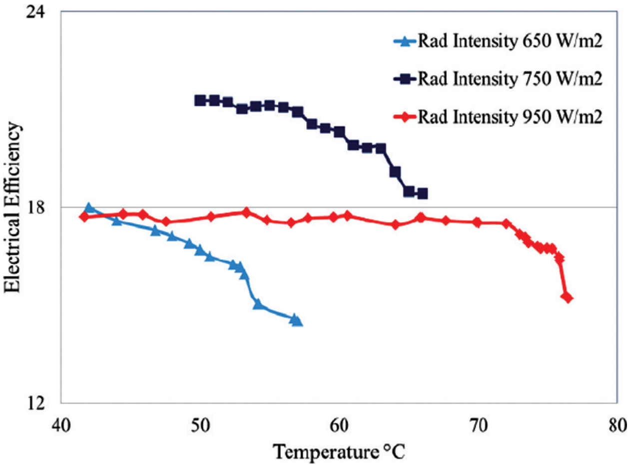

Figure 5. Variation of PV module efficiency with temperature at different radiation intensities.

1) The cooling system was turned on at the critical temperature for the respective irradiation.
2) The same fluid was circulated multiple times across the module till no significant cooling of the module was observed. Although the circulated water had a lower capacity to gain energy from the module due to lower temperature difference between the module and water, this mechanism reduced the need to supply fresh water every time making the system feasible where limited water supplies are available. When the desired water temperature was reached, the freshwater was fed to the system from the cold water supply tank. The recirculation was automatically controlled through an Arduino based system.

The response of the PV module to cooling is shown in Fig. 6 at a radiation intensity of 800W/m^2. As expected, the drop in temperature led to an increase in the efficiency of the module. Similar to Fig. 4, three distinct regions of the module behavior are clearly identifiable. The cooling water was supplied at 26.5°C and was used for domestic usage at 37°C. During the first pass, the cooling water reached a temperature of 33°C which was then recirculated across the module. The heated water was then utilized for bathing, and washing purposes. The overall increase in electrical efficiency due to cooling was 2.4%. The cooling system showed a thermal efficiency of 67.7% with an overall efficiency of the PV/T system of 85%.

Results at the higher irradiation of 950W/m^2 shown in Fig. 7 show an increase in electrical efficiency of the module by 1.43% caused by the introduction of cooling water i.e. as the temperature dropped from 77°C to 67°C, the efficiency of the module increased from 14.78% to 16.21%. The water in this instance was passed across the module three times raising its temperature from 21.5°C to 38.7°C. The overall efficiency of the hybrid system was noted to be 73.83%.

The PV module exhibited the highest electrical efficiency at irradiation of 750W/m^2. Introduction of cooling water at 27°C led to a further increase of 2.33% in electrical efficiency (18.8% to 21.13% as the module temperature dropped from 64°C to 57°C). The PV/T system helped in utilizing the incident energy to useful heat recoverable in the form of hot water at 39.5°C. The overall efficiency of the system was noted to be 85.1%.

The electrical, thermal and overall efficiencies calculated at different radiation intensities for the PV/T system are provided in Table 5. Thermal efficiency range of 55-70% of the hybrid system developed in the current study agrees well with previous work of Amna et al. [31], who claimed a thermal efficiency of 60- 70% and Rawat et al. [33] who noted a thermal efficiency of 50.1%. The PV/T system exhibited an overall efficiency of 70 – 85% at different radiation intensities (Fig. 9), which makes this system

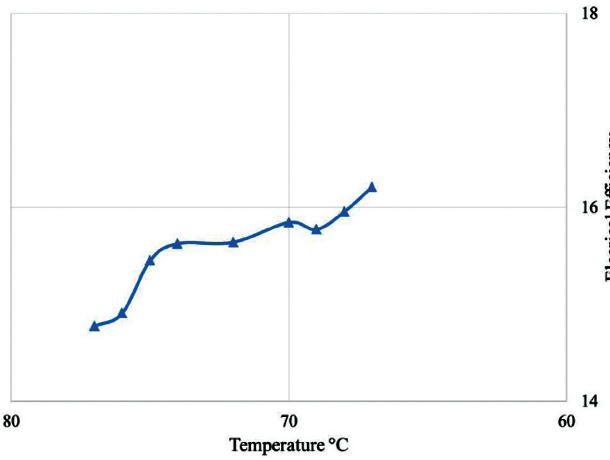

Figure 7. Effect of cooling of PV module on electrical efficiency (Radiation intensity 950 W/m^2).

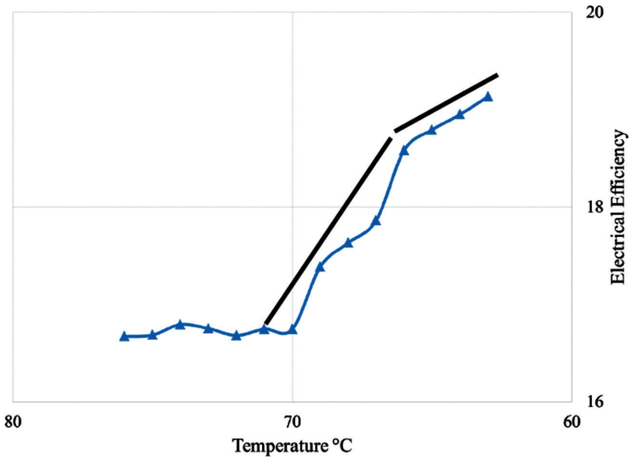

Figure 6. Effect of cooling of PV module on electrical efficiency (Radiation intensity 800 W/m^2).

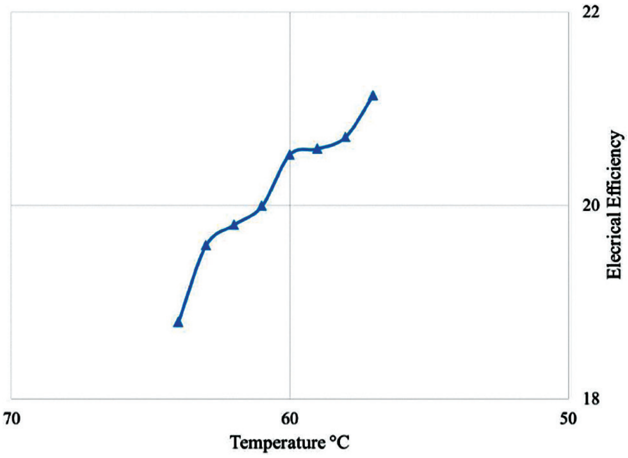

Figure 8. Effect of cooling of PV module on electrical efficiency (Radiation intensity 750 W/m^2).

Table 5. Efficiencies at different radiation intensities of the PV/T system

Supply Temp of Water	Usage Temp of Water	Radiation Intensity	Ambient Temperature	Thermal Efficiency	Electrical Efficiency	Overall Efficiency
°C	°C	W/m^2	°C	η_{Th}	η_{El}	η_{OA}
21.5	38.7	950	43	57.63	16.2	73.83
20	37.0	900	42	56.72	18.3	75.02
26.5	37	800	41	67.7	17.3	85
27	39.5	750	39	64	21.1	85.1

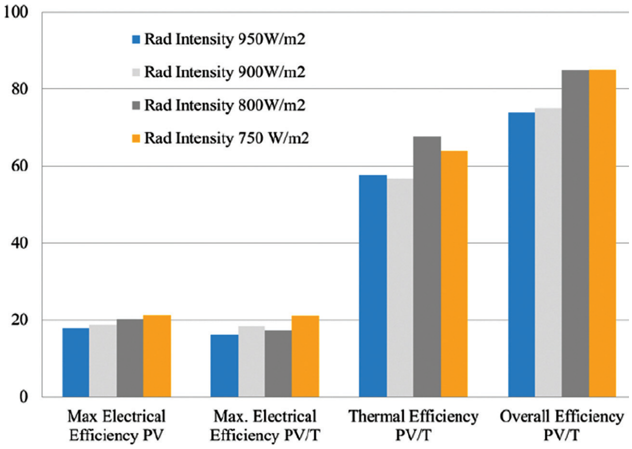

Figure 9. Maximum electrical efficiency for PV and maximum electrical, thermal and overall efficiency of PV/T system at various radiation intensities.

a viable alternative to the conventional PV or thermal systems being used currently.

CONCLUSION

A PV/T system was developed in the current study to evaluate its ability at increasing the overall efficiency of a standard PV module. The tests were conducted in the open air, under hot conditions at a maximum temperature of 43°C. Initial characterization of a 150W mono-crystalline module showed that there exists a critical temperature for which the efficiency of a PV module starts decreasing rapidly without following the 0.5%/°C decrease quoted in the literature. This critical temperature was noted to be a function of radiation intensity and decreased with decreasing intensity. Incorporation of the cooling system resulted in a decrease in the surface temperature of the module by 20% with an increase in electrical efficiency by up to 2.4%. The thermal aspect of the system made the system viable and economically efficient. A maximum thermal efficiency of 67.7% meant that clean water can be made available for any household purpose. The overall efficiency of the hybrid system was 70-85%, which makes this system a viable alternative to the conventional PV or thermal systems being used currently.

NOMENCLATURE

C_p	Specific heat constant at constant pressure (J/kgK)
I	Current (A)
V	Voltage (V)
m	Mass flow rate (kg/s)
T	Temperature (°C)
T_{wi}	Temperature of water at inlet (°C)
T_{wo}	Temperature of water at outlet (°C)
ΔT	Temperature difference (°C)
$LiPo$	Lithium Polymer
PV/T	Photovoltaic/Thermal
k	Thermal conductivity (W/mK)
PCM	Phase change material
η_{El}	Electrical efficiency
η_{Th}	Thermal efficiency
η_{OA}	Overall efficiency

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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