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PERFORMANCE ANALYSIS OF SOLAR PHOTOVOLTAIC SYSTEMS UNDER VARIABLE ENVIRONMENTAL CONDITIONS

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ABSTRACT

In this study, the performance of a solar photovoltaic crystalline silicon system is evaluated under different environmental conditions. The primary aim was to study the effect of solar irradiance, ambient temperature, PV panel temperature, relative humidity, wind speed and dust condition on PV power output, PV power conversion efficiency and PV performance ratio. The outdoor operating conditions were recorded, such as the voltage, current, power output, irradiance, temperature, humidity, wind speed, and dust level. The results indicated that solar irradiance was found to be the most significant factor among the various factors studied for PV power generation. The maximum irradiance obtained was 910 W/m2, recorded at 01:00 PM and when the maximum power output was obtained at 199.12 W. The maximum conversion efficiency of the panel was however obtained at 09:00 AM when the panel temperature was low of 14.67%. The PV efficiency decreases with the excessive heating as the highest panel temperature of 58.3°C was recorded with the lowest efficiency of 13.68%. The increases in dust accumulation, relative air humidity also contributed to the loss in performance and the wind speed had a moderate cooling effect. The highest energy generation and highest performance ratio was observed during clear sky conditions as observed on a daily basis. The study concludes that to achieve the best performance of solar PV under real environmental conditions regular cleaning, appropriate ventilation, installation angle and constant monitoring are necessary.

1. Introduction

Renewable energy has emerged as a keyway of decreasing reliance on fossil fuels and lowering the environmental footprint of traditional energy production. Solar PV technology has attracted a lot of interest among renewable energy technologies, as it directly generates electricity from sunlight and can be utilized for domestic, commercial, agricultural and industrial purposes. Solar PV is seen as appropriate for sustainable energy development due to its cleanliness, scalability and decreasing costs. But PV system performance is closely related to the system's technological design and operating conditions, so performance analysis is critical not only for maximizing energy production but also for enhancing system reliability. (Al-Shahri et al., 2021)

The PV cells used in solar PV systems convert solar radiation to electrical power via semiconductors. The photons strike the PV cells, causing the electrons to become excited, and producing direct current (DC) electricity which can be converted into alternating current (AC) via an inverter. They're commonly found on rooftops, solar farms, water pumping stations, street lighting, and grid-connected power generation. As PV technology has developed, the demand for understanding the behavior of PV has grown beyond just the standard laboratory ratings and into the field. (Aslam et al., 2022)

Environmental factors like solar irradiance, ambient temperature, panel temperature, relative humidity, wind speed and variations in weather, as well as dust, have a significant impact on the performance of solar PV modules. These factors vary continuously during the day and affect the quantity of sun energy received by the module under real outdoor conditions. Thus, the output of a PV system can vary from its rated capacity. Knowing these factors is crucial to forecasting system performance and to make the energy generation more efficient. (Jathar et al., 2023)

The technology of solar PV has matured over the years and made significant advancements in crystalline silicon PV modules, thin film PV technologies, and advanced PV materials. Despite all these enhancements however, real operating conditions still produce performance losses. PV modules are typically tested at standard test conditions (STC) while field conditions are not always uniform. The output of the power and the conversion efficiency will be affected by variations in irradiance, temperature and atmospheric conditions. Thus, a field-based assessment of the actual performance of PV systems is required to determine their actual performance. (Parida et al., 2011)

Solar PV energy systems have one of the greatest problems in maintaining constant energy output in the face of variable environmental and operating conditions. High module temperature, low insolation, dust accumulation, shading and system losses can lead to a decline in PV output. All these problems have an impact on the overall energy yield and can limit the economic advantage of PV installation. Therefore, optimization of solar PV system is important to enhance the performance, lower the losses and efficient utilization of solar energy resources. (Soomar et al., 2022)

PV modules can also suffer from long-term reliability and degradation problems in addition to the short-term environmental impacts. The durability and operational stability of the modules may be impacted by continuous exposure to sunlight, high temperature, humidity, dust and other environmental stresses. Such conditions can lower the ratio of performance and long-term energy generation of the system. So, performance monitoring is crucial not only to analyse the output of the day but also to understand how the performance changes and degrades over time, to assess reliability. (Alimi et al., 2022)

PV performance monitoring and prediction is now enjoying new opportunities thanks to recent advances in artificial intelligence and data-driven energy systems. Environmental and electrical parameters can be analyzed by the intelligent tools and this aids in the identification of performance losses, detection of faults, and to assist in energy management. These methods can be applied to enhance the reliability of renewable energy systems, particularly in cases where the environment is subject to change. This also emphasizes the need to gather precise field data for further predictive analysis and performance optimization. (Ahmad et al., 2021)

In addition, solar PV systems need to be integrated into power networks and the energy production from these needs to be reliable and predictable. Solar energy is intermittent, meaning that power generation can fluctuate with changes in weather conditions and/or sun availability. Therefore, it is crucial to be able to assess PV performance under real environmental conditions for planning, grid integration and energy management. This knowledge of the effects of the environmental conditions on PV output can be used to enhance the reliability of renewable energy generation systems. (Mlilo et al., 2021)

The primary issue in this research is the variability of PV performance due to environmental changes, which result in lower power output, conversion efficiency and system performance. PV modules are rated under standard conditions, but outdoor conditions change and affect their performance in the field. Therefore, it is necessary to perform a real-time PV performance analysis with environmental and electrical parameters. The overall objective of this study is to compare the performance of solar photovoltaic system in different environmental conditions by measuring the various parameters like irradiance, temperature, humidity, wind speed, dust condition, voltage, current, power output, efficiency and performance ratio. (Maka & Alabid, 2022)

This study is important because of its practical applications in solar PV installation, operation and maintenance. The study can help inform more effective cleaning schedules, ventilation, installation practices and ongoing monitoring strategies, if the main environmental factors that impact the PV are identified. The results achieved can be used to optimize the output of PV power, minimize losses in PV performance, and make PV systems in practice more reliable. Performance analysis is crucial for enhancing the sustainability and performance of solar energy systems in the long term. (Said et al., 2018)

2. Methodology

2.1 Study Design

The study is experimental and analytical in nature, where the performance evaluation of a solar PV system under variable environmental conditions has been done. The primary aim of the study was to analyze the impact of varying solar irradiance, ambient temperature, PV panel temperature, relative humidity, wind speed and dust accumulation on the PV power output and efficiency. The study was based on observation of the system under actual outdoor conditions to draw practical performance changes. The study examined both environmental and electrical parameters to determine the major factors responsible for the fluctuation in performance of the solar PV.

2.2 Description of PV System

For this study, a crystalline silicon solar photovoltaic module was chosen because it is a solar module of high use in solar energy applications, and it is well known to be working well under various climatic conditions. The PV system comprised a PV panel, inverter, mounting structure, connecting cables, sensors and data logging unit. The solar panel was placed in an open space where it is not shaded by any other structures, trees, or objects. This way the panel was given the most solar radiation during the observation period. The panel was mounted on a structure that allowed it to be oriented at an appropriate angle towards the sun to maximize sunlight capture, and the direct current produced by the solar panel was converted into alternating current via an inverter for use or further analysis.

2.3 Parameters Measured

Solar irradiance, ambient temperature, PV panel temperature, relative humidity, wind speed, dust condition, output voltage, output current and power output were measured as the environmental and electrical parameters in this study. Solar irradiance was measured to find out the solar radiation received by the PV module. Ambient/panel temperature readings were taken to investigate the impact of heat upon PV efficiency. Relative humidity and wind speed were measured since they affect the air conditions and the cooling rate of the panels. Dust condition was monitored to determine the amount of reduction in the absorption of sunlight due to dust contamination on the surface. The voltage and current output were measured to determine the actual power output of the system.

2.4 Data Collection Procedure

Data were gathered with the outdoor operation in the study period with regular time interval. Environmental parameters like solar irradiance, temperature, humidity, wind speed and dust condition were measured with suitable sensors. Direct measurement of electrical parameters such as voltage and current was taken from the PV system with measuring instruments or a data logging system. All the readings were presented in tabular presentation for systematic analysis. Data collected were carefully reviewed and eliminated for abnormal or incorrect values resulting from shading, sensor error, a temporary disturbance in the system or other external disturbances before analysis was performed. This helped to increase the validity and reliability of the evaluation of the performance.

2.5 Performance Analysis

The output power, conversion efficiency and performance ratio were used to assess the performance of the PV system. These parameters were estimated to find out the actual electrical production, energy conversion capacity and overall operational efficiency of the solar PV system under various environmental conditions.

The output power of the PV system was calculated as:

$$P = V \times I$$

where P is the output power in watts, V is the output voltage in volts, and I is the output current in amperes.

The conversion efficiency of the PV module was calculated as:

$$\eta = \frac{P_{out}}{G \times A} \times 100$$

where η is the conversion efficiency, P_{out} is the output power of the PV module, G is the solar irradiance, and A is the area of the PV panel.

The performance ratio was calculated as:

$$PR = \frac{E_{actual}}{E_{expected}} \times 100$$

where PR is the performance ratio, E_{actual} is the actual energy generated by the PV system, and $E_{expected}$ is the expected energy output under standard conditions. These calculations enabled PV performance evaluation under varying environmental conditions and the major factors affecting the efficiency of these systems were determined.

2.6 Data Analysis

The data collected were analysed with the help of Microsoft Excel or any other statistical software available. The data was structured to enable environmental conditions to be compared with the performance of the PV system on electrical parameters. The relationships between energy output and solar irradiance, efficiency and temperature, and dust condition and energy output were prepared in the form of graphs. These plots facilitated the understanding of the trends and variations of the PV performance with respect to various environmental conditions. The findings from the analysis have been used to identify the primary environmental factors that impact solar PV performance and to identify recommendations for enhancing PV performance through proper installation practices, regular cleaning and continuous monitoring.

3. Results

The results were prepared by analysing the environmental and electrical parameters measured during the study, and they were prepared in accordance with the methodology. The performance of the crystalline silicon PV module was measured in the outdoor environment with the help of solar irradiance, ambient temperature, panel temperature, relative humidity, wind speed, dust condition, output voltage, output current, power output, conversion efficiency and performance ratio. The parameters are directly related to the methodology sections of measured variables, data collection, performance analysis, and data analysis.

3.1 Environmental Data Observation

There was variation in the environmental data over the course of the observation period. The solar irradiance rose slowly from the morning to midday and then dropped during the afternoon. Also, as irradiance increased, so did ambient temperature, panel temperature, and the relative humidity was higher during the morning and lower during the peak hours of sunlight. The wind speed varied moderately and helped to cool the wind temperature of the wind panels in some parts. Dust condition was observed visually and classified as low or moderate. The observed environmental conditions such as solar irradiance, ambient temperature, panel temperature, relative humidity, wind speed and dust condition are presented in Table 1 during the study period.

Table 1. Observed Environmental Conditions

Time	Solar Irradiance W/m²	Ambient Temperature °C	Panel Temperature °C	Relative Humidity %	Wind Speed m/s	Dust Condition
09:00 AM	420	27.2	32.5	68	1.2	Low
10:00 AM	590	29.1	38.4	61	1.5	Low
11:00 AM	735	31.3	45.2	54	1.8	Low
12:00 PM	860	33.5	52.6	47	2.1	Moderate
01:00 PM	910	35.0	58.3	43	2.4	Moderate
02:00 PM	780	34.2	55.1	46	2.0	Moderate
03:00 PM	620	32.4	48.7	52	1.7	Moderate
04:00 PM	455	30.1	39.6	59	1.4	Moderate

Among all the times, the maximum solar irradiance was obtained at 01:00 PM at 910 W/m². Meanwhile, the maximum temperature of the panel was 58.3°C, which shows that the solar radiation was higher the greater the thermal load on PV module. Relative humidity inversely changed with temperature and irradiance, with the highest level occurring at 09:00 AM and the lowest level at 01:00 PM. The hourly variation of solar irradiance, ambient temperature and panel temperature are shown in figure 1 during the observation period.

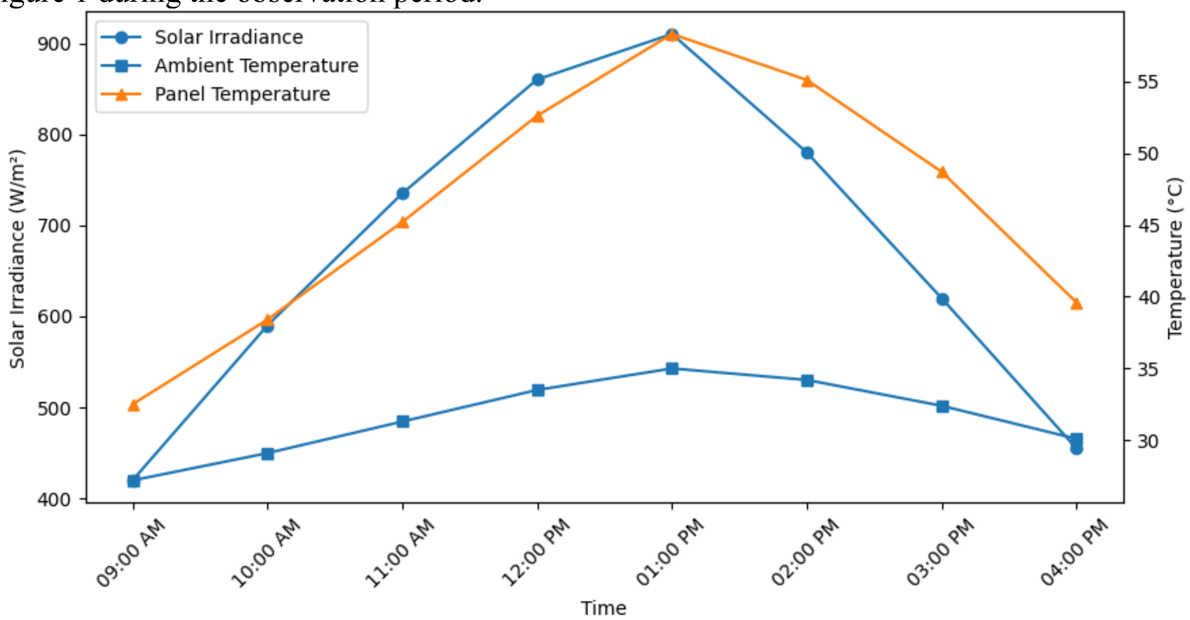

Figure 1. Variation of solar irradiance, ambient temperature, and panel temperature with time

3.2 Electrical Performance of the PV System

The PV system voltage, current and power output were used to evaluate the electrical output of the PV system. The current increased greatly with the solar irradiance, and the voltage varied little. There was a little drop in voltage during peak temperature values. The power output was determined from the values of voltage and current measured. The electrical output of the PV system has been displayed in terms of output voltage, output current and power output for various time intervals in Table 2.

Table 2. Electrical Output of the PV System

Time	Output Voltage V	Output Current A	Power Output W
09:00 AM	31.8	3.10	98.58
10:00 AM	31.5	4.35	137.03
11:00 AM	31.2	5.40	168.48
12:00 PM	30.8	6.25	192.50
01:00 PM	30.4	6.55	199.12
02:00 PM	30.7	5.75	176.53
03:00 PM	31.0	4.60	142.60
04:00 PM	31.4	3.35	105.19

Maximum output power was 199.12W at 01:00 PM when the highest value of irradiance was recorded. The lowest output of power was 98.58 W at 09:00 AM as the irradiance was lowest at that time. The results indicated that output current was significantly affected by the irradiance while the voltage had a relatively constant level but slightly decreased under high panel temperature.

3.3 Effect of Solar Irradiance on Power Output

PV power generation was directly affected by the solar irradiance. The output current and the power output also increased as the irradiance increased. This has been deduced as solar irradiance as the main parameter controlling the electrical output of the PV system. As shown in Table 3, the solar irradiance range vs. the average PV power output shows that the higher the solar irradiance range, the better the PV solar power performance.

Table 3. Relationship Between Solar Irradiance and Power Output

Solar Irradiance Range W/m²	Average Power Output W	Performance Level
400–500	101.89	Low
501–650	139.82	Moderate
651–800	172.51	Good
801–950	195.81	High

The mean power output was raised from 101.89 W (in the irradiance range of 400–500 W/m²) to 195.81 W (in the irradiance range of 801–950 W/m²). This means that the irradiance has a positive correlation with the power generation of the PV. Thus, the greater the solar radiation the better was the energy generating capacity of the system.

3.4 Effect of Panel Temperature on Conversion Efficiency

The conversion efficiency was determined by taking the output power, solar irradiance and panel area. For this analysis, the effective panel area was considered as 1.6 m². The increase in power output with increasing irradiation was offset by a decrease in conversion efficiency with excessive irradiation temperatures. The results of the effect of panel temperature on PV efficiency are shown in table 4, where the panel temperature, solar irradiance, power output, and conversion efficiency are compared.

Table 4. Effect of Panel Temperature on PV Efficiency

Time	Panel Temperature °C	Solar Irradiance W/m²	Power Output W	Efficiency %
09:00 AM	32.5	420	98.58	14.67
10:00 AM	38.4	590	137.03	14.52
11:00 AM	45.2	735	168.48	14.33
12:00 PM	52.6	860	192.50	13.99
01:00 PM	58.3	910	199.12	13.68
02:00 PM	55.1	780	176.53	14.15
03:00 PM	48.7	620	142.60	14.38
04:00 PM	39.6	455	105.19	14.45

The maximum efficiency was found to be 14.67% at 09:00 AM with moderate temperature of the panel. The lowest efficiency was found at 01:00 PM (with a panel temp. of 58.3°C). This indicates that conversion efficiency was lowered due to higher panel temperature, primarily because of the minimal drop in output voltage under the thermal stress condition.

3.5 Effect of Humidity and Dust Condition

The effects of relative air humidity and dust condition also affected PV performance. Increased Humidity in the morning and evening and moderate dust condition from midday onwards. The accumulation of dust over the surface of the panels lowered the amount of sunlight the panels could absorb, and moisture impacted the amount of solar radiation that could pass through the atmosphere. The results presented in Table 5 demonstrate the effect of relative humidity and dust condition on PV performance and how this affects the power output and efficiency.

Table 5. Effect of Humidity and Dust on PV Performance

Time	Relative Humidity %	Dust Condition	Power Output W	Efficiency %
09:00 AM	68	Low	98.58	14.67
10:00 AM	61	Low	137.03	14.52
11:00 AM	54	Low	168.48	14.33
12:00 PM	47	Moderate	192.50	13.99
01:00 PM	43	Moderate	199.12	13.68
02:00 PM	46	Moderate	176.53	14.15
03:00 PM	52	Moderate	142.60	14.38
04:00 PM	59	Moderate	105.19	14.45

The results indicate that during the daytime, the power output was high because of a high irradiance, but the efficiency declined due to the high panel temperature and moderate dust condition. This means that dust and humidity did not have as large an impact on power output as did irradiance but did have some impact on power output losses.

3.6 Daily Energy Generation and Performance Ratio

The performance ratio was used to assess the ratio of the actual to the expected energy output at standard operating conditions. The performance ratio was used to evaluate the overall performance of the PV system. The daily energy production and performance ratio of the PV system are given in Table 6 for various weather conditions.

Table 6. Daily Energy Generation and Performance Ratio

Day	Weather Condition	Average Irradiance W/m²	Actual Energy kWh	Expected Energy kWh	Performance Ratio %
Day 1	Clear sky	720	1.42	1.68	84.52
Day 2	Partly cloudy	610	1.18	1.49	79.19
Day 3	Clear sky	760	1.51	1.76	85.80
Day 4	Dusty condition	690	1.25	1.61	77.64
Day 5	Humid condition	580	1.09	1.40	77.86

Day 3 was the highest energy generation with 1.51 kWh of actual energy generation and a performance ratio of 85.80%. This was attributed to clear sky and a higher average of irradiance. On Day 5 the actual energy generation was the lowest, at 1.09 kWh, primarily because of the humid weather and reduced levels of irradiance. The performance ratio was 77.64% on Day 4 which is the lowest performance ratio, indicating that dust accumulation resulted in a significant performance loss. The comparison of actual and expected energy generation and performance ratio of PV system under various weather condition is shown by figure 2.

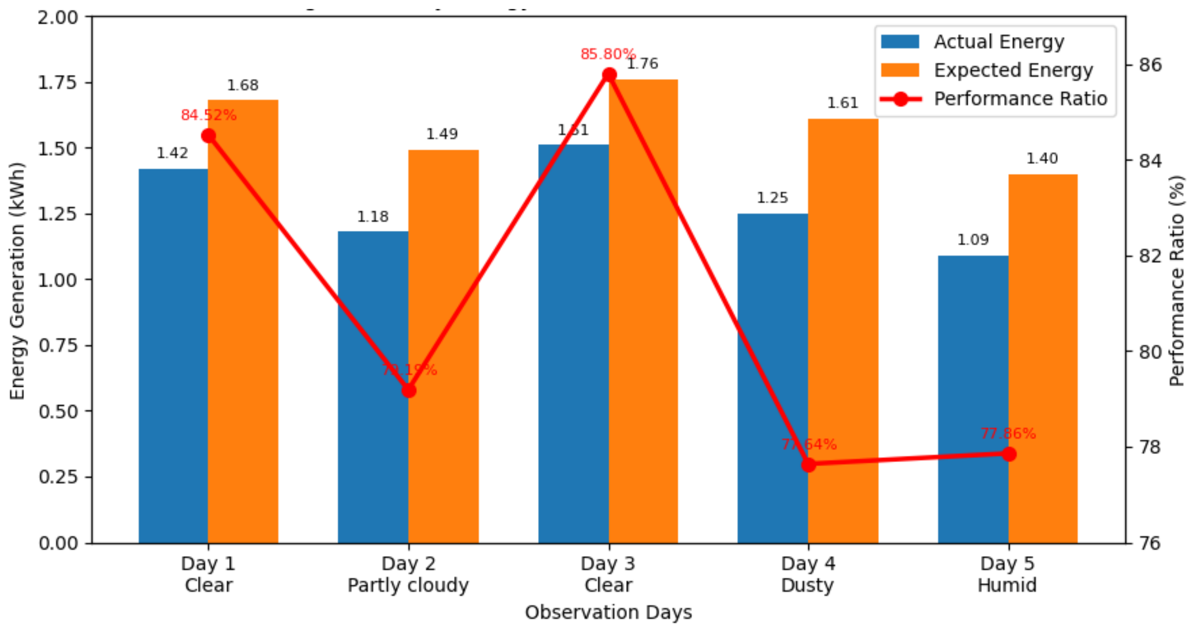

Figure 2. Daily energy generation and performance ratio under different weather conditions

3.7 Summary of Influencing Factors

Overall analysis revealed that the highest influence on power output was solar irradiance. The conversion efficiency was highly dependent on panel temperature and dust accumulation, and humidity were the factors that reduced the conversion efficiency. The moderate positive effect was due to wind speed which assisted the cooling of the panel surface. Figure 3 displays the comparative effect of the environmental factors on the PV performance which shows that the solar irradiance contributed the most to the PV performance, followed by panel temperature and dust condition.

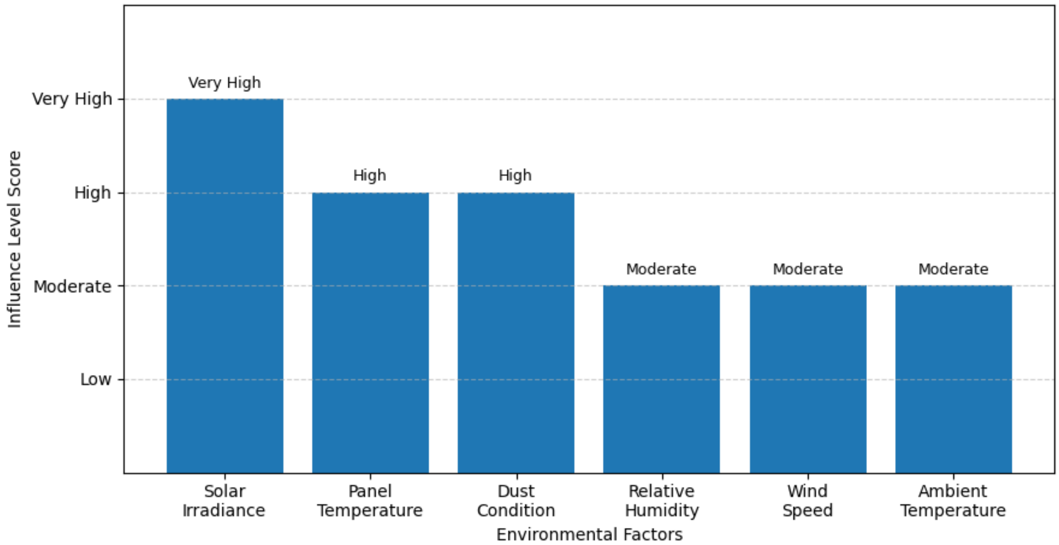

Figure 3. Comparative influence of environmental factors on PV performance

Table 7 summarizes the major factors affecting PV performance and their observed level of influence on the system.

Table 7. Summary of Factors Affecting PV Performance

Factor	Observed Effect on PV System	Level of Influence
Solar irradiance	Increased irradiance increased current and power output	Very High
Panel temperature	Higher temperature reduced voltage and efficiency	High
Dust condition	Reduced sunlight absorption and energy generation	High
Relative humidity	Reduced solar radiation transmission	Moderate
Wind speed	Helped reduce panel temperature	Moderate

Ambient temperature	Increased panel temperature indirectly	Moderate

The results showed that the highest PV performance was obtained when the solar irradiance was high, the PV temperature was moderate, the dust deposition was low, and the wind speed was appropriate. The efficiency and reliability of the PV system could be enhanced through regular cleaning, suitable installation angle, proper ventilation, and continuous monitoring.

3.8 Comparative Analysis of Environmental Factors

The environmental factors had unequal effects on the PV system. The greatest influence on output current and power generation was the solar irradiance. The greatest impact of the panel temperature was on voltage and efficiency. Other performance losses were due to dust conditions and humidity which minimized solar radiation absorption and transmission. A moderate positive effect was observed for wind speed, as it helped to remove the heat from the panel surface. Table 8 shows how environmental factors affect PV performance when compared to the related parameters and influence level.

Table 8. Comparative Effect of Environmental Factors on PV Performance

Environmental Factor	**Main Effect Observed**	**Related Performance Parameter**	**Influence Level**
Solar irradiance	Increased current and power output	Current, power output	Very High
Panel temperature	Reduced voltage and efficiency	Voltage, efficiency	High
Dust condition	Reduced sunlight absorption	Power output, energy generation	High
Relative humidity	Reduced radiation transmission	Irradiance, power output	Moderate
Wind speed	Supported panel cooling	Panel temperature, efficiency	Moderate
Ambient temperature	Increased panel operating temperature	Panel temperature, efficiency	Moderate

The comparison reveals that solar irradiance was the most important parameter that influenced PV power output. But high irradiance also raised the temperature of the panel, resulting in loss of efficiency. So, it is not always the case that the maximum power output corresponds to the maximum efficiency. The optimum performance of the system was achieved when the dust level was low, the irradiation level was high, and the panel temperature was kept to a controlled level.

4. Discussion

This study reveals that the performance of the solar PVs system was significantly impacted by the outdoor environmental factors. Influenced by solar irradiance, ambient temperature, panel temperature, relative humidity, wind speed and dust condition for PV module output voltage, output current, power output, conversion efficiency and performance ratio. Of these parameters, solar irradiance was the most significant, as more solar energy would be converted to electrical energy with an increase in the solar irradiance. Consequently, the output current and power output rose when the solar radiation was higher. This is to indicate that PV performance in the real operating condition is not only dependent on PV module size but also on environmental and operating condition. (Hasan et al., 2022)

The outcome indicated that the solar irradiance rose from the morning to the midday and dropped during afternoon. Likewise, the power output rose from 98.58 W at 09:00 AM to the peak of 199.12 W at 01:00 PM when the irradiance was 910 W/m². This means that there is a positive correlation between the power produced and the irradiance. Increasing power output was not linear with increasing irradiance, however, due to the effects of the system's temperature and dust condition. The increase in irradiance did result in more current generation, however, the increase in panel temperature slightly caused a decrease in voltage and a modification in efficiency. Thus, the main factor for power generation was the irradiance, with the temperature being a limiting factor during peak sun hours. (Shaik et al., 2023)

The conversion efficiency decreased with an increase in panel temperature. The highest panel temperature was 58.3°C at 01:00 PM corresponding to the lowest efficiency of 13.68% at the same time. The lowest panel temperature of 32.5°C was obtained at 09:00 AM and the highest efficiency of 14.67% was obtained at this time. This is an indication that maximum power and maximum efficiency were not achieved simultaneously. With high irradiance there was more power produced and panel temperature was also higher. The voltage output was found to be slightly reduced with the increase in the temperature of the panel, thus decreasing the conversion efficiency. Hence, it is necessary to use proper ventilation and temperature control to enhance the efficiency of PV in hot climate. (Baghel & Chander, 2022)

Another contributor of PV performance loss was dust accumulation. According to this study the dust condition during morning time was low, and from midday onwards was moderate. A high-power production was achieved during the time of maximum irradiance, however, during the time of intermediate dustiness and high panel temperature, the efficiency was reduced. Dust particles that settle on the surface of the panel can block or scatter the sunlight, which decreases its absorption by the panel. This decreases the actual solar radiation received by the PV cells and decreases the amount of energy produced. Hence, the regular cleaning is required to minimize the dust loss and to ensure the stable output from PV system, particularly in a dusty/dry environment. (Salamah et al., 2022)

The effect of relative humidity on PV performance was also observed. Humidity was highest at 68% at 09:00 AM and lowest at 43% at 01:00 PM. High humidity may affect the solar radiation transmission, since part of the solar radiation can be scattered and absorbed by the water vapor in the atmosphere. Humidity was also seen to impact the power output somewhat, but performance was seen to vary with humidity more so during less irradiation conditions. The humidity can also promote the adhesion of dust on the surface of the panel, and this can aggravate the degree of soiling. Therefore, humidity is a parameter that should be taken into account as an indirect but relevant parameter when evaluating PV performance. (Abuzaid et al., 2022)

Wind speed had a moderate positive effect due to its ability to dissipate heat from the surface of the panel. In the said period, wind speed rose from 1.2m/s at 09:00 AM to 2.4m/s at 01:00 PM. The high irradiances, however, had caused the panel temperature to still reach its peak at 01:00 PM. This suggests that wind did some to reduce thermal stress but was not sufficient to prevent panels from becoming hot during the peak sun hours. Installation with appropriate spacing and ventilation can enhance natural cooling and limit the impact on efficiency due to high temperatures. (Younis & Alhorr, 2021)

Comparative analysis indicated that solar irradiance had high influence on PV performance, whereas panel temperature and dust condition had high influences. Moderate influence was demonstrated by relative humidity, wind speed and ambient temperature. This implies that the performance of the PV is dependent upon the simultaneous action of multiple environmental variables. For instance, increasing the irradiance will increase the power output of the panels, but if the panels' temperature is high and dust is accumulating, the conversion efficiency may decrease. Hence, the performance of PV should be evaluated in the context of an integrated environmental assessment and not individually. (Rusănescu et al., 2023)

The results of daily energy generation and performance ratio also showed the influence of the weather condition and surface cleanliness. The best actual energy produced was on Day 3 with 1.51 kWh and the best performance ratio was 85.80% on clear sky conditions. The lowest actual energy generation was on Day 5, in the amount of 1·09 kWh, primarily because of the presence of humid conditions and lower irradiance. It is observed that the lowest performance ratio is 77.64% on Day 4 which highlights the impact of accumulation of dust. The results show that the energy output of the PV systems is better when the sky is clear, the surfaces of the panels are clean and there are no clouds or unstable irradiance. (Rashid et al., 2023)

The practical implication of this study is that PV systems must be regularly monitored and maintained to reduce the losses to the environment. Dust losses can be minimised with regular cleaning of the panels and panel temperature can be controlled by suitable mounting arrangements and ventilation. It is possible to detect performance decline at an early stage using continuous monitoring of the irradiance, temperature, humidity, wind speed, voltage, current, and power output. This kind of monitoring is helpful if you want to know if there is a dust loss, if the system is over-heating, if the system is being shaded or disturbed. (Hasan & Farhan, 2022)

Some of the study limitations are noted. Observation period was short and analysis was conducted with a single crystalline silicon PV module. The dust condition was not measured by a quantitative dust sensor but rather categorized qualitatively as low or moderate dust. Longer monitoring time, more locations, various PV technologies, quantitative dust measurement, and more sophisticated prediction models should be used in future studies. Improved operation and maintenance practices should also be investigated as it can improve energy output and assist in maintaining long term reliability of PV systems. (Iftikhar et al., 2021)

5. Conclusion

The performance of crystalline silicon solar photovoltaic (CSPV) system has been analyzed under different environmental conditions in this study. The results indicated that solar irradiance, panel temperature, humidity, wind speed and dust condition were significant factors affecting PV output and efficiency. Of these, the current and power output response to solar irradiance was the strongest, that is higher irradiance leads to higher current and power generation. The highest value of the power was 199.12 W, which was obtained at 01:00 PM corresponding to an irradiance of 910 W/m². The results also indicated that maximum power output was not necessarily equal to maximum efficiency, however. The highest efficiency of 14.67% was obtained at 09:00 AM and the lowest efficiency of 13.68% was obtained at 01:00 PM when the panel temperature was maximum at 58.3°C. This is the reason why excessive heating of the panels reduces their conversion efficiency, which is manifested by a decrease in the output voltage. Also, dust accumulation and humidity played a role in reducing performance, as they reduced the absorption and transmittance of solar radiation. The moderate positive effect of wind speed was attributed to its role in cooling the panels. In conclusion, the study shows that solar PV performance is influenced by the interplay of several environmental factors. Regular cleaning of the panels, appropriate ventilation, mounting angle and monitoring of environmental and electrical parameters could all help to improve performance. Longer observation period, different PV technology, quantitative dust measurement, and advanced prediction model for better assessment of PV performances are recommended for future research.

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