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An experimental assessment of the performance of solar panels using efficiency enhancement techniques in India's tropical region

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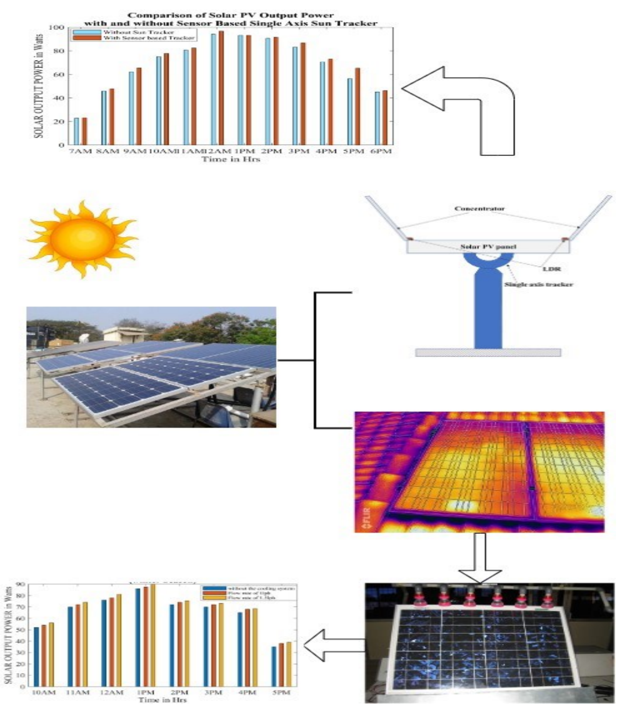
Graphical abstract



Abstract

Due to its abundance and lack of pollution, solar energy will soon be the most popular source of electricity production. Numerous factors, including the temperature effect, solar irradiance effect, shadow effect, incident angle effect, dust accumulation on the solar cell, shunt resistance, types of solar cell materials, mechanical defects in the solar panel, spectral mismatch loss, cable loss, maintenance and cleaning cycle, load mismatching effect, etc., harm the efficiency of solar P.V. power generation systems. This study aims to quantify the impact of these factors and explore efficiency enhancement techniques to mitigate their effects. Among the various factors, solar irradiation and temperature significantly influence solar P.V. panel efficiency. This research investigates the effects of solar irradiation, incident angle, and temperature through simulations and experimental methods using two 100W solar panels. Efficiency enhancement techniques like sensor-based sun tracking and temperature cooling systems are incorporated with conventional solar P.V. power generation systems. The experimental results prove that the efficiency enhancement techniques improved the efficiency of solar panels by up to 12% compared to conventional solar panels.

Keywords: Solar Irradiance effect, Temperature Effect, Incident angle effect, Reflection loss, solar panel efficiency improvement techniques.

1. Introduction

Global environmental change, energy security, and possibly growing weary of petroleum product holds have all pushed the development of renewable power technology (Abubaker Younis *et al.*, 2024; Al-Housani *et al.*, 2019). More than 80% of the world's energy consumption comes from petroleum products, significantly contributing to environmental issues. Renewable power technology is essential because of its reduced impact on ecological degradation and accessibility to unlimited resources. In addition to being accessible, solar energy is the most valuable source of sustainable power. One of the potential economic sectors around environmentally friendly electricity is harvesting solar energy using photovoltaic (P.V.) frameworks to generate power. An outcome of photovoltaic technology is the ability to generate power by converting solar energy into electricity (B. Joseph *et al.*, 2019; Kelmendi *et al.*, 2019).

Several factors negatively impact the efficiency of solar P.V. panel power generation systems, including the incident angle effect (Musa Phiriet *et al.*, 2023; Saeed Adibpour *et al.*, 2023, V. C. Chavan *et al.*, 2023), irradiance effect, shadow effect, temperature effect (Mohamed Lebbi *et al.*, 2024; Yu Sirui *et al.*, 2024; Zhiying Song *et al.*, 2024), and dust accumulation on the solar cell (Abubaker *et al.*, 2024; Letao *et al.*, 2024; K. *et al.*, 2020; Al-Housani *et al.*, 2019; Chairma *et al.*, 2022; Vedulla *et al.*, 2023), cracks in the panel, and types of solar cell materials (B. Joseph *et al.*, 2019; Kelmendi's *et al.* 2019; M. Mousa *et al.*, 2021; W. Abdelaziz *et al.* 2020), load mismatching effect (Monika Verma *et al.*, 2023), shunt resistance, cable loss, maintenance and cleaning cycle (Mohamed Lebbi *et al.*, 2021), spectral mismatch loss, etc.

This study aims to investigate the influence of solar irradiance and temperature effects on the efficiency of solar photovoltaic (P.V.) modules. This investigation is conducted through both simulation and experimental methods using two 100W solar panels. The study aims to identify how these environmental factors affect solar panel performance. Additionally, the paper explores efficiency enhancement techniques such as sensor-based sun tracking and temperature cooling systems. The effectiveness of these techniques in improving the efficiency of solar panels is demonstrated through experimental results. The first portion describes the geographical information of the test site and the experimental setup. The second portion explains the impact of the solar irradiance effect and temperature effect using MATLAB Simulink models and experimental analysis. The third section deals with efficiency improvement techniques that reduce the impact of solar irradiance and temperature on the solar P.V. modules' performance.

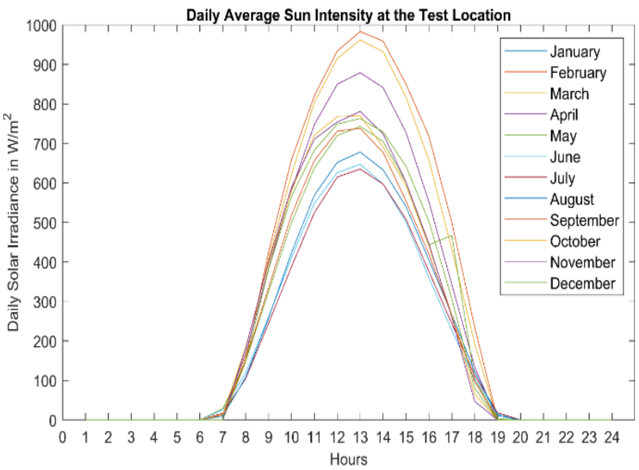


Figure 1. Daily Average Sun Intensity at the Test Location

2. Materials and methods

2.1. Description of test location

The experimental study takes place at R.M.K. Engineering College in an outdoor setting. More information about the geographical details is provided in Table 1. With a land area of 1189 square kilometres (Longitude: 80.270186°E and Latitude: 13.0836939°N), Chennai is the fourth-largest city in India. There are dry and wet seasons in Chennai's tropical climate. Because it is near the geographical equator and the shoreline, it does not experience significant temperature fluctuations. Most of the year is hot and humid. Chennai's yearly mean temperature is 82.1°F or 27.9°C. The annual average rainfall is 1014 mm or 39.9 inches. With just 9 mm and 0.4 inches of rain, February is the year's dry season. With a mean of 9.0 inches | 228 mm, November has the most precipitation.

Table 1. Geographical Description of the Test Site

Test Site	R.M.K Engineering College, Tamil Nadu, India.
Longitude at the test location	80.141°E
Latitude at the test location	13.358°N
Inclination of the solar panel	21°(concerning the horizontal surface)

Figure 1 displays the average daily sun irradiation in Chennai's tropical climate. Figure 2 provides monthly specifics of the environmental temperature, and Figure 3 illustrates the daily relative humidity at the experiment's site.

2.2. Description of the experimental setup

The following experimental configuration is employed to analyze the reduction in the efficiency of the solar P.V. module. The hardware design of the experimental system, as depicted in Figure 4, comprises two 100W polycrystalline solar panels, one with and one without efficiency enhancement techniques. The thermal, mechanical, and electrical characteristics of solar P.V. panels are listed in Table 2. The hardware specifications used in the experimental analysis are tabulated in Table 3.

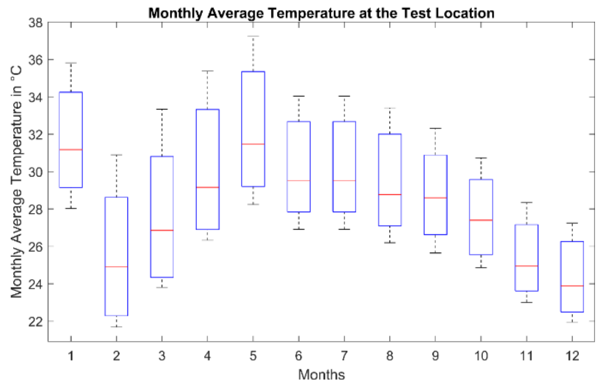


Figure 2. Monthly Average Temperature at the Test Location

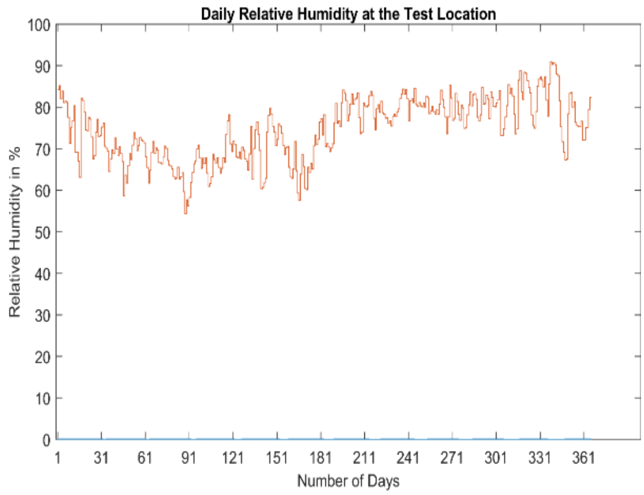


Figure 3. Daily Relative Humidity at the Test Location

3. Results and discussion

3.1. Impact of solar irradiation effect on solar PV module

This section analyzes the impact of solar irradiance on the power output (P_m) and efficiency of solar panels. The analysis is conducted under both simulated and real-time experimental settings, and the findings are presented in Table 4.

Table 2. Hardware Description of Solar Panel

Electrical Parameters		Thermal and Mechanical Parameters	
P_m - Nominal Maximum Power	100W	Solar Cells per Module (No of units) / Arrangement	36 / (9*4)
Voltage at Maximum Power (V_{mp})	17.46V	Length x Width x Thickness	1150 x 675 x 35mm
V_{oc} - Open Circuit Voltage	21.97V	Weight	10.15kg
I_{mp} - Current at Maximum Power	5.73A	Temperature coefficient of Power (P_m), γ (%/ºC)	-0.3845
I_{sc} - Short Circuit Current	6.07A	Temperature coefficient of Voltage (V_{oc}), ß (%/ºC)	-0.2941
Solar Module Efficiency (%)	12.88	Temperature coefficient of Current (I_{sc}), α (%/ºC)	0.0681

Table 3. Hardware Specification of the Proposed System

Equipment	Purpose	Specification
Solar Power / Light Intensity Meter SM – 206	To measure Sun intensity	Size: 132 X 60 X 38 mm
		Accuracy: ±5% of reading
		Range: 1-3999w/m^2 (btu)
		Resolution: 0.1 w/m^2
DC Voltmeter MECO SMP96	To measure Solar panel output voltage	Resolution: 0.001
		DC Voltage: 200V
		Accuracy: ±0.5% of FSD
DC ammeter MECO SMP48	To measure Solar panel output current	Resolution: 0.001
		DC Current: 20A
		Accuracy: ± 0.5% of FSD
Rheostat load	Load	Single-tube single-wire wound
		Current: 10A (maximum)
		Resistive loads: 10 Ω
Canyearn (C01) Infrared Forehead Thermometer	To measure solar panel front and back side temperature measurement	Temperature Range: 32.0°C - 42.9°C
		Response Time: 10s ± 1s
		Measuring distance: 3cm-5cm
		Accuracy: +/- 0.2°C to +/- 0.4°C

According to the simulation and experimental study findings shown in Table 4, Figure 5, and Figure 6, the solar P.V. module efficiency and solar panel output power (P_m) increase with increasing solar irradiation. As seen in Figure 6, the output power P_m is 94.19W with an efficiency of 11.23% when solar irradiation G=1180W/m^2 and temperature of the solar PV module T_{mod}=32.2°C are met. The same solar panel produces P_m=22.82W of output power at lower solar irradiance G=235 W/m^2. The output efficiency is affected by the solar irradiance falling on the solar panel, as noted in this experimental analysis.

3.2. Impact of the angle of incident solar irradiation on solar P.V. module

The primary concern impacting the efficiency of silicon solar cells is the occurrence of reflection losses. When sunlight illuminates the front surface of a solar cell, a portion of the light's energy is converted into electrical energy within the solar panel. In contrast, another portion is reflected off the surface. Various methods have been used to reduce the negative impact of reflection on silicon surfaces. In order to reduce the loss caused by reflection, the commonly used methods include light trapping, surface texturing, and antireflection coatings (A.R.C.). Well-designed antireflection coatings (A.R.C.) can significantly decrease reflection from over 30% to around 2% when compared to bare silicon (Dhanusiya Govindasamy *et al.*, 2023; Dongxin Huo *et al.*, 2024; Majid *et al. et al.* 2024). The efficiency of a solar cell is typically evaluated under conditions of normal incidence.

Figure 4. Visual Image of Experimental Hardware Setup

Nevertheless, solar cells do not consistently get direct sunlight throughout the day, from sunrise until sunset. The reflecting qualities of A.R.C. are varied due to the variation in the degree of polarization of light with changes in the angle of incidence. When constructing anti-reflective coatings (A.R.C.s) for solar cells, it is essential to consider the angular tilt of sunlight to enhance their effectiveness. The relationship between the angle of sunlight and the efficiency of solar panels is presented in Table 5. Figure 7 demonstrates the variations in solar irradiance, solar panel output power, and conversion efficiency caused by changes in the incidence angle.

The solar irradiation falls on the solar panel G=1040W/m^2 at a sun incident angle of 0°, and the output power P_m produced by the solar panel is 92.2W with an efficiency of 11.42%. The light intensity from the sun is the same. Still, due to the solar panel's inclination, the solar panel's incident angle changed to 20°, which reduced the solar irradiation that fell on the solar panel to G=940W/m^2. The solar output power P_m is 90.5 with an efficiency of 12.4%. The same sun-intensity solar panel produces P_m=40.8W of output power at lower solar irradiance G=406 W/m^2 when the incident angle is maintained at 90°. The experimental investigation proved that the solar panel output power was reduced by up to 50% because of incident angle changes from 0° to 90°.

3.3. Impact of the temperature on solar P.V. module

Sun irradiance is the source of solar P.V. power generation systems, and solar P.V. systems do not require thermal heat to produce electricity. Compared to a higher solar P.V. cell temperature module, Lower solar PV-cell temperatures can result in higher efficiencies under similar sun irradiation conditions, boosting power generation and giving the customer more advantages over solar P.V. technology.

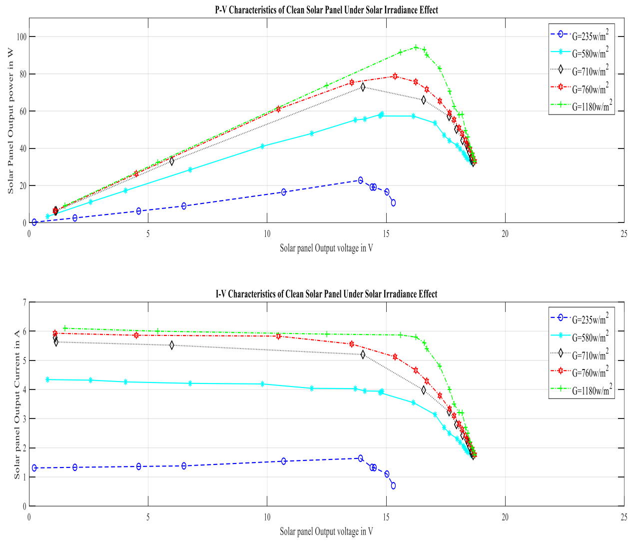


Figure 6. P-V and I-V Curves of Solar Panel Under Irradiance Effect (Experimental Analysis)

Table 4. Solar Irradiance Effect on Solar PV Module Performance

Solar irradiance (G in W/m^2)	Experimental Result			Simulation Result		
	T_{mod}: Solar PV module Temperature (◦C)	P_m: Solar PV Output power (W)	η: Efficiency (%)	T_{mod}: Solar PV module Temperature (◦C)	P_m: Solar PV Output power (W)	η: Efficiency (%)
235	32.2	22.82	12.51	32	23.21	12.72
580	32.1	58.43	12.98	32	59.21	13.15
710	35.1	72.90	13.23	32	73.81	13.39
760	35.2	78.69	13.34	32	79.51	13.48
1180	34.2	94.19	11.23	32	99.71	10.89

Table 5. Sun Irradiance Incident Angle Effect on Solar PV Module Performance (Experimental Analysis)

Incident angle (degree)	G: Solar irradiance (W/m^2)	P_m: Solar panel output power (W)	Efficiency (η in %)
0	1040	92.2	11.42%
20	940	90.5	12.40%
40	830	82.9	12.87%
60	679	75.9	14.40%
80	510	56.3	14.22%
90	406	40.8	12.95%

In this experiment, the efficiency losses on the solar panel caused by temperature were looked at. According to the investigation, considering clean panel conditions, efficiency, and output power Pm decreased as the temperature increased. The effect of solar temperature on the solar P.V. panel output power (P_m) and efficiency yield is examined at the same solar irradiance and different temperature conditions under simulation and real-time experimental conditions, and the results are given in Table 6. The I-V and P-V curves of simulation findings and experimental results for solar panels under the influence of temperature are shown in Figures 8 and 9, respectively.

According to the results shown in Figure 8 and Figure 9, it is understood that under clean solar P.V. panel conditions, with solar irradiation G=1160W/m^2 and temperature of solar module T_{mod}=30.1°C, the output power of solar module P_m= 94.19W with an efficiency of 10.28%. The same solar panel produces output power P_m=70W with an efficiency of 7.71% at solar irradiation G=1160W/m^2 and solar module temperature T_{mod}=45.8°C under high-temperature circumstances. Each degree of temperature increase in a solar P.V. module affects output power by 1.3W to 1.8W and efficiency by –0.3%.

Table 6. Temperature Effect on Solar P.V. Module Performance

G : Solar irradiance (W/m^2)	Experimental Result			Simulation Result		
	T_{mod}: Solar P.V. module Temperature (◦C)	P_m: Output Power of Solar Panel (W)	η: Efficiency (%)	T_{mod}: Solar P.V. module Temperature (◦C)	P_m: Output Power of Solar Panel (W)	η: Efficiency (%)
1151	30.1	94.19	10.54%	30.1	111.25	12.45
1154	35.6	87.3	9.75%	35.6	108.67	12.16
1163	40.5	78.15	8.66%	40.5	97.78	10.94
1170	45.8	70	7.71%	45.8	95.40	10.68

Table 7. Comparative Investigation of Water Spray Cooling System with SPVPGS (Summer Season)

Time (Hr)	G	T_f	T_a	P_{oo}	P_{ow1}	P_{ow2}	T_{iw}	T_{ow}	η_{oo}	η_{ow1}	η_{ow2}
10	710	52	32.2	53	55	57	34.3	36.2	9.62	9.98	10.34
11	820	66	35.3	78.2	78.6	79.3	37.5	39.4	12.29	12.35	12.46
12	950	72	37.8	83.5	83.9	85	38	41.9	11.32	11.38	11.53
1	980	75.6	39.2	86	87.5	90.6	41	44.3	11.31	11.50	11.91
2	880	74.2	41.3	84.2	84.6	85.9	46	47.9	12.33	12.38	12.58
3	720	73.9	43.7	76.2	77	77	40	42.9	13.63	13.78	13.78
4	650	66.2	42.5	65	68	68.5	38	41.5	12.88	13.48	13.58
5	410	52	40.9	39	39.8	40.9	32	33	12.25	12.51	12.85

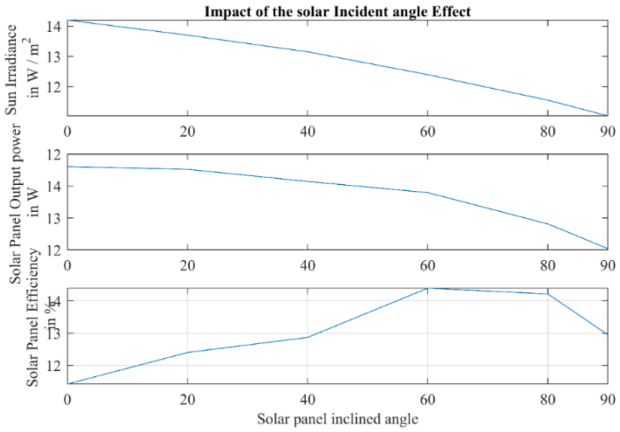


Figure 7. Impact of the Solar Incident Angle Effect

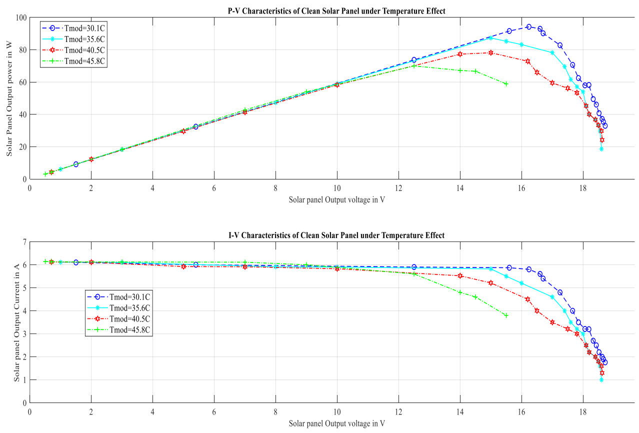


Figure 8. I-V and P-V Characteristics of Solar P.V. Panel under Temperature Effect (Experimental Analysis)

4. Efficiency enhancement techniques

Due to the sun's movement from east to west direction, fixed panel incident angle, and solar panel temperature, the solar panel's output power was significantly reduced. To enhance the efficiency of the solar panel, the solar panel losses like the solar irradiance effect, incident angle effect, and temperature effect are reduced by incorporating efficiency improvement techniques like concentrator, sun tracking system, and temperature cooling system with conventional solar P.V. power generating system. The solar panel with concentrator and tracker setup is shown in Figure 10. Solar panels with temperature cooling systems are depicted in Figure 11. Single-axis solar tracking systems based on sensors have been used to enhance solar panel efficiency by reducing the impact of incident angle. In sensor-based single-axis solar tracking systems, the LDR sensor is utilized to identify the sun's or light source's location. As a result of the high intensity being detected by the LDR sensor unit, the motor unit adjusts the position of the solar panel. Figure 12 details how 100W solar panels performed with and without a sensor-based single-axis sun-tracking device.

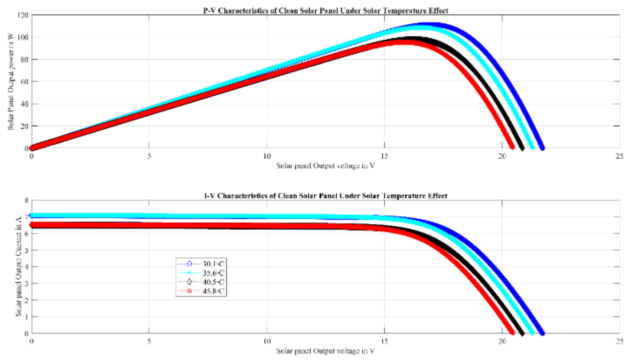


Figure 9. I-V and P-V Characteristics of Clean Solar Panel under Temperature Effect (Simulation Analysis)

The experimental investigation shown in Figure 12 convincingly shows that adding a sun-tracking system to a conventional solar P.V. power-generating system boosts output power by up to 10 Watts. This experimental investigation has highlighted the effects of the front surface water cooling methods used in solar panels. The 100 W polycrystalline solar P.V. panel shown in Figure 11 has a water spray system mounted on top. A pump setup has been used to regulate the water's flow rate. Utilizing the temperature sensor, the water temperature at the input and outlet have been determined. For the summer seasons, respectively, the electrical efficiency of the solar

P.V. system has been examined with and without a cooling system and listed in Table 7. In both Summer and Winter season, the performance of solar panel with cooling system under 2 different flow rates (1lph and 1.5 lph) is measured and compared with conventional SPVPGS which is listed in Table 7 and Table 8 respectively.

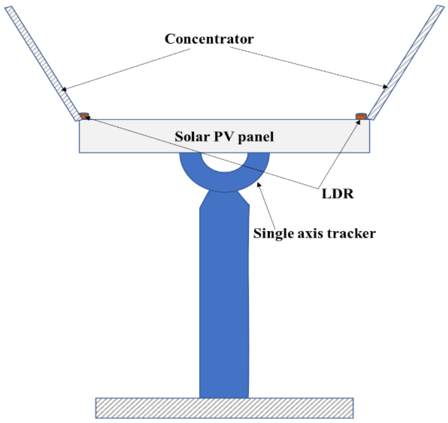


Figure 10. Concentrator with Sun Tracking System

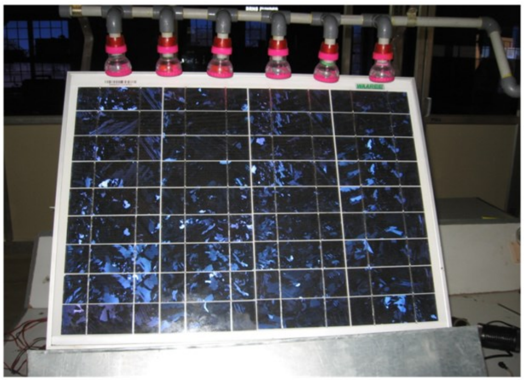


Figure 11. Temperature Cooling System with Conventional Solar Panel

The experimental study depicted in Figure 13 and Figure 14 made it abundantly evident that the water spray system was more effective than the conventional solar P.V. system. The output power of the water spray system is improved by about 6W compared to the conventional system. In order to reduce the impact of temperature and dust on the solar P.V. power production system, the front surface water sprayer system is also utilized to clean the dust accumulation on the solar panel surface. The dust effect also reduces the efficiency of solar panels by up to 60% (K.R.Chairma *et al.*, 2022). Using the proposed system reduces the temperature effect as well as the dust effect.

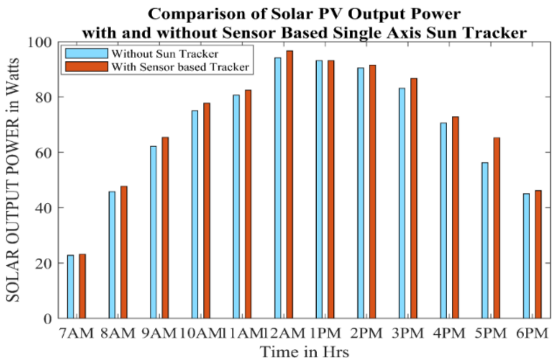


Figure 12. Comparison of Sensor-Based Single-Axis Sun Tracking System with Conventional Solar PV Power Generation System

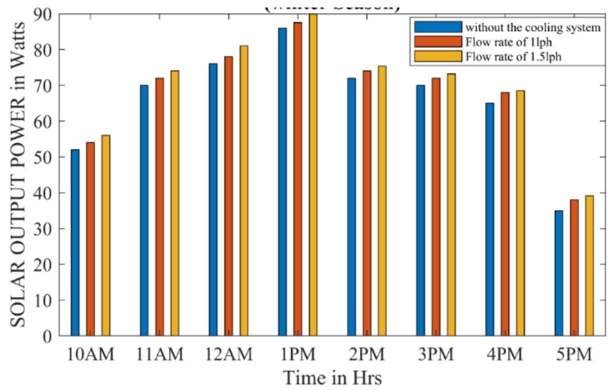


Figure 13. Comparison of Solar Panel Output Power Water Spray System SPVPGS (Winter Season)

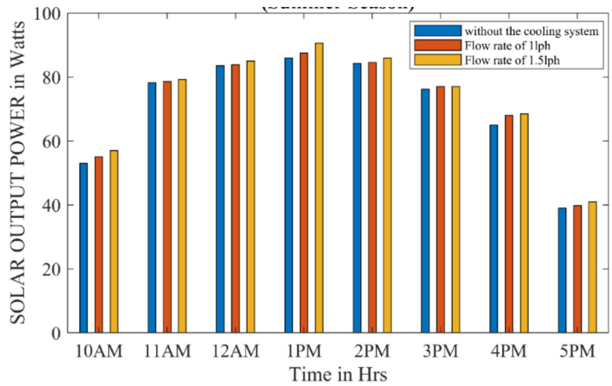


Figure 14. Comparison of Solar Panel Output Power Water Spray System with SPVPGS (Summer Season)

5. Conclusion

Among all renewable energy sources, solar energy provides the most potent defense against the energy problem because it is abundantly available on the Earth's surface. A year's energy needs can be satisfied by the sun's energy in just one minute. India receives five quadrillion kWh of solar energy annually. Over 90% of India receives high solar radiation levels throughout the summer, ranging from 3.0 to 6.5 kWh/m^2 /day. Due to the lower conversion efficiency of solar panels, only 10% of total energy generation in India comes from solar energy. The novelty of this paper lies in its comprehensive approach to evaluating solar panel efficiency by combining simulation and experimental methodologies. It uniquely focuses on quantifying the specific impacts of solar irradiance and temperature on photovoltaic module performance. The study also introduces innovative efficiency enhancement techniques, such as sensor-based sun tracking and active temperature cooling systems, and assesses their practical effectiveness. By integrating these elements, the research provides a more detailed understanding of environmental effects and proposes actionable solutions to mitigate efficiency losses. The experimental validation of these techniques sets this paper apart by demonstrating their real-world applicability and benefits. Using these efficiency enhancement techniques, the efficiency of solar panels increased by up to 12% compared with conventional solar P.V. power generation systems.

Ethical Approval

Not Applicable

Consent to Participate

Not Applicable

Consent to Publish

Not Applicable

Authors Contributions

Conceptualization, Methodology, Resources, Formal analysis, investigation, and Writing - Ms.K. R. CHAIRMA LAKSHMI carried out original draft preparation; Bharath Singh J, Nirmala G., and M.Dinesh Babu carried out supervision, Formal analysis, and Visualization.

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Competing Interests

The authors declare that there is no competing interest

Availability of data and materials

Not Applicable

List of nomenclatures

I_m	-	Solar Panel Output Current in A
P_m	-	Solar Panel Output Power in W
V_m	-	Solar Panel Output Voltage in V
I_{sc}	-	Solar Panel Short Circuit Current in A
G	-	solar Irradiance in W/m^2
T_{mod}	-	solar Module Backside Temperature in °C
V_{oc}	-	Open Circuit Voltage
I_{sc}	-	Short Circuit Current
η	-	Efficiency (%)
T_f	-	Temperature of the Solar Panel Front Surface
T_a	-	Ambient Temperature in °C
P_{ow1}	-	Output Power with a Water Spray Cooling System with a Flow rate of 1 lph
P_{ow2}	-	Output Power with a Water Spray Cooling System with a Flow rate of 1.5 lph
P_{o0}	-	Output Power without a Water Spray Cooling System
T_{iw}	-	Inlet Water Temperature
T_{ow}	-	Outlet Water Temperature
η_{ow1}	-	Efficiency of Solar Panel with Water Spray Cooling System with a Flow Rate of 1 lph
η_{ow2}	-	Efficiency of Solar Panel with Water Spray Cooling System with a Flow Rate of 1.5lph.
η_{oo}	-	Efficiency of Solar Panel without Water Spray Cooling System

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