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Performance Analysis and Future Prospects of Solar Photovoltaic Systems: A Comprehensive Study

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Abstract: The operational performance of a rooftop solar photovoltaic (PV) plant in Aurangabad was analyzed during January 2024 as part of this pilot study. The analysis focused on energy production, carbon offset, irradiance, and system uptime. The plant, with a capacity of 937 kWp using Emmvee Multi Crystalline 72 Cell modules, produced 4.51 MWh of electricity and achieved a carbon offset of 3.70 tons of CO_2. Despite high system uptime, actual production consistently fell short of budgeted targets due to potential environmental or operational constraints. The study highlighted the need for enhanced monitoring, predictive maintenance, and grid integration to maximize energy output and economic returns.
This research aimed to improve PV system efficiency by 3%, increasing the existing 9% efficiency to 12% through design modifications and optimized operational strategies. It contributes to understanding critical factors such as solar partial shading and seasonal energy variation, offering a foundation for large-scale future studies to enhance solar PV system performance and sustainability in support of global renewable energy goals.

Keywords: Solar PV, novel design, sustainability, renewable energy. Solar PV, pilot study, performance analysis, renewable energy.

1. Introduction

Due to the harmful effects of climate change, the process of the global transition to renewable energy sources has currently become a critical strategy to reduce dependence on fossil fuels. Solar photovoltaic (PV) systems are among a range of the most valuable renewable technologies because they could effectively respond to the solar radiation, their cost is scalable and economical. In recent decades, there have been huge improvements in the energy conversion efficiencies and the costs associated with the installation of solar PV technology, making widespread deployment of solar PV feasible in both residential, commercial and industrial sectors. However, the operational performance of solar PV systems still features several challenges to be optimized. These factors are sensitive to temperature, solar irradiances fluctuate, components can be down-time. To reach these goals, understanding system behavior under real world conditions and developing novel strategies that will improve performance and reliability are needed.
In this pilot study, solar PV plant operational performance in January 2024 is considered. The study analyzes key plant metrics such as energy production, carbon offset, irradiance and uptime with an objective of identifying trends and challenges that affect plant efficiency and sustainability. The contributions of this research are actionable guidelines for solidifying the reliability and environmental benefits of solar PV systems.
Additionally, this work sets the foundation for future research efforts to realize advanced technologies and methods for enhanced solar optimization. The research provides a detailed snapshot of performance metrics for a single month of operational data, allowing targeted recommendations and a better understanding of the factors that impact solar PV efficiency. A focused approach such as this underscores the continued necessity for continuous monitoring and analysis to realize sustainable energy goals as well as the impact of solar PV systems on the global energy landscape.
Design and modification of PV system design and installation parameters based on research work, aiming to improve efficiency by 3%, from the existing 9% to 12%, through optimized operational strategies.

2. Methodology

The study analyzed a rooftop solar PV system with a capacity of 937 kWp, using Emmvee Multi Crystalline 72 Cell modules. The system's orientation is 93° South with a tilt angle of 12°, and it employs 16 Huawei Sun2000-50KTL inverters. The system is installed at Aurangabd, Waluj, MIDC location

a) **Data Collection:**

- Plant Production Monitoring: Recording daily and monthly energy production in Wh, MWh, and KWh.
- Carbon Offset Calculation: Quantifying carbon offset in kilograms (kg).
- Energy Export Analysis: Measuring index meter export values (Wh).
- Irradiance Measurement: Monitoring daily solar irradiance (Wh/m²) with fixed installation coefficients.

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➢ Operating Time Assessment: Tracking plant operating time in minutes to identify active production hours and downtime.
➢ Performance Ratio Analysis: Calculating the performance ratio (PR) as the ratio of actual energy output to expected output under ideal conditions.
➢ Uptime Monitoring: Recording uptime percentage to gauge system reliability.
➢ Production vs. Budget: Comparing energy production against budgeted targets for economic performance assessment.

b) **Analytical Methods:** Tools and Techniques for Efficiency and Performance Analysis: Utilizing statistical software, performance monitoring systems, and data visualization tools to analyze collected metrics.
c) **Environmental Impact Evaluation:** Assessing Irradiance and Temperature Dependencies: Evaluating how varying irradiance levels and temperature ranges affect energy generation and system performance.

3. Results and Analysis

A detailed analysis of the solar behavior was conducted on-site over the past year, focusing on the following parameters:
1) Active power variations during day-night cycles and seasonal effects.
2) Carbon offset analysis to quantify environmental benefits.
3) Irradiance behavior analysis to understand solar resource fluctuations.
4) Operating time analysis to identify production trends and efficiency."

This study employs data-driven analysis of the solar PV plant's performance metrics

3.1 Historical Performance Analysis

a) Plant production in units

FY 2023-24 consistently outperforms FY 2022-23 in most months, indicating an improvement in system efficiency or better operational strategies.

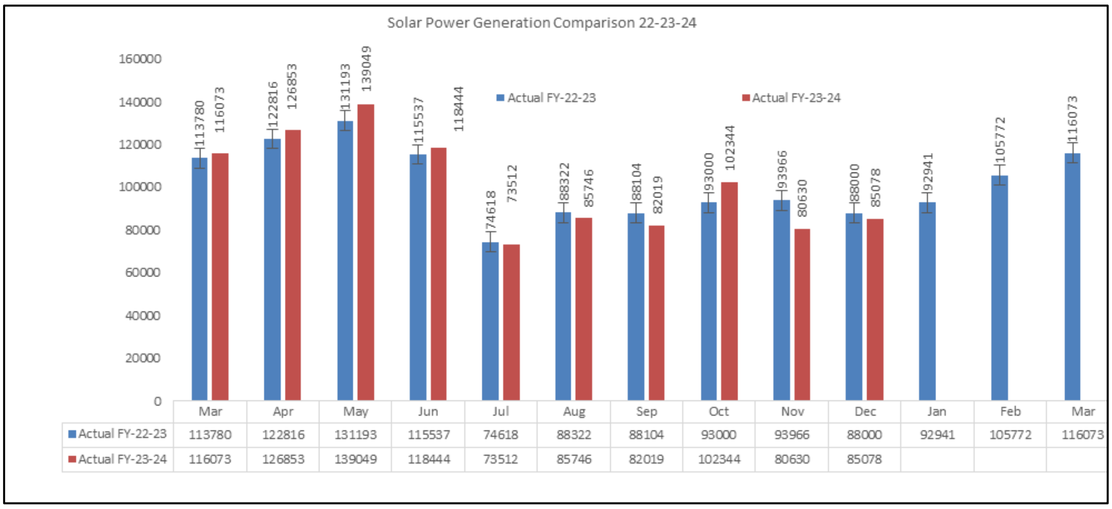

Figure 1: Plant production in units for FY 22-23 & FY 23-24

There is significant seasonal variability in the energy generation data observed across both years, mainly due to changes in solar irradiance levels throughout the year. Consistently seen is that energy production is higher during the months of March, April and May, which corresponds to optimal sunlight conditions during late spring and early summer and bode well for peak solar performance. The highest generation of 139,049 kWh was recorded in May FY 2023-24 compared to May FY 2022-23 (131,193 kWh). Output drops from June to August, and in July it dips noticeably. The source of this drop is probably seasonal monsoonal rains and increased cloud cover, leading to lower solar irradiance. The July output in FY 2023-24 was 73,512 kWh compared to 74,618 kWh in FY 2022-23. The performance gap between the two fiscal years starts to narow down in the September to November period where generation for FY 2023-24 for October 2023 stood at 102,344 kWh, a jump from the previous year's 93,000 kWh, likely because of the operational improvements or favorable weather patterns. During the winter months of December to February, energy generation stabilizes and January exhibits significant gains in FY 2023-24, as optimized plant operations and elevated winter irradiance lead to these gains. This trend underscores the trend in operations and maintenance of the solar PV plant for optimisation PPF (Achievement of optimum performance and efficiency of solar PV plant) and requires attention to seasonal adjustments.

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3.2 Environmental Impact

a) Monthly carbon offset data and its significance

Carbon offset data for January 2024 is the environmental impact of a rooftop solar photovoltaic (PV) system on a roof in Aurangabad. The plant was able to offset a total of 3.70 tons of CO_2 with 4.51 MW of clean energy produced this month. In short, this is the system's ability to replace fossil fuel electricity with solar power based electricity. As illustrated by the chart, the 15th and 16th of January were the highest carbon offset each showing approximately 1,850 kg of CO_2 emission saved per day. These peaks indicate that the solar plant was operated at optimal state, perhaps because of favorable weather and high solar irradiance at that time. The steady energy production points to a system that minimizes greenhouse gas emissions while helping to tackle the matter of the energy generation's environmental impact that is underscoring efforts aimed at sustainability. Nevertheless, the revenue for this period stood at ₹0, signifying that likely, energy was consumed on site, not sold to the grid. Taken as a whole, January 2024 shows that the solar PV plant is contributing towards cleaner energy production and smaller footprints.

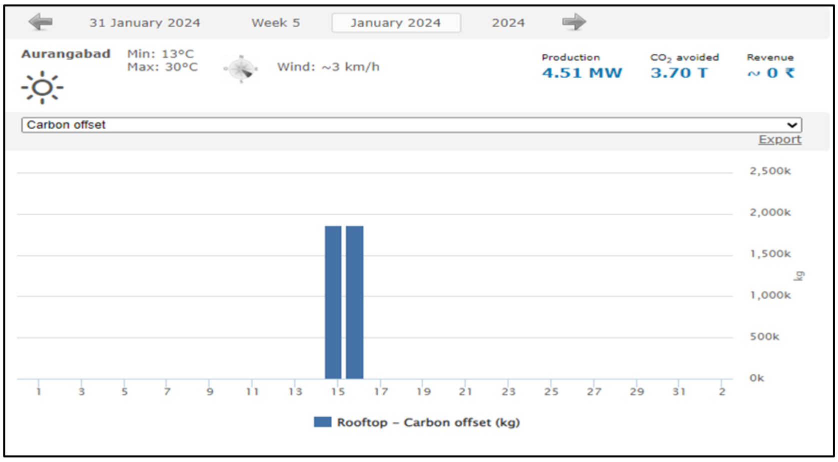

Figure 2: *Plant Carbon offset Monthly in kg*

b) Irradiance Measurement

January 2024 plant's irradiance data shows a cumulative monthly irradiance of 4428.5 Wh/m², meaning total solar energy per square meter of the plant's surface area within that month. Importantly, this irradiance level is a critical factor determining the energy output of the net solar PV system. In the produced 4.51 MW that the plant made throughout January 2024, higher irradiance levels generally led to higher energy output. It means stable sunshine conditions over the month with the CO_2 emission avoided at 3.70 tons.

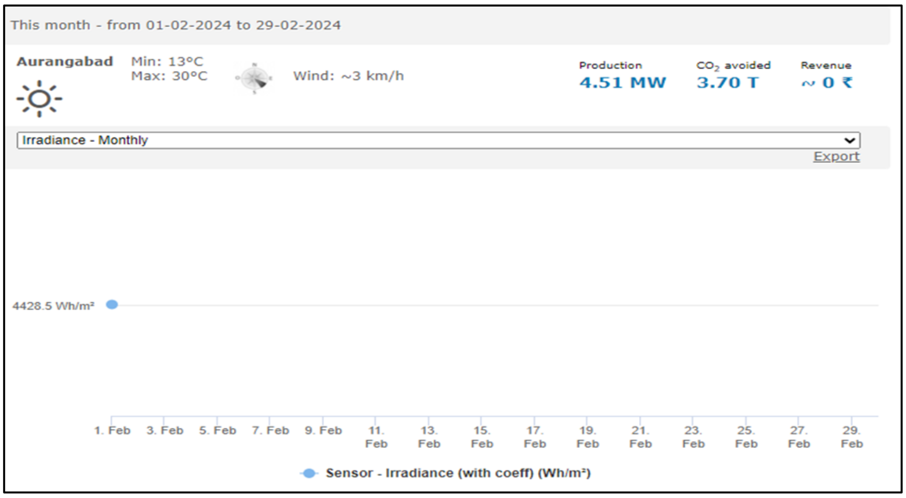

Figure 3: *Plant Irradiance4*

3.3 Operational Performance

a) Plant Production

The solar PV plant in Aurangabad produced a total energy of 4.51 MW in January 2024, with an environmental benefit of 3.70 tons of CO_2 saved.

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Blue bars representing daily production trends showed common energy production of greater than 8 MWh on multiple days, especially between the 11th through the 15th and around the 20th. A notable series of drops in output on the 17th and the 31st, however, imply potential unusual weather, or system downtime. First, as shown by the red line, irradiancy showed cyclical trend, matching the high prodution days, and reaffirmed its importance to drive energy out, directly. Within the temperature ranges of 13°C to 30°C, under very little wind, approx. 3 km/h, the plant operated favorably. The performance, even in the absence of revenue generation (perhaps an experimental or off grid setup) indicates that the system is reliable.

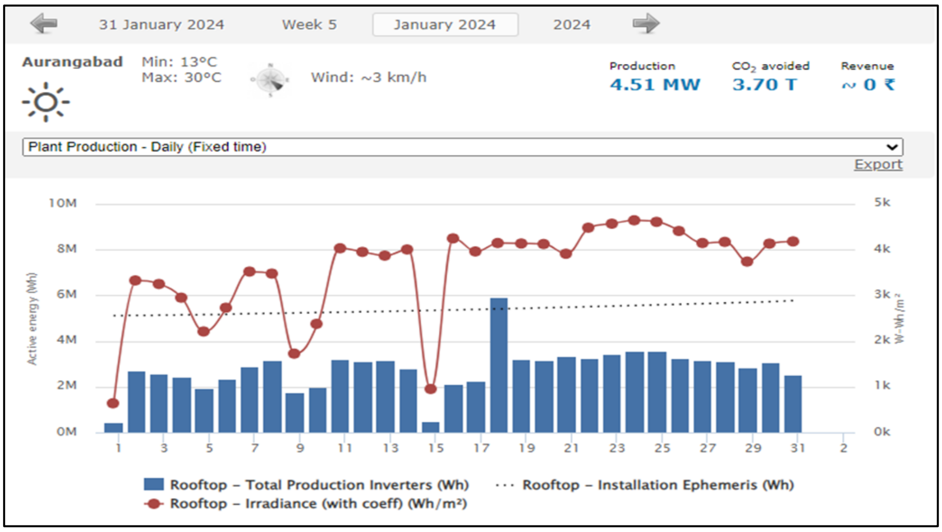

Figure 4: *A month Plant Production*

Addressing downtime through predictive maintenance, integrating energy storage systems to manage output variability, and leveraging weather forecasting tools could further optimize performance. Additionally, exploring grid integration or feed-in tariffs would enhance the financial viability of the plant, maximizing both environmental and economic benefits

b) Plant Index Meter Export

The system achieved a total production of 4.51 MW and successfully offset 3.70 tons of CO_2 emissions, showcasing its contribution to reducing environmental impact. Despite these achievements, the revenue generated was reported as zero, suggesting the absence of financial returns for the energy exported to the grid. The graph reveals that significant energy export activity occurred only on the 15th and 17th of January, with peak exports reaching approximately 2,500M Wh on both days, while the rest of the month showed no recorded energy export.

The observed pattern of intermittent energy export could indicate operational challenges such as downtime, maintenance activities, or limited grid connectivity during the other days of the month. The weather conditions, with temperatures ranging from 13°C to 30°C and wind speeds of around 3 km/h, were generally favorable for solar power generation. However, variability in solar irradiance might have affected the system's performance.

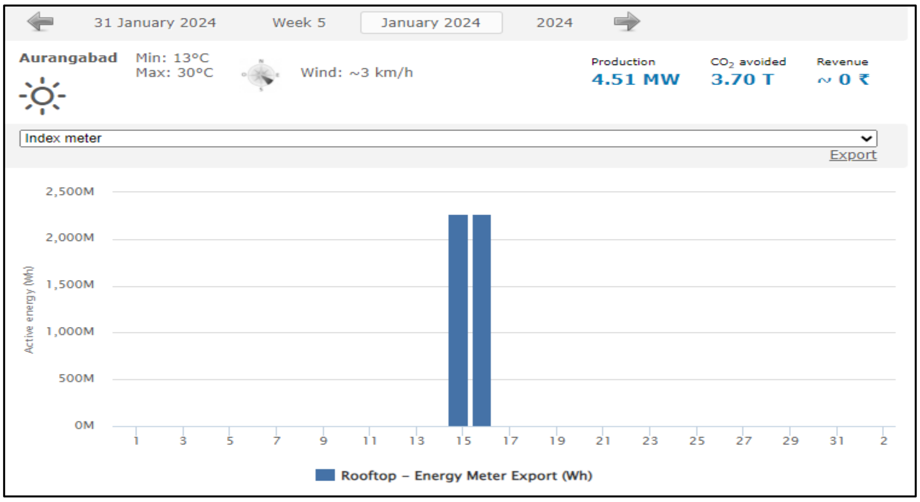

Figure 5*:Plant Index Meter Export*

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This analysis highlights the need to investigate the reasons behind the limited energy export to ensure consistent performance. Addressing operational challenges and exploring policy incentives for monetizing solar energy export could enhance the system's financial and environmental benefits.

c) Plant Operating Time in Minutes

The graph for January 2024 provides insights into the operating time of the solar photovoltaic (PV) plant in Aurangabad. The system maintained a consistent operating time throughout the month, with daily values predominantly near the 600-minute mark, indicative of optimal daylight utilization for energy production. Minor variations in operating time can be observed, likely due to fluctuations in sunlight availability caused by weather conditions such as cloud cover or reduced solar irradiance on certain days.

The plant's consistent performance highlights its reliability in converting available sunlight into energy. Despite achieving a total energy production of 4.51 MW and offsetting 3.70 tons of CO_2, the absence of revenue generation emphasizes the need to explore mechanisms for monetizing the plant's output. Furthermore, this data reinforces the plant's potential for long-term sustainability and contribution to renewable energy goals, provided operational parameters remain steady and external factors are managed effectively.

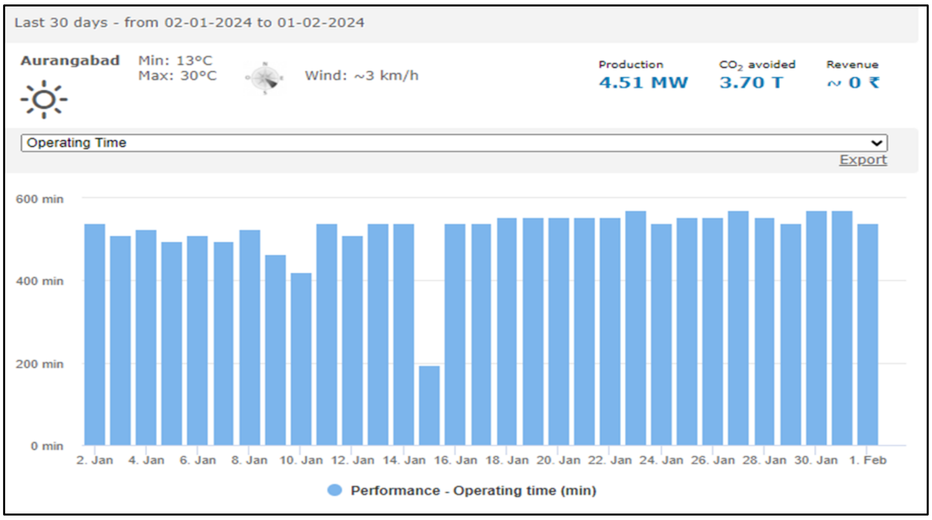

***Figure 6:** Plant operating time in min*

These observations underline the importance of continuous monitoring and potential enhancements to maximize efficiency, including integrating predictive maintenance systems and advanced data analytics for further optimizing plant performance.

d) Plant performance ratio & Irradiance

The performance ratio (PR) and irradiance of the solar PV plant in Aurangabad for January 2024. The irradiance values, represented in red, remained relatively consistent, with occasional dips likely caused by weather conditions such as cloud cover. On most days, the irradiance exceeded 4000 Wh/m², providing adequate sunlight for power generation

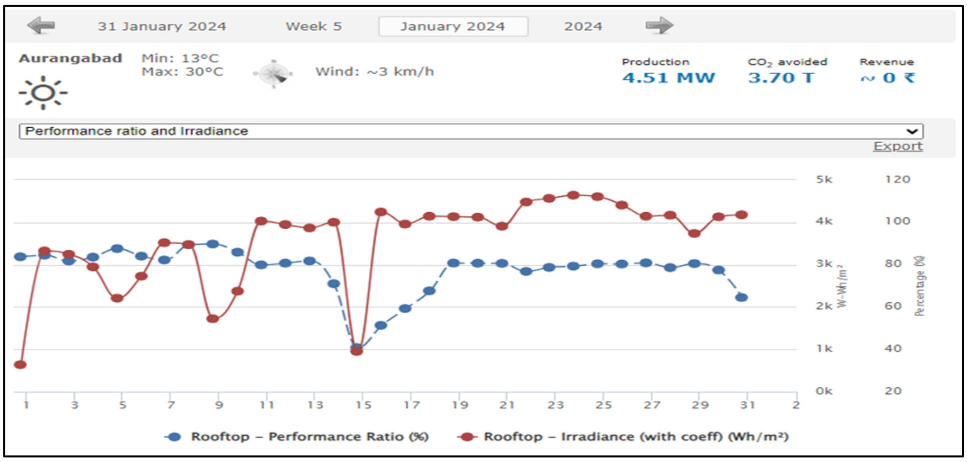

***Figure 7:** Plant performance ratio & Irradiance*

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The performance ratio, depicted in blue, exhibited noticeable fluctuations throughout the month, reflecting variations in the plant's efficiency in converting available sunlight into electricity. Sharp declines in the PR on specific days could be attributed to system inefficiencies, maintenance activities, or external factors such as shading or soiling of panels. A positive correlation was observed between high irradiance levels and improved performance ratios, emphasizing the plant's ability to utilize optimal sunlight conditions effectively. However, the fluctuations in the PR indicate the need for enhanced monitoring and regular maintenance to address inefficiencies and ensure consistent performance. This analysis underscores the potential of the plant to achieve higher operational efficiency with minimal interventions.

e) Plant uptime in percentage

The plant uptime for the rooftop solar photovoltaic (PV) system in Aurangabad during January 2024 remained consistently near 100%, indicating exceptional operational reliability and minimal downtime. This high uptime reflects efficient maintenance practices and effective monitoring, ensuring continuous energy production throughout the month. The plant generated a total of 4.51 MW of energy, contributing to the avoidance of 3.70 tons of CO_2 emissions, underscoring its positive environmental impact by reducing reliance on fossil fuels.

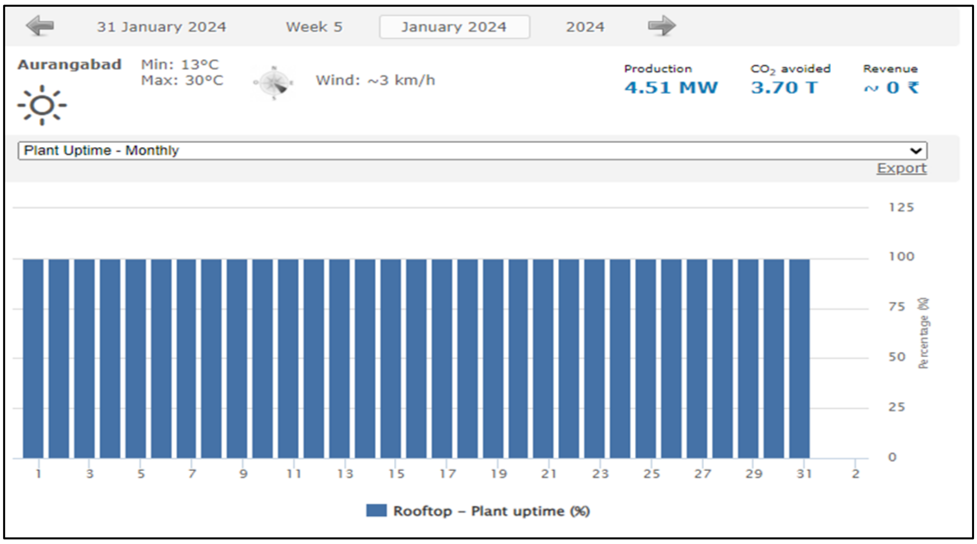

Figure 8; *Plant uptime in percentage*

However, despite the impressive performance, the recorded revenue for the period was ₹0, suggesting that the generated energy may have been consumed on-site or not exported to the grid. This highlights an opportunity to explore revenue-generating mechanisms such as grid export through net metering, battery storage for surplus energy, or leveraging policy incentives and feed-in tariffs. The consistently high uptime positions the plant as a reliable contributor to clean energy generation, but addressing the economic aspect through energy monetization strategies could enhance overall project viability and maximize returns.

f) Plant production Vs Budget

The graph illustrates the rooftop solar plant's actual energy production versus the budgeted projections for January 2024 in Aurangabad.

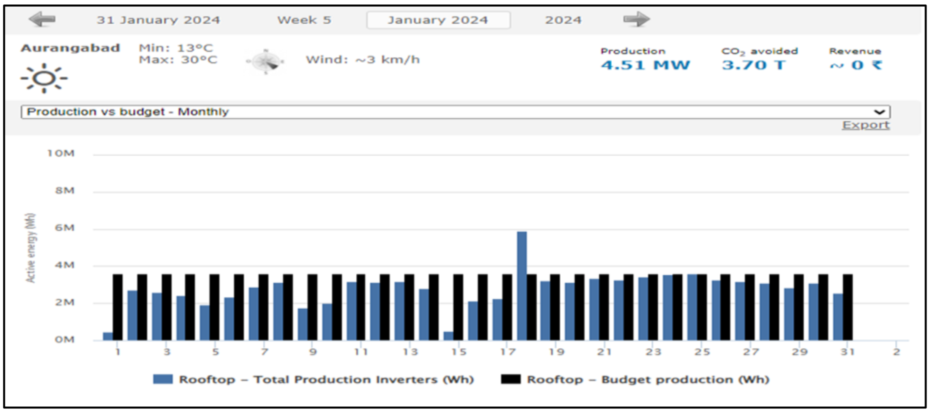

Figure 9: *Plant production Vs Budget*

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The black bars represent the budgeted production, while the blue bars indicate the actual production from the inverters. Throughout the month, the actual production consistently fell below the budgeted targets, with a notable spike around the 17th of January, where the actual production briefly surpassed the budget. This deviation suggests that the plant encountered performance limitations or environmental factors, such as reduced solar irradiance, which prevented it from achieving the forecasted output on most days.
Despite the underperformance, the plant still managed to generate 4.51 MW of energy, contributing to the avoidance of 3.70 tons of CO_2 emissions. However, the revenue remains at ₹0, reinforcing the observation that the energy may have been utilized for internal consumption rather than sold to the grid.
The consistent gap between actual and budgeted production highlights the need for closer analysis of factors influencing energy yield. Potential areas for investigation include panel efficiency, shading issues, weather anomalies, or inverter performance. Addressing these discrepancies could enhance future performance and align actual production more closely with budgetary targets, ultimately improving the overall efficiency and economic viability of the plant.

g) Plant Energy Generation

The energy generation data for January 2024 from the rooftop solar plant in Aurangabad, as monitored by CleanMax, reflects performance across different time frames:

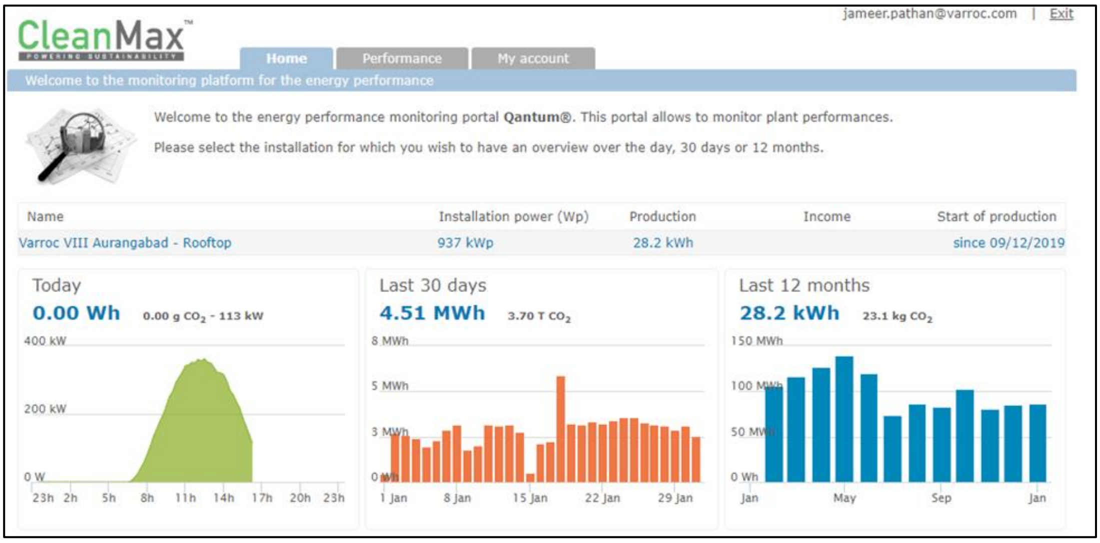

Figure 10: Plant Energy Generation Data

- **Daily Generation (Today)**: The plant recorded **0.00 Wh** of energy production, indicating no generation activity on this specific day. This may be due to weather conditions, maintenance, or lack of sunlight during the observation period. Correspondingly, **0.00 g CO_2** emissions were avoided, aligning with the absence of energy generation.
- **Monthly Generation (Last 30 Days)**: Over the last 30 days, the plant generated **4.51 MWh** of energy, resulting in the avoidance of **3.70 tons of CO_2** emissions. This monthly production reflects consistent generation, although the energy produced is slightly lower than typical expectations, potentially pointing to seasonal variations or reduced solar irradiance during January.
- **Annual Generation (Last 12 Months)**: Over the past year, the plant produced a total of **28.2 kWh**, contributing to the avoidance of **23.1 kg of CO_2** emissions. The annual energy generation trend, illustrated by the bar chart, shows peak performance around May, likely due to higher sunlight availability, while other months display moderate to lower outputs.

The monitoring platform provides insights into energy trends and CO_2 savings, supporting sustainability goals. The slight underperformance in January suggests areas for operational assessment to enhance efficiency and ensure consistent energy yield throughout the year.

4. Conclusion

Analysis of performance of the rooftop solar photovoltaic (PV) plant in Aurangabad for the January 2024 shows the plant is efficient enough to serve clean energy generation and help in carbon emission reduction. The plant not only has shown positive health impact with a total energy production of 4.51 MWh with a carbon offset of 3.70 tons of CO_2 but reaffirms the importance of solar PV systems in driving sustainability goals forward.
Seasonal variability, irradiance and uptime operational all have influences on the plant energy output, as is highlighted in the research. The plant had a fairly high uptime of nearly 100% based on actual and the budgeted production but certain discrepancies between them indicate some areas for further optimization in the production process.

Underperformance relative to projections was due to factors including fluctuations in the irradiance, potential shading and intermittent grid exports.
The analysis key insights are: continuous monitoring, predictive maintenance and integration of advanced technologies towards all effective improvement in system efficiency and reliability. To fully capitalize on the environmental and economic benefits, the operational challenges will be addressed and inverter performance will be improved coupled with the means of generating revenue (grid export mechanisms and policy incentives).
Finally, the results from this study provide insight into the future direction of innovation in PV system designs, energy storage solutions and grid integration strategies. With continual improvement through operational practices and technological advancements, the plant can take further advantage of productivity to promote broader renewable energy adoption and to promote the global transition to a low carbon future.

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