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Preformation and Possible modification of Hotel Sarowar Solar Mini-Grid System Nepal on the basis of Maximum and Limit Power Point Tracking

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Abstract

Solar mini-grid systems (SMGS) are essential for promoting sustainable energy solutions by providing reliable and cost-effective electricity, especially in remote and off-grid areas. Their performance is influenced by factors such as seasonal variations, maintenance efficiency, and reliance on external power sources. This study evaluates the energy yield, consumption patterns, and performance ratio (PR) of the 140 kWp SMGS at Hotel Sarowar for 2022 and 2023 to assess its efficiency and sustainability. Data was obtained taken from Topsun Energy Pvt. Ltd., Sanobharyang, Nagarjun-02, Kathmandu, Nepal and processed using Sublime Text to clean and verify uniformity. Given the manageable dataset, calculations were performed in Excel. The findings reveal significant fluctuations, with an overall decline in energy yield in 2023 compared to 2022. For instance, energy yield in July 2023 dropped sharply to 10.23 MWh from 23.82 MWh in July 2022. August 2022 recorded a negative yield of -4.12 MWh, whereas August 2023 saw an improvement to 8.38 MWh. PR variations were also observed, with a notable increase from -15.2913 in August 2022 to 8.0191 in August 2023, reflecting system improvements. However, declines in PR during April, May, and November 2023 suggest potential inefficiencies. To address these fluctuations, integrating advanced Maximum Power Point Tracking (MPPT) and Limited Power Point Tracking (LPPT) techniques is recommended to optimize energy capture and ensure stable operation under varying environmental conditions.

Keywords: Solar mini-grid, energy yield, performance ratio, MPPT, LPPT, system efficiency

Introduction

The global transition toward renewable energy has spurred significant interest in solar power systems, particularly in regions with limited access to centralized electricity grids. Nepal, with its abundant solar resources and challenging terrain, has increasingly adopted SMGSs to provide reliable and sustainable energy to remote communities and businesses.

While the country has seen a growing number of SMGS, this study focuses on a specific case: the Hotel Sarowar SMGS. This system serves as a representative example to analyze the performance, challenges, and potential improvements of SMGSs in similar contexts. The efficiency and reliability of SMGSs are heavily influenced by the ability to optimize power extraction from PV panels, which is often affected by environmental factors such as solar irradiance, temperature, and shading. To address these challenges, advanced power tracking techniques, such as MPPT and LPPT, have been developed. MPPT ensures that the PV array operates at its maximum power output under varying conditions (Esram & Chapman, 2007). By integrating these techniques, SMGSs can achieve higher energy yields and improved operational efficiency.

Energy plays a crucial role in modern society, underpinning socio-economic development and quality of life. In Nepal, a country characterized by its rural population—over 80% of whom live in remote areas—energy consumption is significantly below the global average (Surendra et al., 2011). The nation's energy sector heavily relies on traditional sources such as fuel wood, crop residues, and animal dung, which collectively account for approximately 86% of total energy consumption. Currently, only 40% of the population has access to electricity, with rural electrification standing at a mere 29%. This reliance on biomass for energy needs presents various environmental and public health challenges (Rajkarnikar et al., 2021). Nepal's energy landscape is further complicated by its dependence on imported refined fossil fuels, which strains its fragile economy (Lohani et al., 2023). Despite its vast potential for renewable energy resources—such as hydropower, solar power, wind energy, and bioenergy—these resources remain underutilized due to geographical, technical, political, and economic barriers (Meeks et al., 2024). This paper reviews the current status of Nepal's renewable energy technologies (RETs), including micro-hydro, solar power, wind energy, biofuels, improved cook stoves, and improved water mills. It also examines the opportunities and challenges associated with RETs and offers recommendations for their advancement and implementation (Basnet, 2024).

Nepal's energy mix predominantly features traditional biomass (66.54%) and fossil fuels (27.24%), reflecting high energy poverty levels (Shrestha et al., 2024). Despite the decreasing costs of solar photovoltaics, modern renewable energy's share remains below 3% (Basnet, 2024). The analysis suggests that aggressive policy measures are necessary to support clean energy adoption, emphasizing solar generation with battery storage and complementary technologies like off-river pumped hydropower. The paper also explores how decentralized renewable energy sources, such as micro-hydro plants, could address electricity constraints in developing regions. Evidence indicates that these mini-grids have led to modest but statistically significant increases in manufacturing and employment, although their impacts in more remote areas are less pronounced (Meeks et al., 2024). A review of Nepal's rapid rural electrification highlights that this progress has been driven by favorable political and socio-economic conditions, including democratization and large-scale foreign employment. However, challenges remain in achieving geographical and economic equity, and further work is needed from an energy justice perspective (Basnet, 2024).

As Nepal transitions from a history of load-shedding towards energy self-sufficiency, with plans to add 20 GW of hydropower over the next decade, assessing the current grid's stability is crucial. This paper presents a comprehensive evaluation of the power system's stability, including voltage, angle, and frequency stability, using various assessment tools. The results indicate that while the grid is robust in terms of frequency stability, there are areas prone to voltage instability, and the integration of PV generation affects stability margins (Shrestha et al., 2024). In grid-connected solar PV systems, the boost converter with MPPT optimizes energy extraction from solar resources. The inverter, essential for converting DC to AC, plays a critical role in managing current flow before it is fed into the grid. This paper also discusses the application of Voltage Source Inverters (VSI) and the limitations of LPPT under specific conditions of surplus power generation (Dhaneria, 2020; Mohammed et al., 2017; AbdEl-Gawad & Sood, 2017).

The integration of MPPT in SMGSs enhances efficiency and operational stability by optimizing power extraction and preventing overvoltage disturbances. MPPT dynamically adjusts the operating point based on varying solar irradiance and temperature conditions, with advanced control algorithms such as the Lyapunov model reference adaptive control significantly improving tracking performance (Pan et al., 2009). Additionally, modern Incremental Conductance (IC) algorithms outperform traditional methods by providing faster and more stable tracking of the maximum power point (Saxena et al., 2024). The system design benefits from integrating DC-DC converters with MPPT controllers, ensuring efficient power extraction, voltage regulation, and effective battery charging (Armstrong & Hurley, 2004). Performance evaluations indicate that systems incorporating MPPT and CPG achieve efficiency increases of up to 33.04%, demonstrating their effectiveness in real-world applications (Sudiharto et al., 2022). Despite these advantages, challenges remain in managing complex control systems and ensuring reliability under fluctuating environmental conditions. The Hotel Sarowar SMGS is a critical initiative to address Nepal's energy challenges. However, its performance over 2022 and 2023 revealed significant fluctuations. These inconsistencies highlight the vulnerability of SMGSs to environmental and operational challenges, underscoring the need for optimization. The research gap identified in this study underscores the need for further investigation into optimizing SMGSs in Nepal, particularly focusing on enhancing MPPT strategies and addressing system stability issues. The findings will also provide valuable insights for similar systems, promoting the broader adoption of renewable energy solutions.

Methods and Materials

The integration of solar PV systems within mini-grid frameworks enhances energy supply reliability, particularly in rural areas, by optimizing energy generation, storage, and distribution through intelligent control systems. Studies indicate varying energy outputs, with the Thabang SMGS generating 83.206 MWh/year in 2021, while the Sugarkhal SMGS produced 64.14 MWh/year, demonstrating differences in system performance (Karna et al., 2024). Efficiency improvements have also been observed, as seen in the Sugarkhal system, where the capture factor increased from 9.76% to 10.47% over two years (Karna et al., 2024). Advanced frequency controllers like Fuzzy self-tuned PID effectively manage power fluctuations, ensuring stable energy supply (Abdelkareem et al., 2024), while decentralized control architectures enable cost-effective expansion by allowing each PV unit to autonomously manage its output (Opiyo, 2018). Additionally, hybrid systems integrating energy storage solutions—such as the battery-backed micro-grid in Ethiopia—help balance supply and demand during low solar generation periods (Checklie et al., 2023). Despite these advancements, challenges remain in accurately predicting consumption and ensuring sustainability, which can be addressed by integrating advanced metering infrastructure, improving operational efficiency and community engagement (Marful et al., 2023). Solar cell technology has progressed throughout time, from single-crystal silicon to flexible film, organic, dye-sensitized, as well as perovskite cells. Material enhancement, construction, contact systems, as well as characterisation techniques have all been targeted as ways to improve solar cell performance. The Shockley diode model is a popular model for solar cell analysis because it allows for extensive analysis and modelling to optimise the efficiency of solar cells and capacity, such as the single-diode model demonstrated in Figure 1.

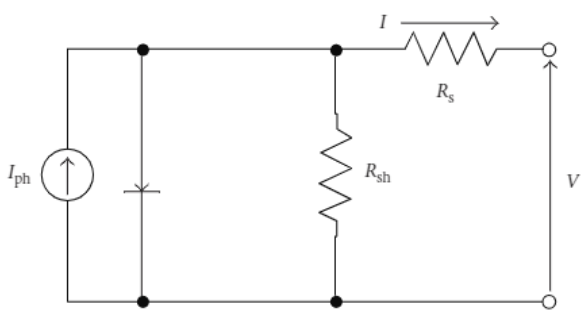

Figure 1: Solar cell model with a single diode (Diantoro et al., 2018).

The output current of an ideal solar cell is found as (Kumar & Singh, 2018),

$$I = I_{ph} - I_s \left[\exp\left(\frac{qV_{OC}}{N_s KAT_0}\right) - 1\right] \quad (1)$$

In the ideal scenario, beam produced power is directly proportional to irradiation brightness, and photovoltaics provide a reasonable estimate. If we consider a mathematical representation of a photovoltaic cell (real/practical cell type) containing infinite R_s (series resistance) along with Rp (parallel resistance), then the diode current becomes

$$I_d = I_s \left[\exp\left(\frac{q(V + IR_s)}{N_s KAT_0}\right) - 1\right] \quad (2)$$

When R_s is taken into account, the resulting current of the module with N_s cells in series becomes:

$$I = I_{ph} - I_s\left[\exp\left(\frac{q(V + IR_s)}{N_s KAT_0}\right) - 1\right] \quad (3)$$

When the solar energy system is coupled in series and parallel, the current using equation (3) is

$$I = N_p \times I_{ph} - N_p \times I_s\left[\exp\left(\frac{q(V + IR_s)}{N_s KAT_0}\right) - 1\right] \quad (4)$$

The incident flux has a relationship to the photocurrent (I_{ph}), and thus not dependent on voltage (or R_s). The photocurrent generated by solar radiation along with the temperature influenced by it can be computed as

$$I_{ph} = [I_{SC} + K_i(T_0 - T_r)] \times \frac{G}{G_{ref}} \quad (5)$$

The single-diode model, which consists of a single diode component including five electrical parameters, constitutes one of the simplest representations of PV panels' intrinsic nonlinear features. Castaner and Silvestre created an implicit mathematical formula known as the usual I-V characteristic equation (Castaner & Silvestre, 2002).

$$I = I_{ph} - I_s\left[e^{\frac{V+IR_s}{A_0 NV_t}} - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (6)$$

V is the PV voltage that is generated, Io is the diode's saturation current, A_o is the ideality factor, and R_s, R_{sh}, along with N are the serial resistance (Ω), the parallel resistance (Ω), and the total quantity of solar cells in a series string within the panel, respectively. The thermal voltage (Vt) can be mathematically stated as $V_t = kT/q$, where k is the value of the Boltzmann constant (1.380649×10^{-23} J/K) and q is the elementary charge (1.61×10^{-19} C). Further circuit analysis can create a mathematical association between I_{ph} along with the incident ambient condition of the photovoltaic cell (radiation, G, and temperature, T) as reported (Femia et al., 2017).

The total electricity delivered by the PV system over the course of a given period divided by the nominal generating capacity of the installed PV system is known as the final yield of the PV plant (Y_f), which is expressed in kWh/kWp. It specifies the number of hours the PV system must operate at nominal power $P_{pv,rated}$ each day in order to match its monitoring contribution to the net daily load.

$$Y_f = \frac{E_{AC}}{P_{pv,rated}} = \tau_r \times \frac{\left(\sum_{day} P_A\right)}{P_{pv,rated}} = Y_a \times \eta_{pv,\ system} \quad (7)$$

The PV system's efficiency is $\eta_{pv,sys}$, the reference yield (Y_r), which is expressed in kWh/kWp, is derived by comparing the measured reference irradiation ($G_{I,ref}$) of the PV system to the global solar irradiation of the desired location. One kW/m^2 is the value of $G_{I,ref}$ under standard test conditions (STC). The peak sun hour (PSH) occurs every year. The reference yield is the total quantity of theoretical energy present at a specific location for a specific amount of time. It represents the exact energy that was observed.

$$Y_r = \tau_r \times \frac{\left(\sum_{day} G_I\right)}{G_{I,ref}} \quad (8)$$

The PR is the proportion of actual output as compared to anticipated output for a particular reporting period. It serves as a gauge for the overall impact on the rated output of the PV system. It shows the overall impact of output losses on the plant's rated array caused by environmental factors like temperature and irradiation along with system element inefficiencies like the inverter, cabling, connections, or failure, etc. (Kavuma et al., 2022).

$$\text{Performance Ratio (PR)} = \frac{Y_f}{Y_r} \quad (9)$$

To assess the performance, energy yield, and power characteristics of the SMGS installed at Hotel Sarowar, Pokhara, Nepal with 140kWp capacity and data from the years 2022-2023 were used. Although the SMGS was established in 2021, data from that year is limited to only 3 months, and data for 2024 is available for just 6 months. For uniformity and comparative analysis, the study focuses on the data from 2022 and 2023.

Result and Discussion

The energy yield data for the SMGS with a 140 kWp capacity, measured in megawatt-hours (MWh) for each month of 2022 and 2023 is shown in figure 2. The data reveals significant fluctuations in energy yield across months and between years. In 2023, the energy yield was consistently lower in comparison to 2022, with some months showing negative yields, particularly in August. The comparison of energy yield data between 2022 and 2023 highlights several important trends and anomalies. In general, the overall yield for 2023 shows a decline compared to 2022, suggesting potential operational or environmental changes affecting the performance of the SMGS. For the study the data is taken from Topsun Energy Pvt. Ltd., located in Sanobharyang, Nagarjun-02, Kathmandu, is a company specializing in renewable energy solutions, particularly solar energy systems. Topsun Energy Pvt. Ltd. offers products and services that include the design, installation, and maintenance of solar power systems. In addition, Topsun Energy Pvt. Ltd.company is monitoring system of Hotel Sarowar SMGS.

In general, 2023 shows more consistent and stable yields when compared to 2022. Most months in 2023 either match or exceed the yields from the previous year, indicating that the system performed more efficiently during this period. This improvement could be attributed to factors such as better system operation, improved maintenance practices, or more favorable environmental conditions. However, there are still some notable variations that warrant attention. One of the most concerning observations is the negative yield recorded in August 2022, where the system produced -4.12 MWh. A negative yield suggests that the system either consumed power or experienced a significant malfunction. This could be due to several factors, such as equipment failure, panel shading, or particularly unfavorable weather conditions. This anomaly in performance should be investigated further to identify the root cause of the system's underperformance during that month.

Another concerning aspect is the zero yields in both September and October 2022. The complete lack of power generation in these months is highly unusual and indicates a potential system failure or significant environmental impact that hindered energy production. The absence of any yield during these months should prompt a thorough review of the system’s operational status, maintenance logs, and any external factors such as extreme weather or prolonged periods of cloud cover. On a more positive note, the winter months (December, January, and February) generally show stable performance, with December 2023 achieving the highest monthly yield of 11.46 MWh as shown in figure 2. These months typically face lower solar energy generation due to shorter daylight hours and lower sun angles, yet the system appears to maintain reliable output even during these challenging conditions. This suggests that the SMGS has the ability to deliver consistent performance throughout the year, despite the seasonal variations in solar irradiance.

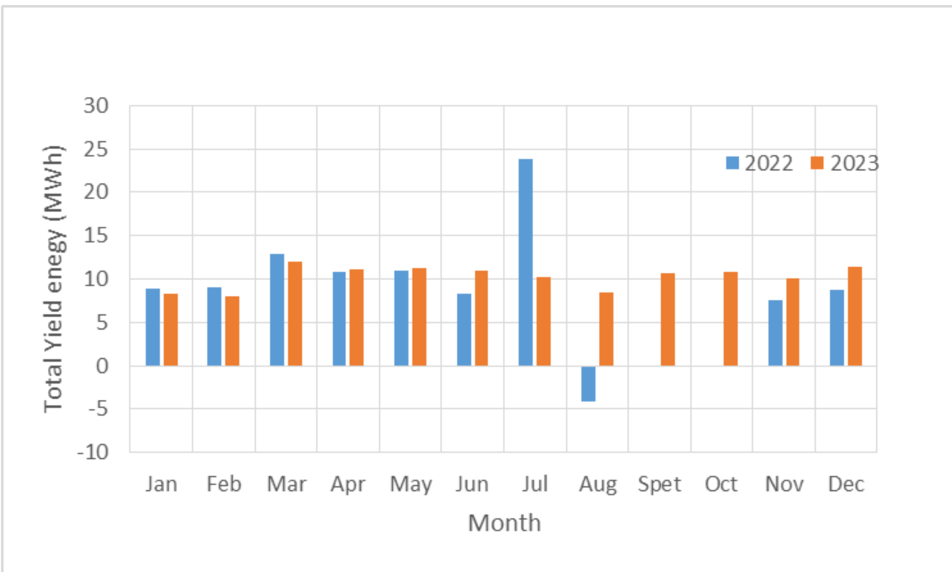

Figure 2: Comparison of total energy yield by Hotel Sarowar SMGS in 2022-2023

The peak yield for 2022 occurred in July, where the system produced 23.82 MWh. This was the highest yield of the year and likely reflects optimal weather conditions, such as clear skies or increased solar irradiance during the monsoon season. This highlights the potential for high generation during favorable months, but also points out the underperformance in other months, particularly in comparison to the system’s maximum capacity of 140 kWp. The overall performance of the SMGS in 2022 and 2023 indicates good energy production, but there are clear areas that require attention. The system's performance could benefit from a detailed analysis of the months with significant yield drops, especially in August, September, and October 2022. Potential issues with system maintenance, equipment malfunctions, or environmental impacts need to be addressed to ensure that the system operates consistently at or near its maximum capacity. The analysis of system capacity utilization shows that even during peak months, the SMGS did not reach its full potential, as in the case of July 2022 when it generated 23.82 MWh. The system's capacity factor, which is calculated by comparing actual output to the maximum possible output, suggests that there is room for improvement in terms of maximizing the plant's efficiency. Monitoring the system's performance more closely, particularly during high-output months, can help optimize its operation and improve overall performance.

Figure 3 illustrates the annual energy consumption patterns for Hotel Sarowar's SMGS in 2023. The total energy dynamics for the year include 214.103 MWh of externally supplied energy, 85.813 MWh of internally supplied energy, 85.813 MWh of self-consumption, and 11.239 MWh of energy fed back into the grid. Throughout the year, the energy consumption patterns vary significantly. July stands out with a high level of self-consumption and internal energy supply, accompanied by a notably lower reliance on external energy sources. This suggests that during this month, the SMGS was particularly effective in meeting the hotel's energy needs, reducing the dependency on external power sources. Conversely, in August, September, and November, the pattern shifts. During these months, the hotel relied heavily on external energy supplies, with maximum external energy usage observed. In contrast, the internal energy supply, self-consumption, and energy fed into the grid were at their lowest. This could indicate periods of lower solar energy production or higher energy demands, requiring greater support from external sources to meet the hotel's needs.

Figure 3: Energy Balance of Hotel Sarowar SMGS in 2022

For the remaining months of the year, the energy distribution between internal and external supply, self-consumption, and grid feeding is more balanced. This suggests that the SMGS operated effectively, with a relatively stable pattern of energy generation, consumption, and grid interaction during these periods. Overall, the data highlights the variability in energy consumption patterns at Hotel Sarowar, driven by seasonal changes in solar energy production and fluctuating energy demands. The SMGS performance peaks in July, showcasing its potential to reduce external energy dependency, while other months illustrate the system's limitations and the necessity of external energy sources to ensure uninterrupted power supply.

Ideal Power of PV module Hotel Sarowar SMGS

The computation detail of power at different irradiances and temperature is based on the Solarex MSX60 PV module, a conventional 60 W module made up of 36 polycrystalline cells connected in series, was used in the investigation. The module's specs, as shown in Table 1, were used for modelling at 25°C. The characteristics are as follows: maximum power (P_{max}) of 60 W, voltage with maximum power (V_{mp}) of 17.1 V, current with maximum power (I_{mp}) of 3.5 A, short-circuit current (I_{sc}) about 3.8 A, along with open-circuit voltage (V_{oc}) of 21.1 V (Solarex, 1998). These criteria served as the foundation for analysing the PV module's performance and attributes in the study.

Table 1: Specification of solar PV module used in this research Solarex MSX60 at 25 ºC

Parameters	MSX60 Specification
Maximum power (Pmax)	60 W
Voltage @ Pmax (Vmp)	17.1 V
Current @ Pmax (Imp)	3.5 A
Short-circuit current (Isc)	3.8 A
Open-circuit voltage (Voc)	21.1V

Figure 4 illustrates the output voltage of the solar PV module across different temperatures and irradiance levels. Temperature ranges from 11 °C to 34 °C, based on historical data obtained from the World Weather Online Data Center, while irradiance levels range from 4.4 to 4.8 kWh/m²/day, as sourced from the Global Solar Atlas. The data reveals that the maximum power generation occurs at a temperature of 11 °C with an irradiance of 4.8 kWh/m²/day, which is higher compared to the irradiance level of 4.4 kWh/m²/day. This trend is consistent across both temperature extremes observed. Specifically, at 34°C, the power generated with an irradiance of 4.8 kWh/m²/day is still higher than that with 4.4 kWh/m²/day. The MPPT at Hotel Sarowar is characterized by the voltage values corresponding to maximum power at different temperatures and irradiances as shown in figure 4. These voltage values are critical in optimizing the energy output of the SMGS as they reflect the system’s ability to adapt to varying environmental conditions. The MPPT ensures the system operates at its optimal point, where maximum energy is extracted from the solar panels under different irradiance levels. At Hotel Sarowar, with average irradiance levels of 4.688 kWh/m²/day GHI, the SMGS is expected to adjust efficiently to temperature variations, ensuring consistent power generation despite seasonal changes or fluctuations in solar intensity. This dynamic adjustment of voltage based on temperature and irradiance conditions is crucial for maximizing the performance and energy yield of the solar power system.

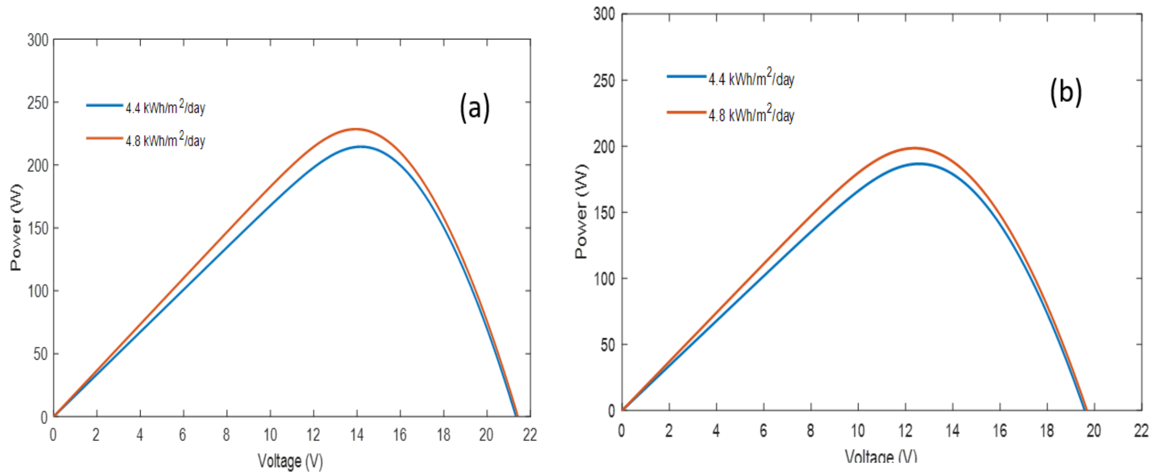

Figure 4: Output power of solar PV module (a) at 11 ºC and (b) at 34 ºC of Hotel Sarowar SMG

In terms of absolute values, the maximum power output observed at 11°C is approximately 250 W, whereas at 34°C, the maximum power output is around 200 W. This indicates that the PV module performs more efficiently at lower temperatures, with a significant reduction in power output at higher temperatures despite similar irradiance levels. The SMGS at Hotel Sarowar is situated in an environment with favorable solar irradiation conditions. The Direct Normal Irradiation is 3.543 kWh/m² per day, while the Global Horizontal Irradiation (GHI) is 4.688 kWh/m² per day, and the Diffuse Horizontal Irradiation (DIF) is 2.335 kWh/m² per day, indicating a good mix of direct and diffuse sunlight. The system benefits from a Global Tilted Irradiation at the optimum angle (GTI opta) of 5.198 kWh/m² per day, with an optimal panel tilt angle (OPTA) of 29°. The air temperature is 19.3°C, conducive to efficient solar panel performance, and the terrain elevation is 990 meters, offering clear air for improved solar radiation capture (Global Solar Atlas, 2025). These factors suggest the SMGS is well-positioned for effective energy generation, with the potential for optimal performance given proper system management. The figure 4 shows that GHI of this region lies in this region of irradiance 4.4-4.8 kWh/m^2/day. So, this nature of power is also fit to considered Hotel Sarowar SMGS.

Performance of Hotel Sarowar SMGS

The analysis of the PR for the SMGS over the months of 2022 and 2023 reveals several insights into the system's performance dynamics, more detail in figure 5. In January, the PR increased from 6.4009 in 2022 to 6.7227 in 2023, indicating a slight improvement in performance or efficiency at the start of the year. February saw a more pronounced enhancement, with PR rising from 6.3077 to 7.3777, suggesting a significant boost in system efficiency or output. March also experienced a moderate increase from 4.5617 to 4.9917, reflecting a positive trend in performance. However, this upward trend does not continue uniformly throughout the year. In April, the PR decreased from 5.9519 in 2022 to 5.5098 in 2023, indicating a decline in system efficiency. Similarly, May saw a decrease from 6.0925 to 5.6050, suggesting reduced performance during this period. June exhibited a notable drop in PR from 7.8992 to 5.8545, reflecting a significant reduction in performance or operational issues.

The performance in July shows a remarkable recovery, with PR increasing from 2.7036 in 2022 to 6.4321 in 2023. This substantial improvement indicates a recovery in system efficiency or a successful resolution of previous issues. August is particularly noteworthy: while the PR was a negative -15.2913 in 2022, it rebounded dramatically to 8.0191 in 2023. This sharp recovery suggests that August 2022 may have experienced severe system inefficiencies or failures, which were successfully addressed by August 2023. September and October also show improvement, with PR values of 6.0300 and 6.1039 in 2023, respectively, compared to zero PR in 2022. This change indicates a significant enhancement in data collection or system performance during these months in 2023. In contrast, November saw a decrease in PR from 7.7675 to 6.4143, suggesting a decline in performance compared to the previous year. December followed a similar trend with a decrease from 6.5301 to 5.1309, indicating reduced efficiency or performance issues.

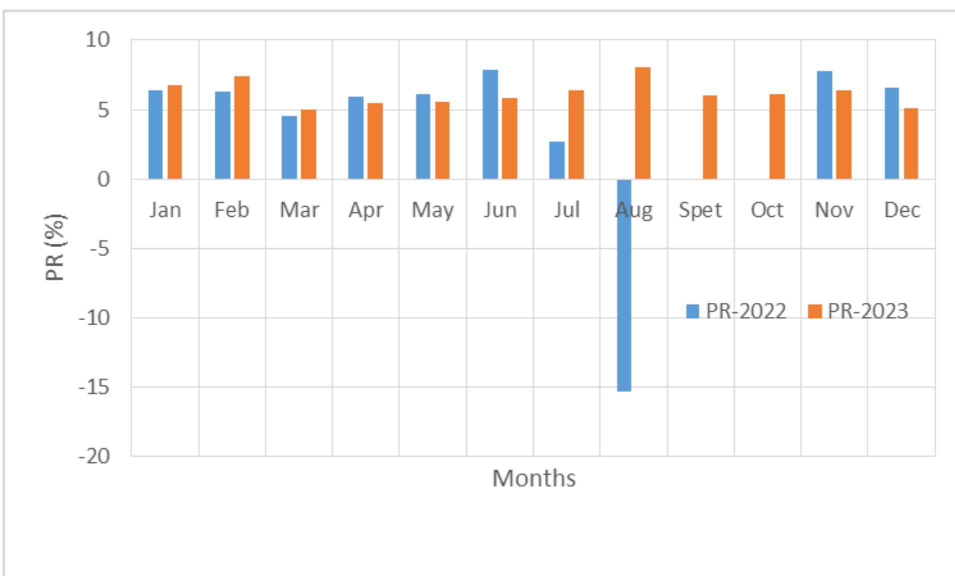

Figure 5: Performance of Hotel Sarowar SMGS

While there is a notable improvement in PR for many months in 2023 compared to 2022, there are also periods of decline. The significant recovery observed in August and the improvement in September and October highlight successful enhancements or adjustments made to the system. However, the decreases in performance during April, May, June, November, and December warrant further investigation to address any underlying issues affecting system efficiency. This analysis provides a comprehensive view of the system's performance trends and suggests areas for potential optimization and improvement.

he energy yield analysis of Hotel Sarowar's SMGS for 2022 and 2023 reveals significant monthly fluctuations in energy generation, with 2023 showing generally improved stability despite lower overall yields compared to 2022. Notable performance anomalies include negative yields in August 2022 (-4.12 MWh) and zero yields in September and October 2022, indicating possible equipment failures, shading, or extreme weather conditions. The peak yield was recorded in July 2022 (23.82 MWh), reflecting favorable solar conditions, while December 2023 achieved the highest winter yield (11.46 MWh), demonstrating the system's ability to maintain efficiency despite seasonal variations. Energy consumption patterns for 2023 further highlight SMGS's operational efficiency. A total of 214.103 MWh was externally supplied, while 85.813 MWh was internally generated, with the same amount used for self-consumption and 11.239 MWh fed back into the grid. July 2023 exhibited optimal self-consumption and minimal reliance on external power, whereas August, September, and November showed increased dependency on external energy due to reduced solar generation.

Given the performance trends and system capacity of 140 kWp, MPPT remains the preferred technique for SMGS. MPPT is crucial in maximizing power extraction, especially during high-irradiance months like July. It ensures optimal utilization of available solar energy and improves system efficiency. However, LPPT be considered during low-irradiance periods, such as early mornings, late evenings, or cloudy days, to maintain stable power output and prevent excessive switching losses. LPPT could also help during winter months (December–February) when solar generation is lower, ensuring consistent energy supply without frequent MPPT fluctuations. For Hotel Sarowar SMGS, MPPT is essential for maximizing energy production during peak months, while LPPT could be selectively used for enhanced stability during low-irradiance conditions. A hybrid MPPT-LPPT approach may optimize performance and ensure efficient energy utilization across varying environmental conditions.

Optimization through MPPT and LPPT Integration

The analysis of the Hotel Sarowar SMGS performance across 2022 and 2023 reveals significant fluctuations in energy yield and PR. These fluctuations indicate that while the system has shown improvements in certain months, there are also notable periods of decline that require attention. To enhance the efficiency and reliability of the SMGS, several modifications and optimizations are recommended, particularly in the context of MPPT and LPPT techniques. The system's performance data indicates that external factors, such as changes in irradiance and temperature, significantly impact energy yield. MPPT algorithms are essential for optimizing the energy harvested from solar panels by continuously adjusting the operating point to capture the maximum available power. Integrating advanced MPPT algorithms tailored to the specific environmental conditions of the Hotel Sarowar SMGS can help improve the consistency of energy production, especially during periods of fluctuating irradiance. Additionally, LPPT techniques can be employed to limit the power output during peak irradiance periods to prevent overloading and ensure stable operation. This is particularly relevant in scenarios where the grid's capacity to absorb excess energy is limited. Implementing a hybrid MPPT-LPPT approach can maximize energy capture during low irradiance periods while preventing energy wastage or system instability during peak production times.

Conclusion

The performance analysis of the Hotel Sarowar SMGS reveals significant variations in energy output and PR across different months in 2022 and 2023. While improvements were observed in several months, notably in January, February, July, and August, there were also notable declines during April, May, June, November, and December. The fluctuation in performance can be attributed to external factors such as temperature and irradiance levels, as seen in the PV module's response to changing environmental conditions. Temperature analysis showed that the solar module performs more efficiently at lower temperatures, with the maximum output observed at 11°C. However, performance decreases significantly at higher temperatures, despite similar irradiance levels. This highlights the need for system adjustments to mitigate temperature-related inefficiencies. To optimize system performance, it is recommended to integrate MPPT and LPPT techniques. MPPT will ensure the system operates at optimal power output across varying irradiance levels, while LPPT will help manage power during peak periods to prevent overloading and ensure grid stability. A hybrid approach combining both MPPT and LPPT is suggested to maximize energy capture while maintaining system stability and efficiency. Further investigation is needed to address the root causes of performance declines during certain months, focusing on potential system inefficiencies and optimization opportunities.

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