Experimental Investigation of Photovoltaic Module Performance under Varying Environmental Conditions and Configurations

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Abstract-We conducted a series of experiments to investigate the behavior and performance of photovoltaic (PV) modules under different environmental conditions. Our aim was to gain insights into the factors that influence the performance of PV modules and to optimize their design and operation for various applications in the renewable energy sector.

In the first experiment, we analyzed the I-V and P-V characteristics of PV modules under varying radiation levels. We found that increasing radiation levels led to an increase in the output current and power of PV modules. These findings have important practical implications for the design and optimization of PV systems, as they suggest that increasing the amount of incident radiation can improve the output power of PV modules and, consequently, the overall performance of PV systems in applications such as solar power plants and rooftop solar installations. In the second experiment, we investigated the I-V and P-V characteristics of series and parallel combinations of PV modules. We found that series combinations increase the output voltage, while parallel combinations increase the output current. The configuration of PV modules can be optimized according to the power requirements of the load, with series combinations preferred for high-voltage applications and parallel combinations preferred for high-current applications. In the third experiment, we studied the effect of changes in the tilt angle on the output of PV modules. We found that adjusting the tilt angle of the modules could significantly improve their performance. The performance of PV modules is affected by the incident angle of sunlight, and adjusting the tilt angle of the modules can maximize the amount of incident radiation and improve their output power. An optimal tilt angle can vary depending on the latitude of the installation site. Finally, in the fourth experiment, we evaluated the effect of temperature on the efficiency of the modules. We found that the efficiency of PV modules decreased with increasing temperature levels. Proper thermal management, such as the use of cooling systems, can improve the efficiency of PV modules in high-temperature environments.

In conclusion, our experiments provide valuable insights into the behavior and performance of PV modules under various environmental conditions and configurations. We observed that the performance of PV modules can be optimized by controlling environmental factors such as temperature, radiation, and tilt angle. The configuration of PV modules can also be optimized according to the power requirements of the load. These findings can be useful for designing and optimizing the performance of PV systems for various applications in the renewable energy sector.

I. INTRODUCTION

The demand for renewable energy sources has been growing in recent years, driven by concerns over climate change and the need to reduce greenhouse gas emissions. Solar energy, in particular, has emerged as a promising renewable energy source due to its abundance, availability, and affordability [1]. Solar photovoltaic (PV) technology is a key component of solar power systems and is responsible for converting sunlight into electrical energy. However, the performance of PV modules is affected by various environmental factors, including temperature, radiation, and tilt angle [2].

In this study, we conducted a series of experiments to investigate the behavior and performance of PV modules under varying environmental conditions. The aim of this study was to gain insights into the factors that influence the performance of PV modules and to optimize their design and operation for various applications in the renewable energy sector. The experiments were conducted in a laboratory setting, and the results were analyzed to draw conclusions about the performance of PV modules.

One of the primary factors that affect the performance of PV modules is temperature. As the temperature of a PV module increases, its efficiency decreases due to the decrease in the open-circuit voltage and the increase in the diode saturation current [3]. To investigate the effect of temperature on the efficiency of PV modules, we conducted an experiment where we varied the temperature of the modules while measuring their current-voltage (I-V) and power-voltage (P-V) characteristics. The results showed that the efficiency of the PV modules decreased as the temperature increased, with the efficiency dropping by around 0.07% per degree Celsius increase in temperature. This finding has important implications for the design and operation of solar power systems, as it highlights the need for effective temperature management to optimize the performance of PV modules.

Another factor that affects the performance of PV modules is radiation. The amount of sunlight that a PV module receives can vary depending on the time of day, season and geographic location. To investigate the effect of radiation on the performance of PV modules, we conducted an experiment where we varied the radiation levels while measuring the I-V and P-V characteristics of the modules. The results showed that the efficiency and output power of the PV modules increased with increasing radiation levels, up to a certain point, beyond which further increases in radiation had little effect. This finding highlights the importance of designing solar power systems that can effectively capture and utilize the available solar radiation.

In addition to radiation, the tilt angle of a PV module can also significantly impact its performance. The optimal tilt angle for a PV module depends on the geographic location and the time of year, as it affects the amount of sunlight that the module receives [4]. To investigate the effect of tilt angle on the output of PV modules, we conducted an experiment where we varied the tilt angle and measured the power produced by the module. The results showed that the output of the PV modules varied significantly with changes in tilt angle, with the optimal tilt angle depending on the time of year and the geographic location. This finding has implications for the design and installation of solar power systems, as it highlights the need for careful consideration of the tilt angle to optimize the performance of PV modules. Finally, we investigated the behavior and performance of series and parallel combinations of PV modules by performing an experiment and and measuring their I-V and P-V characteristics. Series combinations of PV modules involve connecting them in a string, while parallel combinations involve connecting them in a parallel circuit [5].

II. EXPERIMENTAL METHOD

A. Experimental set-up

The set-up of the experiment is shown in Fig. 1. The description of the various components is provided as under.

1. Artificial Light Source:- The spectrum of the light source must match the spectrum in which the PV operates. Thus, a halogen lamp is chosen as the light source. The spectrum of halogen compared[6] to the solar spectrum and the spectrum of a blackbody at 5500K is shown in the Fig.2

Further, the intensity of solar radiation in the spectral range of the PV module is 550 W/m^2, this value is the intensity of the solar radiation falling on the PV module. The solar radiation falling on the PV modules is parallel. Thus, instead of one halogen lamp of 1800 W, we use 12 halogen lamps of 150W each. To provide uniform radiation, the modules are arranged in a 4 x 3 aspect ratio.

2. Measuring/Connection Panel:- Various meters like, an Ammeter to measure the current flowing through the circuit, a Voltmeter to measure the potential difference across the PV modules and temperature measurement (Thermocouple) are provided. It also consists of a Charge controller unit and an Inverter of 50W rating to convert DC from the PV module to AC. It also has two Batteries with ratings of 4.5 Ah, 12V each. It also has an AC load and a DC load.

3. PV Module:- Two PV module setups (polycrystalline, of rating 40W, Voc=21.60V, Vm=17.80V, Im=2.25A each). These units may connect in several configurations based on experiments/measurements. Polycrystalline Si was used as a material because polycrystalline Si cell modules are cheap and widely used as rooftop solar power.

*4. Cooling Fan:-*The PV module tends to get heated up in the operation, resulting in a change in efficiency. Thus to cool the modules, a total of 8, DC centrifugal (blower/squirrel-cage) fans are used.

*5. Charge Controller Unit:-*It comprises two parts:

*5.1 Converter unit:-*The system has a DC-DC converter with a power rating of 25 watts, a Nominal voltage of 12V, and a maximum load current rating is 2A. It can run in either Auto or Manual mode as required.

5.2 Data logger-plotter unit:- A data logger-plotter is used for plotting the I-V and P-V characteristics directly to the computer.

B. Experimental procedures & observations

We have done four experiments which are discussed as following-

1. To demonstrate the I-V and P-V characteristics of PV modules with Varying radiation.

1.1 Circuit Diagram:- The circuit diagram for this experiment is shown in Fig. 3(a).

1.2 Experimental procedure:- Firstly, the components of the control board should be identified and connected correctly following the circuit diagram. Next, the module or array output connected to the plotter unit ports that correspond to current and voltage sensors. The plotter unit and the computer also connected using a Serial bus cable (RS-232) to record and store the data obtained from the solar panels.

For setting the radiation level, a pyranometer was used. The average of three readings taken from three different locations on the panel, and radiation level set to 110 W/m2. To obtain the open-circuit voltage (Voc), short-circuit current (Isc), and maximum power point (MPP) of the solar panels, the potentiometer was set to the maximum value, and the values for V=Voc, current I, and power are recorded.

Load was varied using the potentiometer to obtain the I-V and P-V characteristics of the solar panels. After recording of the data I-V and P-V characteristics plotted using the data obtained from the previous steps. This step helped us to visualize the performance of the solar panels under different load conditions.

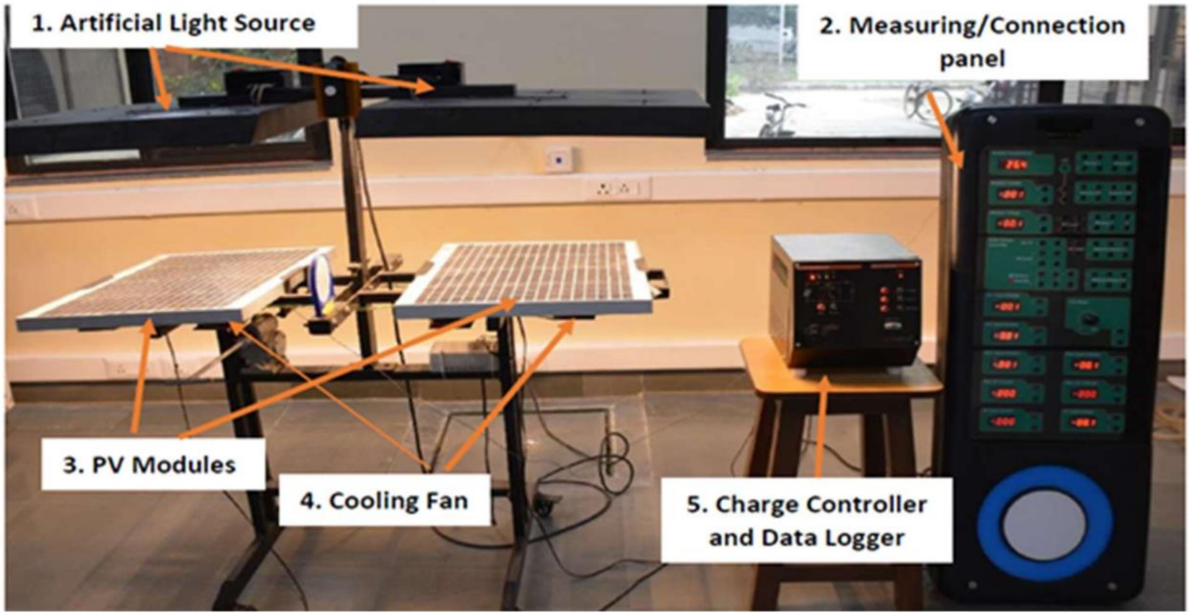

Fig. 1. Experiment setup

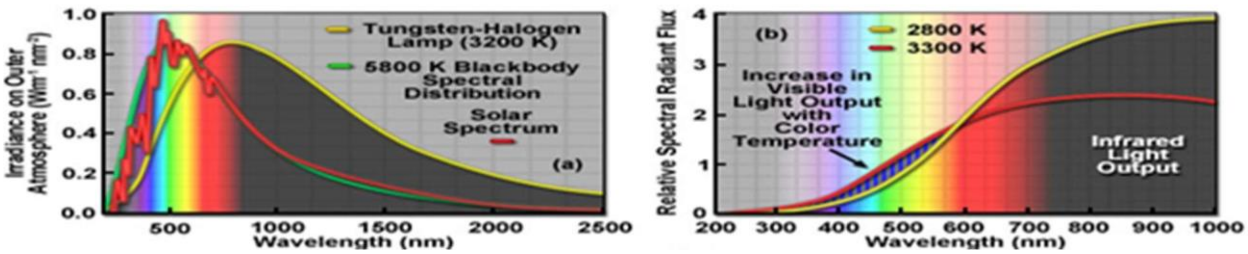

Fig. 2. Spectrum of Halogen lamp

1.3 Observations:-

We took three sets of the following readings:-

Set-1:-Readings are in TABLE I

Set 2 & Set 3:-Data is recorded at 214 and 331 W/m^2 by Data logger which is used for plotting the graph.

2. To demonstrate the I-V and P-V characteristics of series and parallel combinations of PV modules.

2.1 Circuit diagram:- Circuit diagrams for series and parallel connections can be seen in Fig.3(b) & Fig.3(c) repectively.

2.2 Experimental procedure:- To conduct this experiment, the control board connected according to the circuit diagram, once in series and then in parallel. Then, the output from the solar panel module connected to the plotter unit ports related to the current and voltage sensors. The plotter unit and PC connected via a serial bus cable (RS-232 cable). Radiation level was set to an average of approximately 110 W/m^2 using pyranometer (Average of three different locations on the module).

By setting the potentiometer maximum, the open-circuit voltage (Voc), current (I), and power was recorded. Then load varied using the potentiometer, and the I-V and P-V characteristics of the solar panel plotted based on the readings obtained from the previous step. To obtain a more comprehensive understanding of the solar panel's performance under different radiation levels, we repeated the procedure for two more radiation levels: 220 W/m^2 and 330 W/m^2.

2.3 Observations:- Observations for series and parallel connections are taken.

2.3.1 Series:-

Set 1:-Readings are in TABLE II

Set 2 & Set 3:-Data is recorded at 225 and 321 W/m^2 by Data logger which is used for plotting the graph.

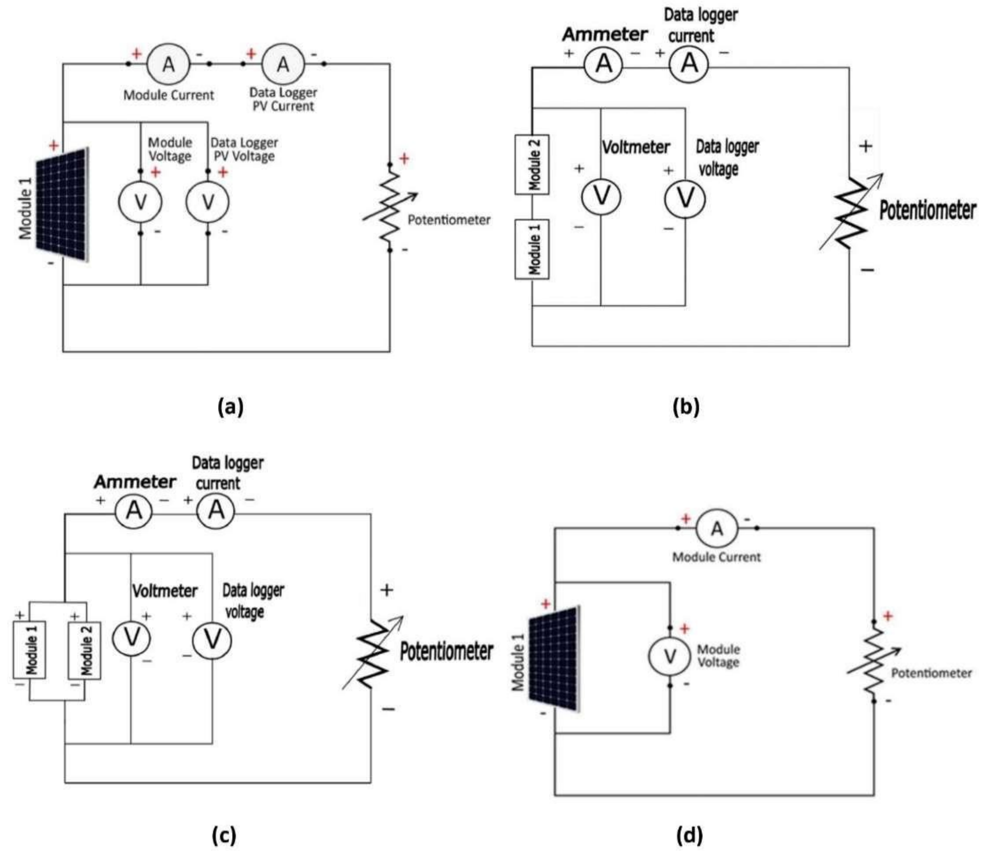

Fig. 3. Circuit diagram for (a) Analyzing various characteristics with varying radiation level, (b) Studying the series connection of modules, (c) Studying parallel connection of modules, (d) Analyzing the effect of tilt angle and increase in temperature on PV module.

Fig. 4. Solar panel installed on the rooftop of Hall-2 IIT Kanpur having a tilt angle of 18.86 degree

2.3.2 Parallel:-

Set-1:- Readings are in TABLE III

*Set 2 & Set 3:-*Data is recorded at 225 and 359 W/m^2 by Data logger which is used for plotting the graph.

3. To demonstrate the effect of change in tilt angle on the output of PV modules.

*3.1 Circuit Diagram:-*Circuit diagram can be seen in Fig.3(d)

TABLE I. Readings for Experiment-1

Sr.No.	Irradiance(W/m^2)	Temperature(C)	Voltage(V)	Current(A)	Power(W)
1	112	22.9	17.6	0.085	1.496
2	112	22.6	17.4	0.087	1.5138
3	112	22.2	17.3	0.088	1.5224
4	112	22	17.3	0.09	1.557
5	112	21.6	17.1	0.092	1.5732
6	112	21.7	17	0.095	1.615
7	112	21.5	16.9	0.097	1.6393
8	112	21.5	16.4	0.104	1.7056
9	112	21.4	15.7	0.112	1.7584
10	112	21.3	15.4	0.114	1.7556
11	112	21.3	14.4	0.122	1.7568
12	112	21.3	13.3	0.126	1.6758
13	112	21.2	12.5	0.127	1.5875
14	112	21.2	11	0.13	1.43
15	112	21.1	9.5	0.13	1.235
16	112	21.1	7.7	0.133	1.0241
17	112	21	6.9	0.133	0.9177
18	112	20.5	6.5	0.133	0.8645
19	112	20.5	6	0.134	0.804
20	112	20.6	4.7	0.134	0.6298
21	112	20.6	3.8	0.134	0.5092
22	112	20.7	1.9	0.135	0.2565
23	112	20.7	0.8	0.135	0.108
24	112	20.6	0.7	0.137	0.0959
25	112	20.5	0	0.138	0

TABLE II. Readings for Experiment-2 (Series connection)

Sr. No.	Irradiance(W/m^2)	Temperature(C)	Voltage(V)	Current(A)	Power(W)
1	110	21.6	25.3	0.06	1.518
2	110	22	25	0.126	3.15
3	110	22.2	24.7	0.125	3.0875
4	110	22.2	24.4	0.127	3.0988
5	110	22.4	23.8	0.126	2.9988
6	110	22.5	23.3	0.126	2.9358
7	110	22.6	23.1	0.128	2.9568
8	110	22.6	22.6	0.127	2.8702
9	110	22.5	21.9	0.127	2.7813
10	110	23.2	21.1	0.13	2.743
11	110	23.2	20.9	0.127	2.6543
12	110	23.4	19.7	0.128	2.5216
13	110	23.5	18	0.129	2.322
14	110	23.6	16.8	0.128	2.1504
15	110	23.7	15.8	0.131	2.0698
16	110	23.7	14.9	0.13	1.937
17	110	23.6	13	0.134	1.742
18	110	23.5	11.7	0.134	1.5678
19	110	24	10.1	0.135	1.3635
20	110	24.1	8.7	0.134	1.1658
21	110	24.2	7.5	0.134	1.005
22	110	24.3	5.6	0.136	0.7616
23	110	24.4	4	0.137	0.548
24	110	24.4	3	0.139	0.417
25	110	24.5	1.3	0.138	0.1794
26	110	24.6	0.9	0.139	0.1251
27	110	24.7	0.1	0.138	0.0138

TABLE III. Readings for Experiment-2 (Parallel connection)

Sr. No.	Irradiance(W/m^2)	Temperature(C)	Voltage(V)	Current(A)	Power(W)
1	113	24	18.2	0.086	1.5652
2	113	24.4	18	0.105	1.89
3	113	24.4	17.9	0.11	1.969
4	113	24.6	17.7	0.13	2.301
5	113	24.7	17	0.174	2.958
6	113	24.6	16.7	0.188	3.1396
7	113	24.9	16.2	0.205	3.321
8	113	24.9	15.8	0.217	3.4286
9	113	25	15.3	0.227	3.4731
10	113	25	14.5	0.241	3.4945
11	113	25.1	13.6	0.251	3.4136
12	113	25.2	12.5	0.256	3.2
13	113	25.3	11.6	0.26	3.016
14	113	25.3	10.5	0.261	2.7405
15	113	25.4	10	0.263	2.63
16	113	25.4	8.3	0.268	2.2244
17	113	25.4	7.7	0.266	2.0482
18	113	25.5	6.5	0.269	1.7485
19	113	25.9	5	0.27	1.35
20	113	25.9	2.2	0.271	0.5962
21	113	25.6	1.5	0.27	0.405
22	113	25.7	0.5	0.274	0.137
23	113	25.7	0.2	0.274	0.0548

Table IV. Readings for Experiment-3

S. No.	Tilt(degree)	Radiation(W/m^2)	Voltage(V)	Current(A)	Power(W)
1	0	328	16.9	0.368	6.2192
2	5	315	16.8	0.365	6.132
3	10	324	16.3	0.352	5.7376
4	15	337	15.2	0.328	4.9856
5	20	347	14.1	0.306	4.3146
6	25	371	13.4	0.289	3.8726
7	30	401	12.3	0.266	3.2718
8	35	398	11	0.237	2.607

Table V. Readings for Experiment-4

Sr. No	Radiation(W/m^2)	Temperature(°C)	Voltage(V)	Current(A)	Power(W)	Efficiency(η)
1	331	21	18	0.352	6.336	9.571
2	331	23	17.9	0.349	6.2471	9.437
3	331	25	17.9	0.345	6.1755	9.329
4	331	27	17.8	0.342	6.0876	9.196
5	331	29	17.7	0.339	6.0003	9.064
6	331	31	17.3	0.33	5.709	8.624
7	331	33	17.1	0.329	5.6259	8.498
8	331	35	17.1	0.326	5.5746	8.421
9	331	37	17.2	0.326	5.6072	8.471
10	331	39	17	0.324	5.508	8.321

3.2 Experimental procedure:- We made the connections as shown in the circuit diagram for the module being tested. Next, an inclinometer placed on the module to measure its angle of inclination. Again, pyranometer was used to set the radiation level to 330 W/m^2.

The load resistance or potentiometer was set to a specific value and not varied once it set. This step ensured that the load resistance is kept constant throughout the testing process. Finally, the tilt angle changed in steps and readings of parameters such as voltage (V), current (I), and power (P) was taken from the voltmeter, ammeter, and wattmeter at every tilt angle being changed.

3.3 Observations:- Readings are in Table IV

4. To demonstrate the Effect of Temperature on the Efficiency of the module.

4.1 Circuit Diagram:- Circuit diagram can be seen in Fig.3(b) (same circuit diagram as for Experiment-3)

4.2 Experimental procedure:- We made the connections as per the above circuit diagram for module-2. After making the connections, we set the average radiation ≅ 331 W/^ by taking the readings from 3 locations on the panel: { Top + Middle + Bottom }/3 using a pyranometer. Set the load resistance (potentiometer) setting to a Specific value & note down the readings of V and I with every change in temperature.

4.3 Observation:- Readings are in Table V

III. RESULTS & ANALYSIS

Results and analysis for all four parts of experiments are as follows-

1. To demonstrate the I-V and P-V characteristics of PV modules with Varying radiation and temperature level.

Results:- In this experiment, we investigated the I-V and P-V characteristics of a photovoltaic (PV) module under varying levels of radiation. The PV module used for this experiment had a maximum power output of 40 W.

The I-V and P-V characteristics of the PV module showed a clear dependence on the radiation and temperature levels. As the radiation level increased, the maximum power output of the PV module also increased, while the open-circuit voltage remained relatively constant. At the highest radiation level of 331 W/m^2, the maximum power output of the PV module was 6.3 W, while the open-circuit voltage was 18 V. We also plotted various graphs like Isc, Voc, F.F., Pmax & Efficiency vs Radiation level which are shown in Fig. 5.

Analysis:- The current generated by a solar PV module is directly proportional to the amount of incident radiation & efficiency also increases as the solar radiation increases. As the intensity of solar radiation increases, more photons are available to be absorbed by the module, resulting in more electrons being excited and generating a higher electrical current. Solar PV modules are most efficient when exposed to high levels of solar radiation.

The open-circuit voltage (Voc) of a solar PV module increases with increasing radiation intensity due to more available energy to excite electrons. The trend is shown by the I-V curve and is subject to various factors such as temperature and shading. However, the maximum power point voltage (Vmpp) limits the amount of voltage that can be generated.

The fill factor (FF) of a solar PV module generally decreases as the radiation level increases due to changes in the resistance and temperature of the module. However, the exact dependence of FF on radiation level can vary depending on various factors such as shading, cell quality, and module design.

2. To demonstrate the I-V and P-V characteristics of series and parallel combinations of PV modules.

Results:- Comparing the I-V and P-V curves of the series and parallel combinations, we observed that the series combination had a higher maximum power output than the parallel combination. This is because the series combination had a higher open-circuit voltage, which allowed for a higher power output at the peak of the P-V curve. However, the parallel combination had a higher short-circuit current, which made it more suitable for applications where a high current is required.

We also showed variations of other parameters like I-V, P-V characteristics and Isc, Voc, F.F., Pmax, Efficiency vs Radiation level for Series and Parallel in Fig. 6 & Fig. 7 respectively.

Analysis:- Short circuit current (Isc) increases in parallel connection because more solar energy is captured by the multiple modules working together, resulting in a higher output current. In contrast, in a series connection, the current is limited by the lowest current of the individual modules, so increasing the number of modules in a series does not increase the output current. Instead, the voltage increases as the modules are connected end-to-end, resulting in a higher output voltage.

In a series connection of solar panels, the maximum power transfer occurs when the load resistance is equal to the equivalent resistance of the series connection, and the efficiency is lower than that of a parallel connection. In a parallel connection of solar panels, the maximum power transfer occurs when the load resistance is equal to the equivalent resistance of the parallel connection, and the efficiency is higher than that of a series connection. However, the choice between the series and the parallel connection depends on the specific application and requirements of the solar PV system.

3. To demonstrate the effect of change in tilt angle on the output of PV modules.

Result:- In our analysis we saw that power is maximum (Approx 6W) when the tilt angle is zero degree and it decreased as the angle is increasing, can be seen in Fig. 8. By this data we inferred that output of the PV modules varied with the time of day and the season. During the summer months, the output of the PV modules was highest at noon, while during the winter months, the output was highest in the early afternoon. This is because the sun's angle changes throughout the day and throughout the year, and the optimal tilt angle changes with it.

*Analysis:-*The power output of a solar PV system is influenced by the tilt angle of the solar panel. The optimal tilt angle is determined by several factors and can be calculated using solar geometry equations or software tools. The power output increases with the tilt angle up to a certain point and then decreases due to overheating and reduced efficiency, resulting in a bell-shaped curve. In our setup, the halogen lights (Artificial sun) is fixed at 0 degree and the solar modules are tilted.

The trend of power output with tilt angle can be explained using a polynomial regression equation. This equation can be found by fitting a polynomial curve to the given data points using regression analysis. The resulting equation could be used to predict the power output for any given tilt angle. However, without more context and information, it is not possible to provide a specific equation. We tried to fit a curve for regression using Python, which is shown in Fig. 9.

4. To demonstrate the Effect of Temperature on the Efficiency of the module.

Result:- The results showed that as the temperature of the solar PV module increased, the efficiency of the module decreased which can be seen in Fig. 10. Specifically, when the module was tested at a temperature of 21°C, the efficiency was measured to be 9.5%. However, as the temperature of the module increased to 39°C, the efficiency decreased to 8.3%. The data collected from the experiment revealed a clear negative correlation between temperature and efficiency, with the efficiency decreasing by approximately 0.07% per degree Celsius increase in temperature. The decrease in efficiency was mainly due to the decrease in the open-circuit voltage of the module as the temperature increased.

Analysis:- The output power of a solar panel decreases as its temperature increases. This is because the bandgap energy of the semiconductor material widens at higher temperatures, reducing its ability to absorb solar radiation and lowering efficiency and power output. Increased temperature increases the internal carrier recombination rates. Additionally, higher temperatures can increase the resistance of the conductive pathways, further reducing power output.

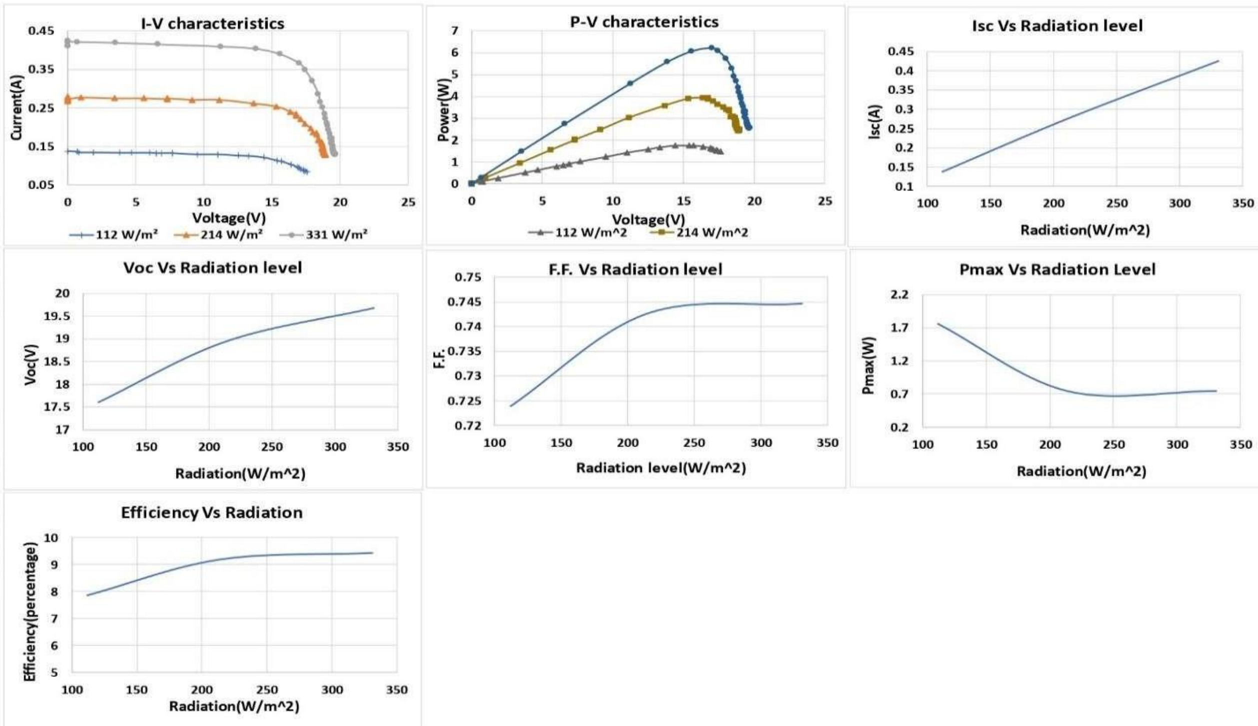

Fig. 5. Plots for the various parameters for variation in radiation level.

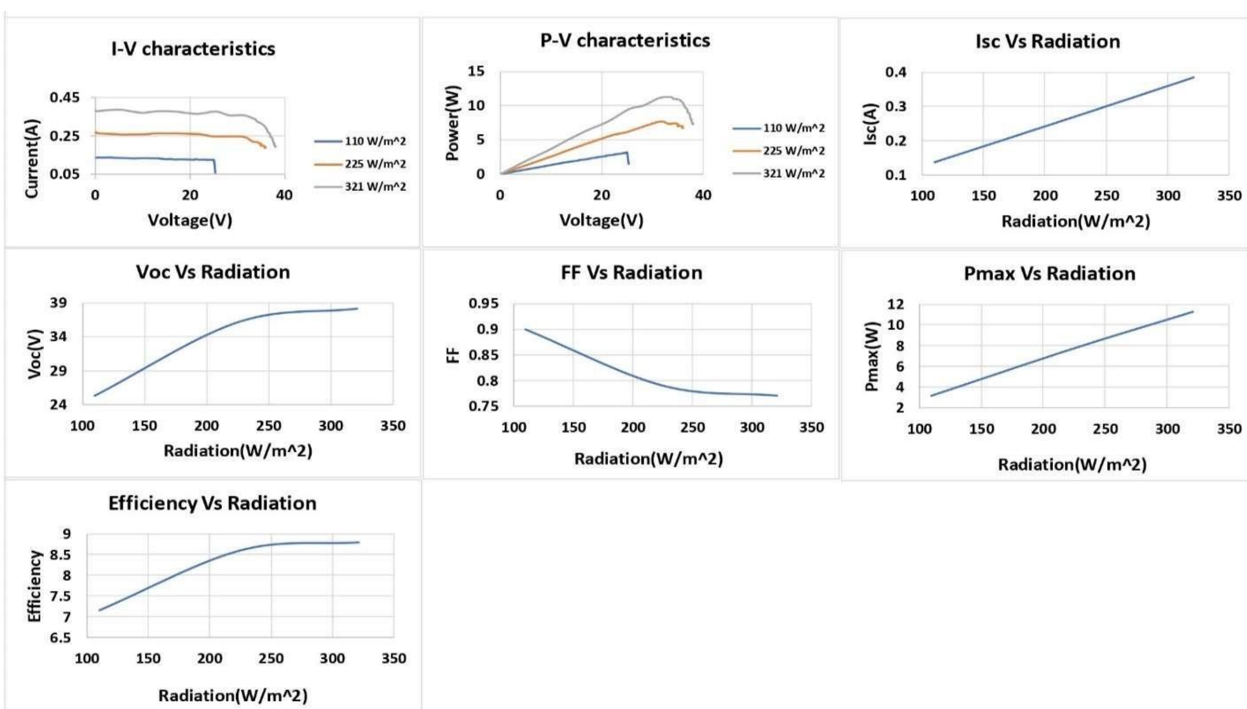

Fig. 6. Plots for the various parameters for variation in radiation level in series connection of modules

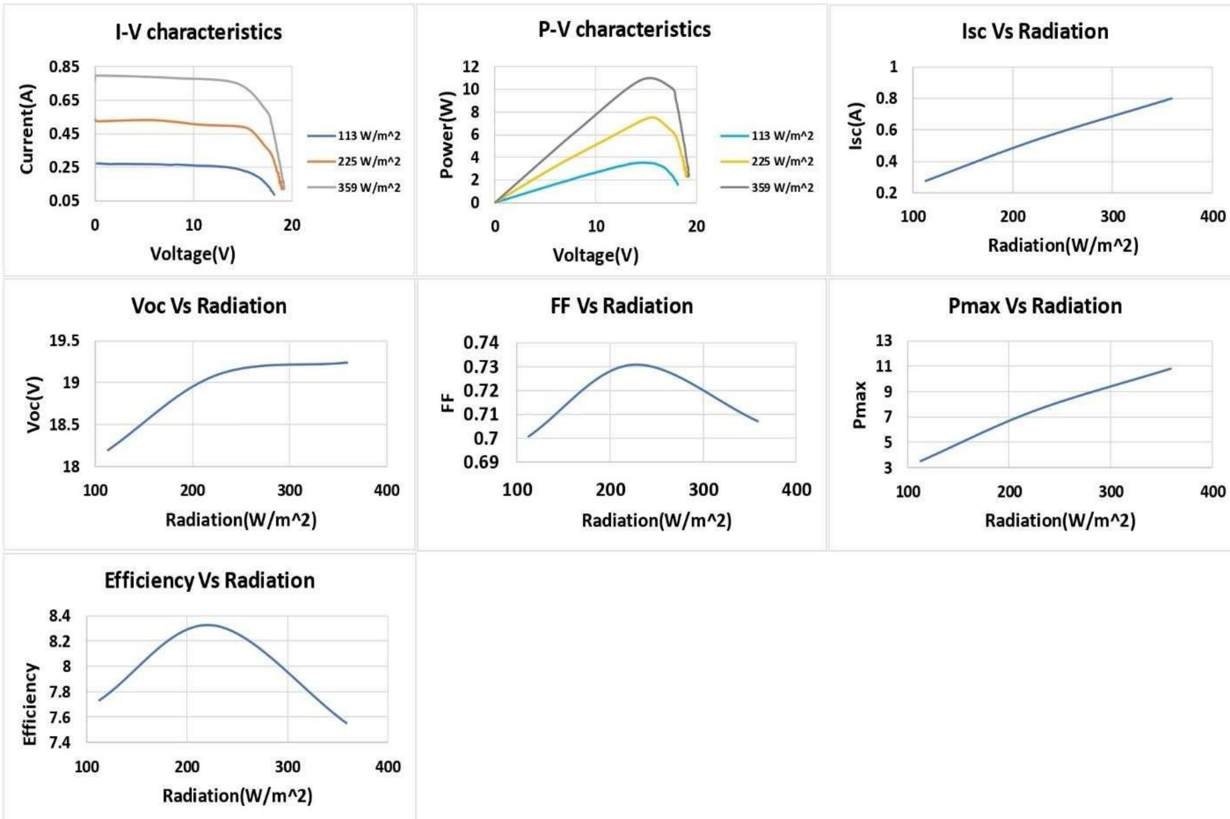

Fig. 7. Plots for the various parameters for variation in radiation level in parallel connection of modules

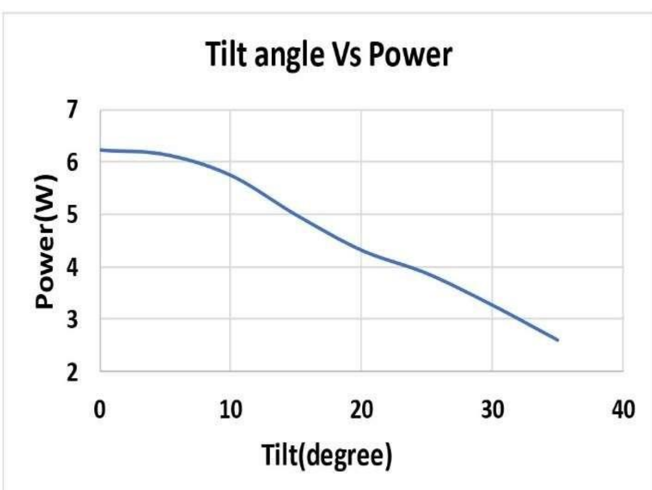

Fig. 8. Tilt angle and power output variation

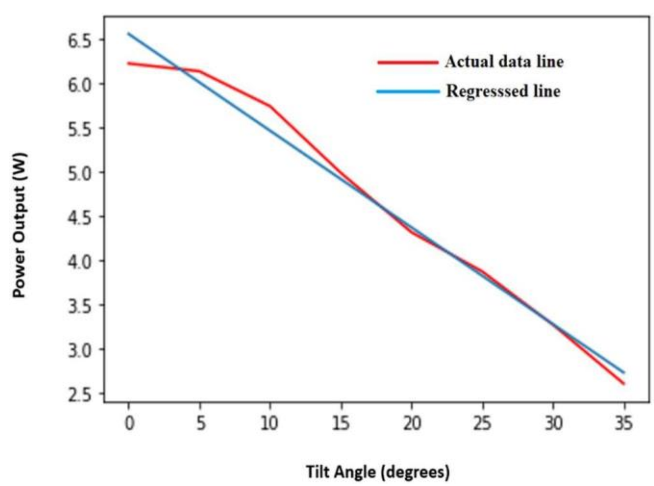

Fig. 9. Curve fitting of power vs tilt angle trend

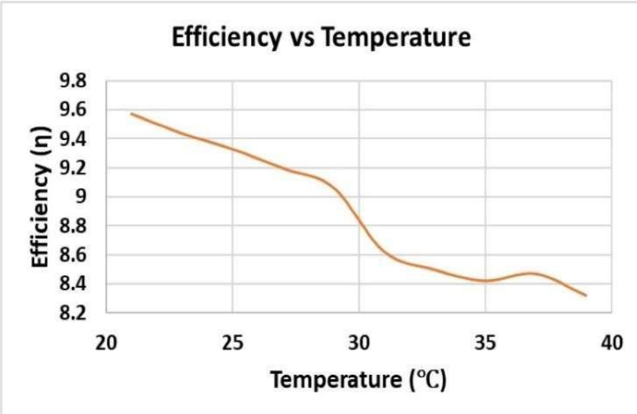

Fig. 10. Variation of efficiency with temperature of modules

IV. CONCLUSION

The experimental study conducted on photovoltaic (PV) modules highlights that the performance of PV systems can be optimized by controlling environmental factors such as temperature, radiation, and tilt angle. The study found that temperature significantly affects the efficiency of PV modules, with efficiency decreasing as temperature increases. Proper thermal management, such as cooling systems, can improve the efficiency of PV modules in high-temperature environments. Radiation levels also affect the performance of PV modules, with increasing radiation levels leading to an increase in the output current and power of PV modules. However, the performance of PV modules decreased with increasing temperature levels. Therefore, controlling the temperature and radiation levels can optimize the performance of PV modules, particularly in regions with high temperatures and low radiation levels.

The study also found that the configuration of PV modules can be optimized according to the power requirements of the load. Series combinations increase the output voltage, while parallel combinations increase the output current. Thus, the configuration of PV modules can be optimized according to the power requirements of the load, with series combinations preferred for high-voltage applications and parallel combinations preferred for high-current applications. The tilt angle of a PV module can significantly impact its performance. Adjusting the tilt angle of the modules can significantly improve their performance. The performance of PV modules is affected by the incident angle of sunlight, and adjusting the tilt angle of the modules can maximize the amount of incident radiation and improve their output power. An optimal tilt angle can vary depending on the latitude of the installation site.

In conclusion, the study has important implications for the design and operation of solar power systems. Effective temperature management, consideration of radiation levels, and careful consideration of the tilt angle are essential for optimizing the performance of PV modules. Additionally, the configuration of PV modules can be optimized according to the power requirements of the load. These findings can be useful for designing and optimizing the performance of PV systems for various applications in the renewable energy sector. Future research can explore the use of new materials and technologies for PV modules and investigate their performance under different environmental conditions.

V. ACKNOWLEDGEMENT

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