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ORIGINAL STUDY

Experimental Study of Energy Conversion Efficiency Improvement of Photovoltaic (PV) Module Using Hybrid Cooling System

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Abstract

The elevation of the photovoltaic module operating temperature resulting in diminution of its energy conversion efficiency is one of the key limitations to its application. A decrease of power delivered performance by 0.4−0.5 % per 1 $^{\circ}C$ rise over its Standard Test Condition (STC) accounted for the overheating of the PV module. This study evaluates the energy conversion efficiency improvement of a PV module using hybrid cooling system. An hourly segmented hybrid cooling system made up of aluminum fins as passive cooling segment and helical structured copper tubules for water conduction as active cooling segment helps to improve the energy conversion efficiency performance of the PV module. A temperature reduction of 8.3 $^{\circ}C$ and an energy conversion efficiency improvement index of 3.87 were estimated for the hybrid cooled PV module over the reference PV module. The hybrid cooled techniques to the PV module significantly reduced the thermal stress effect at the PV module cell junctions and an improved energy conversion efficiency was obtained.

Keywords: Hybrid cooling system, Energy conversion efficiency, PV module operating, Temperature, Generated energy consumption, Poor performance

1. Introduction

Electrical energy has been the yardstick to the modern technology and economic diversification across the globe. The adoption of ambient energy sources and the development of effective micro-grid technologies have been accelerated by the world's energy difficulties and their effects on the environment. When compared to other ambient energy sources, solar energy is ubiquitous and environmentally friendly [1]. Solar energy is the radiant and heat energy that is naturally produced by the sun. It could be assumed the best renewable energy for being non-polluting, silent and inexhaustible [2]. Through the use of a photocell, sunlight is directly converted into energy during solar-electric (photovoltaic) generation. Therefore, precise selection and dependable performance of the solar energy conversion system require proper knowledge of PV system performance under diverse operating situations [3]. Silicon-based solar PV modules typically convert about 20 % of the solar irradiance impinges on it into electricity and losing the remaining significant amount as heat. The trapped heat becomes burden to the PV cells and may damage it [4,5]. A hybrid PV-Thermal systems which combined direct solar irradiance conversion into electricity with solar thermal electricity conversion into electricity had showed a significant enhancement in converting solar energy [6]. Passive cooling systems seems cheaper, uncomplicated with better a more valuable thermal efficiency compared to active cooling systems [7].

Researchers are interested in the relationship between solar cell temperature and conversion efficiency because manufacturers' data and research

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findings support the idea that efficiency declines as temperature increases. For each degree above 25 °C, efficiency decreases on average by 0.45 % [1,8]. Reducing operating temperature of a PV module leads to enhancing its efficiency and slowing the pace of thermal damage. The state-of-the-art in solar cooling has mostly focused on the early stages of system development. Cooling is most necessary when solar energy is available. There are three basic methods of cooling PV module; passive, active, and hybrid method along with three main cooling materials; air, water, and phase change materials. It is essential that photovoltaic module cooling means should be an integral part of the PV system to address the effect of elevated temperature on the PV module power output [9].

Benato et al. [10] carried out experiment on surface water cooling of PV module using three nozzles. The primary data analysis using numerical approach estimates the setup efficiency of the PV module. The result of his work shows that active cooling with water gives highest efficiency, the installation cost and plant arrangement complexity makes the innovation not eligible for adoption.

Ekiz et al. [7] experimentally studied the effect of heat sink surface form on PV cooling effectiveness. A flat surface fine and tread surface heat sinks were fixed separately through paraffin/aluminum to the back surface of two identical PV modules with the third PV module as reference module were experimentally investigated. The best electrical efficiency improvement of 5.74 % was recorded for the PV module with tread surface heat sink along a temperature reduction of 16.5 %

Zubeer et al. [11] experimentally verified the comparison between air cooling, water cooling and fins cooling on two PV modules. He used a numerical analysis to estimate the output efficiency of each cooling technique, water cooling was identified to have effective impact on the PV panel performance, fins cooling also seemed an effective means but free air cooling did not gave a proportional efficiency to the air mass flow. His findings provide technical approaches to hybrid technology.

Siecker et al. [2] theoretically studied and review different techniques of cooling PV modules the temperature conservation and efficiency improvement of the techniques were compare, the results show that each method of cooling the PV has its advantage and disadvantage with emphases on no specific adopted technique could completely eliminate the overheating problem of an operational PV module.

Bevilacqua et al [12]; Dewi et al. [13]; Dizier [14] studied an active automatic cooling of a PV module using a classical experimental method with purely surface water cooling technique on an open mounted solar panel. The results gave a better output efficiency improvement but substantial part of the output energy was consumed in the process for water pumping.

Arifin et al. [15] experimentally studied the effect of heat sink properties on solar cell cooling system. Heat sink of 2 mm thick at the base and 3 mm thick fins were used for the experiment with the number of the used fins varying from 5, 10 and 15 of aluminum and copper materials. The results show that the effect of cooling capacity base on conductivity value of material used is insignificant compare to the number of used fins which is highly significant in the process.

Hariri et al. [5] experimentally studied the effectiveness of cooling PV modules using a hybrid cooling systems made of phase change materials and heat sink material. Paraffin + steel foam mixture along with inclined finned were used on a tested module, Paraffin + steel foam mixture along with flat finned were used on another tested module, and a referenced PV module were tested in the experiment. An overall electrical efficiency improvement approximately to 5.09 % and 6.18 % over the referenced module were recorded respectively.

The literature review on PV module cooling systems revealed that the application of only passive or only active cooling system is fast and easy to implement. None of the two cooling systems is yet to provide a desired temperature reduction and energy conversion efficiency for a PV module. The discrepancy between the temperature reduction and the energy conversion efficiency of the cooling systems are also in question. The active cooling system which seems to be better, utilized most of its power output in the cooling process.

This study uses a hybrid cooling system to provide a better temperature reduction and improved energy conversion efficiency for a PV module. The better agreement between the two factors in comparison to the previous researches justified the effectiveness of the used hourly segmented hybrid cooling system over the other two cooling system.

2. Theoretical analysis

The first law of thermodynamic is use to generalize the input solar irradiance to the PV modules, the output electrical energy delivered at the PV modules terminal and energy lost from the system. Eqs. (1)−(4) give the illustrations.

$$Q_s = P_{max} + Q_l \tag{1}$$

Where Q_s is solar irradiance, P_{max} is electrical maximum power output and Q_l is loss energy.

$$Q_s = \tau G_s A \tag{2}$$

Where τ is cover transmittance of the PV module, G_s is nominal solar irradiance and A is active surface area of the PV module.

$$P_{max} = I_{max} \times V_{max} \tag{3}$$

Where P_{max} is electrical maximum power output, I_{max} is the PV module maximum current and is the PV module maximum voltage.

$$Q_l = Q_{conv} + Q_{rad} + Q_{hs} \tag{4}$$

Where Q_{conv}, Q_{rad} *and* Q_{hs} are the heat loss by convention, heat loss by radiation and heat sink to the PV module.

Newton's law of cooling is used to determine the quantity of heat loss by convection from the PV module as given in Eq. (5).

$$Q_{conv} = h_{conv} A(T_c - T_a) \tag{5}$$

Stefan-Boltzman law of radiation is used to determine the quantity of Q_{rad} dissipated from the PV module as given in Eq. (6)

$$Q_{rad} = \epsilon A \sigma \left(T_c^{\,4} - T_a^{\,4} \right) \tag{6}$$

Where Q_{rad} is heat loss by radiation, ϵ is emissivity of the module, A is, active surface area of the PV module, σ is Stefan-Boltzman constant, T_c is temperature of the PV module and T_a is ambient temperature.

Fourier's law of heat conduction is used to determine the thermal conductive parameters of the fins as given in Eq. (7)

$$Q_{row} = -\frac{KA\Delta T}{l} \tag{7}$$

Where Q_{row} is heat flux of each cooling fin, K is thermal conductivity constant, ΔT is change in temperature and l is length of the fin.

An endless boundary condition is assumed between the Copper tube and the PV module makes the total instantaneous heat sink to the panel available in the Copper tube. Therefore, the rate at which the heat sink is conducted away is determined using Eqs. (8) and (9). The thermodynamic properties of the PV module and the fins, and physical dimensions of the PV module layers are held constant throughout the study.

$$Q_{hs} = \frac{mc\Delta T}{t} \tag{8}$$

Where Q_{hs} is heat sink in the PV module, m is mass of water and t is the time of flow.

The flow rate is obtained as given in Eq. (9).

$$V = \frac{Q_{hs}}{\rho c \Delta T} \tag{9}$$

Where V is water flow rate, ρ is density of water and c specific heat capacity of water.

The instantaneous energy conversion efficiency model of a PV module is given in Eq. (10).

$$\eta = \eta_{ref}\left[1 - \beta\left(T_{cell} - T_{ref}\right)\right] \tag{10}$$

Where η is the PV module efficiency, η_{ref} is the PV module efficiency at T_{ref}, T_{ref} is the PV module reference temperature, β is the PV module temperature coefficient and T_{cell} is the temperature of the PV module.

The energy conversion efficiency of the PV modules were estimated using the following numerical algorithm,

$$\eta = \frac{\int_{t_1}^{t_2} P dt}{A \int_{t_1}^{t_2} G dt} \tag{11}$$

t_1 *and* t_2 are the initial and final time of measurement, dt is the change in temperature over the time of measurement, A is the area of the PV module, G is the solar radiation and P is the PV module power output.

The power output P of the PV module given in Eq. (12) is given as the product of the terminal current I and voltage V delivered to the 1 MΩ resistor load connected.

$$P = IV \tag{12}$$

3. Materials and methodology

3.1. Materials

The materials used in the study consist of two 80 W monocrystalline solar PV modules, a hybrid cooling system made up of 49.9 cm ×5cm × 0.1cm Aluminum fins array on aluminum brace as passive unit and copper tubing fins of 1 cm diameter slotted under the aluminum brace and directly adjacent to the aluminum fins as active unit, brushless DC water pump, flow meter and water reservoir.

3.2. Methodology

A free to space PV module's temperature variation effect on energy conversion efficiency experiment was carried out on the two PV modules. The characteristics of the PV modules are provided on the Table 1. The PV modules were mounted on fixed rack testbed staged on top of Physics department, Obafemi Awolowo University, Osun state Nigeria, 7 m above ground and tilt at 17° to real life solar irradiance. The PV modules were disposed on the rack to avoid mutual shading and a water reservoir of 5 L sizes was erected in between the PV modules and toward the top of the experimental PV module to supply water on gravity flow to the back of the PV module through an Annubar flow meter which operates on Bernouilli's Theorem with accuracy variation of $\pm 1\%$ *to* $\pm 2\%$ of the actual flow. A resistor of $1\,M\Omega$ resistance is connected as load across the terminals of each PV module. 6fins of aluminum and an average water flow rate of 12 ml/min are used in passive and active units of the hybrid cooling system respectively for the experiment. A micro submersible brushless DC water pump of 4-6v, 0.6–1.8 W and 150 L/H configuration was used to return the cooling water from lower reservoir of 7 L sizes to the upper reservoir. The variables set to be measured are precisely the energy conversion efficiency improvement related parameters of the PV modules. The PV modules back surface temperature, ambient temperature and solar irradiance are measured by DS18B20 temperature sensors and calibrated GL5528 LDR light sensor respectively and interphase with Arduino mega board directly connected to SD card module with SD card plugged in to log the data from 6:30am to 5:30pm at 5 min interval. The passive segment of the hourly hybrid cooling system was featured between 6:30am-9:00am and 3:00pm-5:30pm while, the active segment was featured between 9:00am-3:00pm. The data are compounded in 30 min interval for easy implementation in analysis. Plate 1 and Fig. 1 show the picture of the experimental setup.

Table 1. Summary of the used Monocrystalline PV Modules Characteristic Specifications.

Characteristic Description	Manufacturer Data Sheet Value
Nominal Power (W)	80
Voltage at (P_{max}) (V)	17.5
Current at (P_{max}) (A)	4.58
Open Circuit Voltage (V_{oc}) (V)	21.55
Short Circuit Current (I_{sc}) (A)	4.85
Number of cells in the module	36
Output tolerance	±5%
AM at STC	1.5
Irradiance level G at STC (W/ m^2)	1000
Operating Temperature at STC	25°C
Length (m)	1.033
Breadth (m)	0.499
Active Area (m^2)	0.5155

3.3. Evaluation of impact of the energy consumed by the DC water pump

The energy consumed by the brushless DC pump was evaluated with Eq. (13)

$$E_{wp} = P_{wp} \times t \tag{13}$$

Where, E_{wp} = *energy consumed by the dc pump*,

P_{wp} = power rating of the dc pump and

t = total time of operation of the dc pump

The Aluminum fins used 12 ml of water per min.

The quantity of water used up for 6 h $= 12 \times 60 \times 6 \times 0.001$

$= 4.32\, l$

The dc pump is rated 150 l/h,

Therefore time required for $4.32l = 1.728$min

$\approx 1.7\, mins$

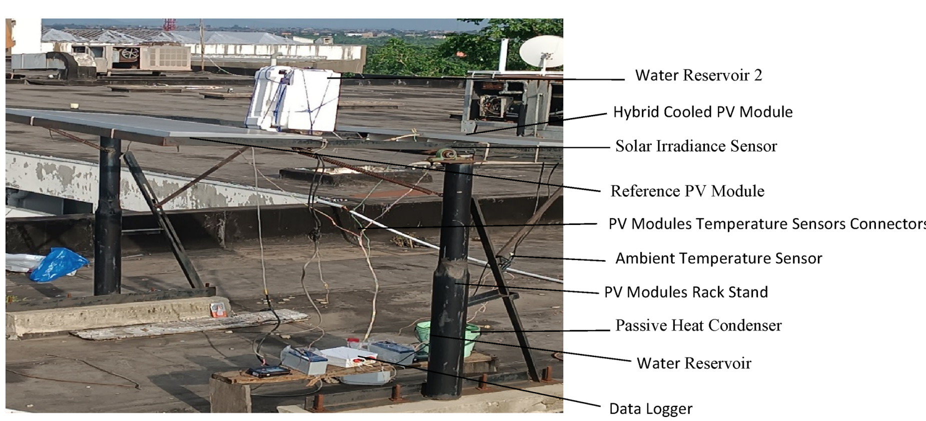

Plate 1. Experimental setup of the study.

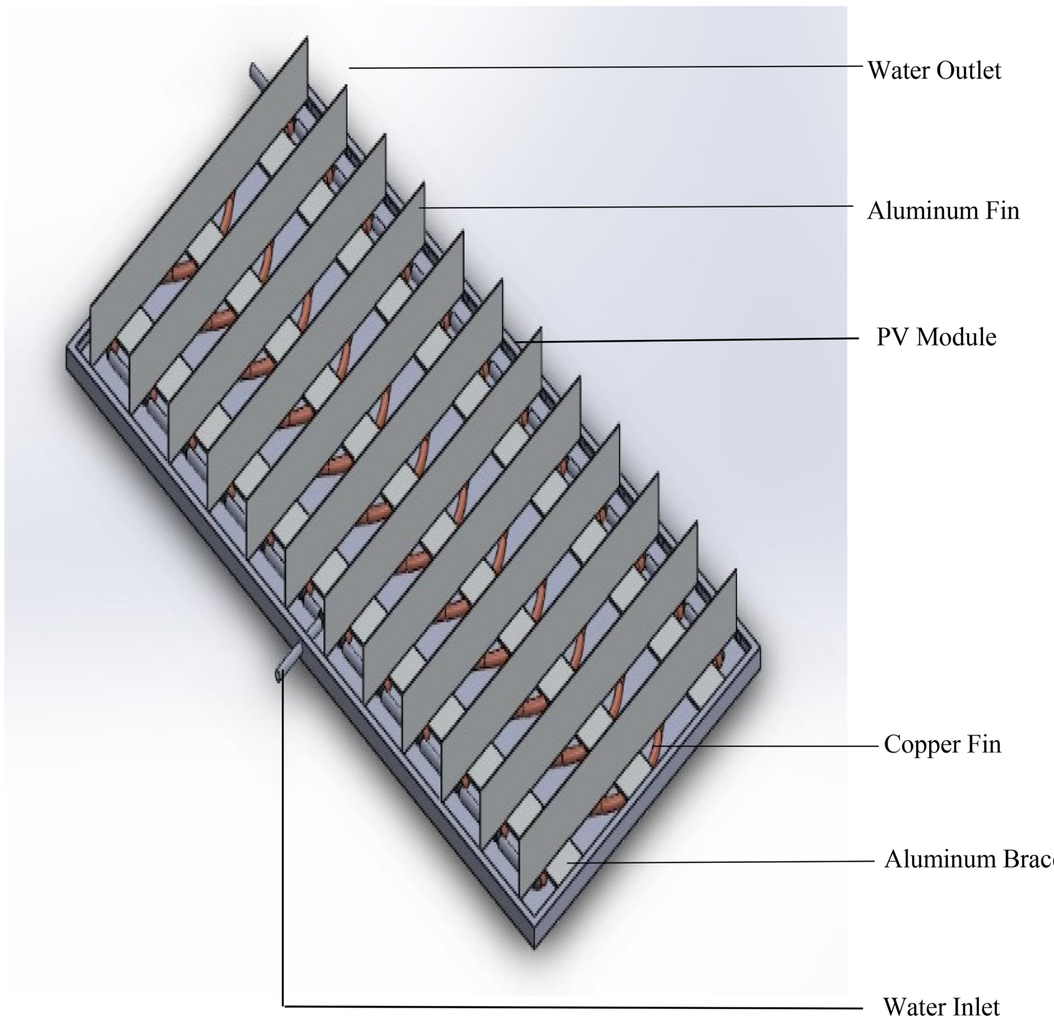

Fig. 1. PV modules along with the hybrid cooling systems.

$$E_{wp} = 1.2 \times \frac{1.728}{60}$$

$$E_{wp} = 0.03456\ Wh$$

3.4. The energy conversion efficiency parameters of the optimal experiment

The daily variation of the solar irradiance along with the measured energy conversion efficiency parameters for the optimal experiment day is given on Table 2.

3.5. Boundary conditions assumptions

The analysis was streamlined by making the following assumptions:

- Isotropic and homogeneous fin material.
- Minimal thermal contact resistance.
- Heat transfer is one-dimensional.
- Energy transfer reaches a steady state.
- No heat is produced inside the fin.
- A constant heat transfer coefficient (h) across the fin's whole surface.

By neglecting the capacity effects of these parts, the temperatures of the tender, solar cells, and back plate only vary in the direction of working fluid flow.

4. Results and discussion

The study experiment provides results for the use of hybrid cooling system on the back surface of the examined PV module and the reference PV module. The PV modules back surface temperature, ambient temperature, solar irradiance, power and the corresponding energy conversion efficiency of each PV modules under study were logged accordingly. The results are analyzed to determine the relative significance of the hybrid cooling system on the PV

Table 2. The energy conversion efficiency parameters of the optimal experiment.

Time	G	T_a	T_1	T_2	P_1	η_1	P_2	η_2
(min)	(W/m^2)	(C)	(C)	(C)	(W)	%	(W)	%
6:30am	0	0	0	0	0	–	0	–
7:00am	156.49	22.51	23.23	22.68	1.432	1.77515	2.079	2.57719
7:30am	297.65	22.62	25.62	22.81	16.082	10.4813	19.008	12.3882
8:00am	439.65	22.71	27.1	22.98	28.059	12.3807	33.33	14.7064
8:30am	538.67	22.93	29.35	23.12	37.587	13.5361	46.87	16.8792
9:00am	639.91	23.12	33.15	26.53	50.84	15.4122	56.898	17.2487
9:30am	678.13	23.61	34.13	28.52	59.946	17.1485	71.832	20.5487
10:00am	716.23	24.9	34.67	29.15	65.688	17.7915	75.895	20.5561
10:30am	721.98	25.1	37.83	31.28	52.65	14.1466	63.902	17.1699
11:00am	728.87	26.4	42.87	35.46	48.034	12.7843	56.784	15.1132
11:30am	780.89	26.92	48.13	40.86	48.216	11.9779	54.81	13.616
12:00noon	937.38	27.35	57.57	43.71	42.848	8.86736	50.427	10.4358
12:30pm	779.93	29.15	58.96	47.11	41.106	10.2242	50.485	12.557
1:00pm	725.83	30.27	60.23	49.13	38.9	10.3967	45.991	12.2919
1:30pm	695.02	29.85	56.31	45.32	36.764	10.2614	44.196	12.3357
2:00pm	662.2	28.82	54.17	41.91	33.063	9.68573	41.412	12.1316
2:30pm	558.56	27.91	53.81	38.51	30.846	10.7129	37.268	12.9433
3:00pm	454.61	27.83	52.67	35.99	22.127	9.44198	31.375	13.3883
3:30pm	344.94	26.35	49.93	34.29	20.212	11.367	27.244	15.3217
4:00pm	231.24	25.46	47.33	33.11	19.375	16.2539	23.856	20.0131
4:30pm	146.07	25.38	42.69	32.07	9.292	12.3404	13.5	17.9288
5:00pm	58.57	25.01	39.87	31.59	0.459	1.52026	2.697	8.93275
5:30pm	29.53	24.92	31.15	27.03	0.062	0.40729	0.372	2.44376
6:00pm	15.26	0	0	0	0	0	0	0
Mean	514.6522727	25.86909091	42.76227273	33.78	31.98127273	10.85969864	38.64686364	13.70578636
Standard Deviation	258.1588797	2.366472075	11.5251034	8.054151386	18.64929083	4.535774989	21.35540735	4.699314505
Standard Deviation of Mean	53.82984753	0.493443538	2.403150183	1.679406657	3.888645949	0.945774464	4.452910251	0.97987481
Z-score at Noon	0.818014579	1.85969196	1.515624343	1.905849451	0.370991441	−0.102077073	0.343900551	−0.300870768
Margin of Error	44.03360006	0.91765298	3.642272917	3.200696256	1.442654363	−0.096541889	1.531358291	−0.294815687
% of Margin Error	8.555990597	3.547295047	8.517491436	9.475122131	4.510934807	−0.888992343	3.962438725	−2.151030804
Precision	9 %	4 %	9 %	9 %	5 %	1 %	4 %	2 %

Where P_1 is the Power Delivered by the Reference PV Module (W), P_2 is the Power Delivered by the Hybrid Cooled PV Module (W), η_1 = Conversion Efficiency of the Reference PV Module, η_2 = Conversion Efficiency of the Hybrid Cooled PV Module.

module. The temperature reduction and the energy conversion efficiency improvement indices of the hybrid cooling system were estimated along with uncertainty precision of the experiment data for reliability of the research outcome.

This section details the analysis of the observed parameters and their gradual variation impact on this study. The variation effects were analyzed as follow;

4.1. Characterization of the PV modules temperatures variation

The ambient, reference PV module and the hybrid cooled PV module temperatures (T_a, T_1 and T_2 respectively) under study were simultaneously measured and logged from sunrise to sunset each day of the experiment. The graph in Fig. 2 gives the summary of the temperature variation for the PV modules in an experiment day.

4.2. Characterization of the energy conversion efficiency of the PV modules

The energy conversion efficiency of each PV module under study was estimated accordingly using the Eq. (11). The detail of the results were provided on Table 2. The graph of the estimated results is provided in Fig. 3. The significant appreciation of the hybrid cooled PV module curve, specifically between 8:00am to 5:00pm of the day

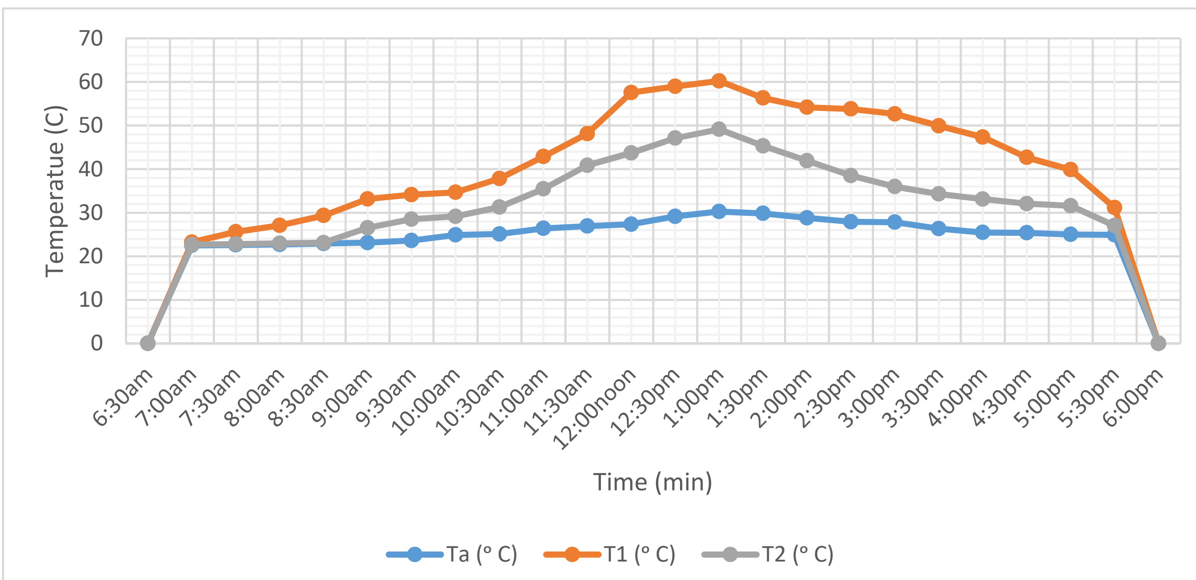

Fig. 2. PV modules and ambient temperatures versus time.

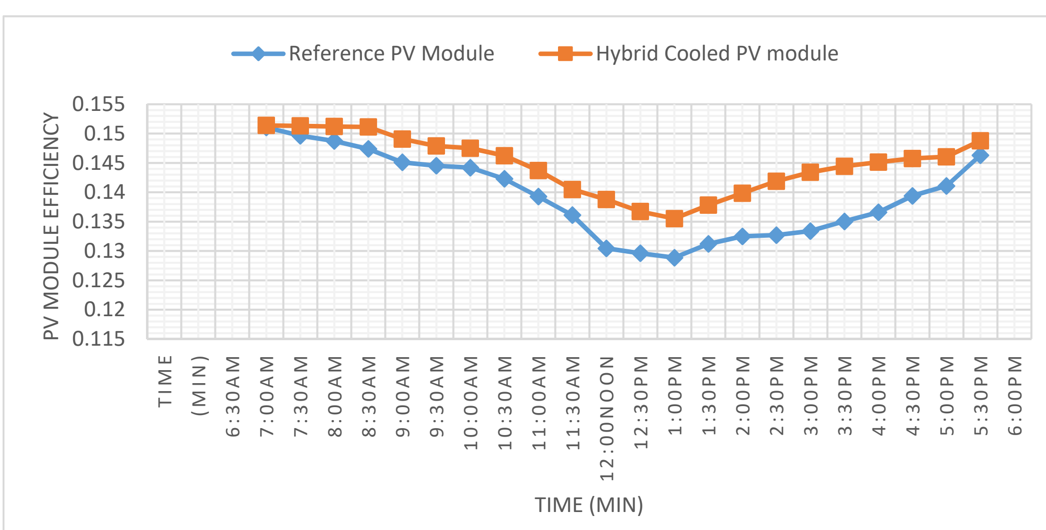

Fig. 3. PV module efficiency versus time.

Table 3. Comparison of the results of current study with previous studies using other cooling systems.

Cooling System Implemented	PV Module Temperature Reduction (°C)	PV Module Energy Conversion Efficiency Improvement %
[10]: Active	24	2.09
[16]: Active	3	2.3
[17]: Passive	15.13	1.5
[18]: Passive	24.07	1.39
[19]: Active	31.9	2
[20]: Passive	7.5	2.34
Current Study (2023): Passive Unit	6.2 (21.04 %)	3.30
Active Unit	10.4 (21.15 %)	2.49
Hybrid System	8.3 (21.26 %)	2.89
[5]: Passive	21.67 %	6.18
[7]: Passive	16.5 %	11.35
[21]: Passive	78.27 %	9.42
[1]: Active	4.59 %	2.23

was due to the ability of the cooling system to effectively counter the thermal stress that usually occurred at the PV cell junctions. Therefore, the mobility of the ejected electrons is facilitated and more currents delivery were recorded at the terminals. The realization of the lost energy in the reference PV module is shown in the figures. The enhancement effect of the hybrid cooling system on the PV module significantly allay the thermal stress experienced in the reference PV module.

Generally, the average hourly efficiency best performance was observed at around 12noon - 4pm of the day. These show that earlier cooling of the cooled PV module gave a better approach to the PV module cell junctions temperature rise. The passive cooling segment of the hybrid cooled PV module featured a better energy conversion efficiency but less total energy production compared to the active segment of the cooled PV module. This is due to low level of solar irradiance at the segment coupled with performance of the PV cells averagely below the threshold temperature.

Therefore, the elevation of the total energy delivered in the active segment of the hybrid cooled PV module, is characterized by the higher level of solar irradiance. This is due to the cooling of the PV module to operate within the optimal temperature range, which shows an improvement in energy conversion process at long run.

4.3. Comparison of the results of current study with the other studies using different cooling system

The achievement of the current study can better be justified in comparison with the previous studies of the same concept. The study experimental results for the dry season is used in the results analysis and discussions of this study. The temperature and efficiency differences between the hybrid cooled and the reference PV modules obtained for the raining season were insignificant. Therefore, the raining season experimental results were considered irrelevant to the study. The PV module cooling is of different approaches been passive, active or hybrid, all are based on temperature reduction and efficiency improvement. The summary of the resent studies results and the current study were provided on Table 3 for better justification of the current study.

5. Conclusion

In this study, a hybrid cooling system was used to reduce the thermal stress experienced at the PV module cells' junction. The segmented hybrid cooling approach was solely applied to PV module for direct conversion of solar irradiance to electrical power. It conserved the power which could have been wasted at the period of low solar irradiance if the systems should have been active cooling alone likewise the poor solar irradiance conversion to power at the period of higher solar irradiance if the systems were to have been only passive cooling. The innovative hybrid cooling system's distinct structural design sets it apart from other heat sink methods that have been used for the same purpose in the past. Similarly, by implementing active cooling only at a strategically high solar irradiation to the PV module and the hourly division of the cooling technique ensured conservation of the converted energy. This made it possible to precisely lower the accompanying high temperature, which may have seriously slowed down the energy conversion process at the junctions of the hybrid-cooled PV module cells. When compared to the majority of other available literature, the energy conversion efficiency yield obtained by using the active cooling system for 6 h further demonstrated the innovation of the inmoved cooling system, as shown in Table 2. Similarly, compared to the majority of other available research, there was a greater alignment between the temperature reduction and the energy conversion efficiency given by the passive cooling segment, as also shown in Table 2. These results show how effective is the mechanism in enhancing the energy conversion efficiency of the PV module. The hybrid cooling system offers a better advantage in terms of greater energy production support, uses materials of very low environmental impact, easy to mount and maintained, consume very less energy in operation and cost effective. The cooling system is also recyclable at the ends of its conserved life. The use of hybrid cooled techniques to cool the PV module showed a significant remedy to the thermal stress effect at the PV module cell junctions and an appreciated energy conversion efficiency curve was obtained. In effect, it can be concluded that the hybrid cooling system has proved to be effective, as the improvement in temperature reduction and energy conversion efficiency in this study is higher than some of the selected studies of different cooling approaches. The objectives of the study were achieved successfully. Finally, energy conversion efficiency improvement in Photovoltaic (PV) modules should be a continuous process using the best approach. The following recommendation are deemed necessary for further study in this field:

- The effect of the hybrid cooling system PV module using phase change material as heat conducting fluid in active segment can be considered for investigation.
- Investigation of the Combine Heat and Power study of optimized hybrid cooled photovoltaic power system.

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Conflict of Interest

The authors affirm that none of them have any conflicts of interest that might have looked to have influenced the research described in this study.

Ethical Approval

Ethical information is not applicable to the manuscript.

Data Availability

The authors hereby certifies that the manuscript contains all the information required to uphold the integrity of this research project and its applicability as a secondary data source for future studies. The Author hereby grants full and exclusive rights to the data in the manuscript.

Author Contributions

O. S. Babalola; Conceptualization, Supervision and Writing - review and editing.

O. W. Olademeji; Conceptualization, Methodology, Investigation, Software, Validation, Writing – original draft, Project Administration and Visualization.

J. B. Samson; Software, Resources and Writing – review and editing.

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