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Original Research

Implementation a 10 MW Grid-Connected Solar Photovoltaic System in India

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Abstract:

This study presents the design, optimization and performance analysis of a 10 MWp grid-connected solar photovoltaic (PV) systemin North India. A sequential approach is applied for SPV system design using PVSyst software, following by execution and feasibility assessment. Two PV technologies Hanwa (13.41 MWp) and Waaree (1.505 MWp) modules are modelled using PVSyst meteorological data to ensure accurate performance estimation. The optimized system comprises 47,140 modules arranged in strings of 20 modules, achieving a nominal capacity of 14.92 MWp and occupying 75 acres with a total module area of 92,144 m^2. Total annual energy production is 22,651.4 MWh. The performance ratio (PR) ranges from 72.6% to 75.7%, the Capacity Utilization Factor (CUF) varies between 14.4% and 20.3%. System and array capture losses are 0.46 kWh/kWp and 1.44 kWh/kWp respectively. The key performance indicators like Gross Monthly Energy Yield (1,887.62 MWh/month), Daily Energy Yield (62.06 MWh/day), Array Yield (1,518 kWh/kWp/year), and Final Yield (1,518 kWh/kWp/year) are analyzed. The novelty of this study lies in its experimental validation using a dual-string setup monitored through real-time SCADA data, which effectively quantified soiling impacts showing an average daily degradation of 0.7% in uncleaned modules and confirmed the accuracy of simulation results.

Keywords: Grid-tied solar photovoltaic systems; Performance ratio; Photovoltaic efficiency; Soiling losses; Daily cleaning strategies

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1. Introduction

Electrical energy consumption is growing rapidly due to population growth, improving living standards and industrial advancement. The energy demand-supply gap is widening, placing significant pressure on conventional energy generation resources. The limited conventional energy resources are depleting and pollute the environment during generation and transmission. Therefore, the need for green alternatives is urgent need of present time. Alternative energy generation methods are essential to meet the growing demand of electricity addressing the climate challenges. Among the various renewable energy sources, solar photovoltaic (PV) systems, has emerged as a promising choice due its abundant availability, low maintenance, and long-term environmental benefits [1].

Solar photovoltaic (PV) systems are pivotal in the global shift towards renewable energy, converting sunlight into electricity and offering a clean alternative to fossil fuels. These PV systems are classified into on-grid, off-grid, and hybrid configurations. The off-grid systems include energy storage, allowing power backup even without sunlight, but they are costly and bulky [2]. On-grid systems, connected directly to the grid, are cost-effective, compact, and less hazardous as they lack battery storage, making them the most preferred option for simplicity and affordability. Hybrid systems can charge storage from both the grid and solar PV, combining features of the other two [3].

Government initiatives in renewable energy research and development are crucial to reducing generation costs and encouraging international collaboration for advanced technologies [4]. Integrated Photovoltaic systems, are gaining attention in India. India is a country with immense solar potential with an average solar insolation of 4 – 7 kWh/m^2/day and receiving over 300 sunny days annually. With initiatives like the National Solar Mission and ambitious renewable energy targets, solar PV installations are expanding rapidly. Large-scale grid-connected PV systems are increasingly being installed to supplement conventional generation and reduce carbon footprints. Despite being in the developmental stage, rooftop PV systems have proven effective for power supply in specific regions of India [4, 5]. Accurate system sizing is crucial to avoid over-sizing or under-sizing, which can increase costs. Selecting the appropriate combination of PV modules and inverters to meet desired parameters-such as voltage, current, power, and MPPT count-is critical. Systematic design, simulation, and performance evaluation are crucial for ensuring optimal operation of these systems under different climatic conditions [6]. Tahir et al. five case studies, focusing on the optimal design of PV panels using the System Advisor Model (SAM) for performance and financial analysis 10 MW PV systems in the UAE using SAM, PVsyst, and PVGIS for performance and financial analysis [7]. Shamsi et al. discussed designing and managing photovoltaic energy systems integrated with double-conversion uninterruptible power supplies, and developed a method for selecting the appropriate number of panels based on environmental conditions [8]. Rang et al. investigated the optimal configuration of a grid-connected PV system, establishing mathematical models for PV panels and storage batteries, and proposed two operating strategies for systems with and without storage [9]. Boruah et al. [10] utility-run rooftop PV power plants with battery energy storage systems were demonstrated to enhance energy storage and grid resilience at the distribution network level. Rout et al. [11] proposed a grid-connected rooftop PV system as a viable alternative to land-based arrays, highlighting challenges such as regulations, grid connectivity, and voltage stability issues. Obeng et al. [12] assessed the technical and economic feasibility of a 50 MW grid-tied PV plant using PVsyst for performance simulation. Pachauri et al. [13] conducted a techno-economic analysis of a grid-connected solar PV-fuel cell hybrid system for a small shopping complex in India, focusing on cost management and power flow between the system and the utility grid. Aziz et al. [14] analysed the feasibility of a solar PV microgrid system for both grid-connected and outage conditions based on a household case study in Baghdad. Mokhtara et al. [15] developed a sector coupling strategy for a grid-connected PV/battery/H_2 hybrid energy system at a university campus in Algeria. Grid-connected SPV systems are mainly impacted by dust accumulation, decreasing sunshine exposure and energy output. Geographic and seasonal variation affects the SPV system's efficiency due to airborne dust, wind speed, rainfall, moisture, and dust storms. Wasim et al. [16] reported seasonal soiling variations in Qatar based on a multi-year field study, underlining how environmental conditions affect photovoltaic (PV) performance in desert regions. Sajid et al. [17] examined the sources and modeling of dust soiling and introduced a tangent search-based algorithm aimed at optimizing power extraction in PV systems. Mostefaoui et al. [18] found a 26 – 34% drop in PV performance due to dust accumulation in the Saharan region of southern Algeria (Adrar). Similarly, Styszko et al. [19] linked elevated levels of airborne particulate matter with increased soiling rates on PV panels. Javed et al. [20] employed artificial neural networks to model the impact of soiling in Doha, Qatar, demonstrating the potential of machine learning in performance prediction. Falope et al. [21] emphasized the significant influence of environmental conditions and system design on dust deposition rates. Olivares et al. [22] studied the effects of soiling on PV surfaces using controlled experiments with glass samples. In a related study, Bakhsh et al. [23] observed a 2% reduction in glass transmittance within the first day of dust exposure in Saudi Arabia. Boyle et al. [24] documented an 11% loss in light transmission over five weeks in Colorado. Charabi and Gastli [25] reported up to an 81% performance decline due to combined dust accumulation and temperature-related constraints. Kazem et al. [26] found that PV efficiency dropped by 0.248% for every degree Celsius increase in temperature. A notable event analyzed by Al Siyabi et al. [27] examined the impact of a March 2022 dust storm in Spain, which led to an 80% reduction in the national PV capacity factor on the storm's most severe day. Micheli et al. [28] conducted a comparative study of two identical 7 kWp PV systems, highlighting substantial performance losses attributable to dust accumulation. Sahouane et al. [29] further explored methods for estimating soiling effects in Southern Spain, emphasizing the variability in dust impact across different climates.

The literature review highlights similar research works and identifies research gaps addressed in the present paper as novel contributions. For the current study, the PV system design and simulation are carried out using PVsyst, a comprehensive and widely adopted software tool. PVsyst facilitates the pre-sizing of inverters and PV panels, ensuring that neither component is undersized. To achieve an accurate system design PVsyst requires key input parameters such as geographical location, tilt angle, azimuth orientation, PV module and inverter specifications, as well as shading conditions [30, 31, 32, 33, 34].

This study investigates the optimization and performance of a 10 MWac grid-connected PV system located in North India using PVSyst simulations supported by experimental validation against soiling impacts. The study also explores seasonal performance variations, energy yield characteristics, and the impact of environmental factors such as soiling, monitored through a SCADA-

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based system. By focusing on both simulation and real-time operational data, the study contributes valuable insights for improving design practices and enhancing the efficiency of utility-scale PV installations in Indian conditions.

Several studies have explored the design and development of solar PV systems considering the overall performance analysis. Key findings and contributions of the present work include the following.

- System sizing: Grid-connected solar plant has an installed capacity of 14.92 MWp and a maximum output of 10 MWac, consisting of two PV arrays arranged in 2,357 strings of 20 modules each and connected to ten 1000 kW-C inverters.

- System performance: The designed system achieved an annual energy production of 22,651.44 MWh/year with an average PR of 74.26%. Monthly variations in the CUF is ranged from 20.3% in April and May to 14.4% in January, ensuring reliable infrastructure integration.

- Yield metrics: Reference Yield (Y_r), Array Yield (Y_a), and Final Yield (Y_f) highlighted peak values of 8.44 kWh/kWp (Y_r) and 5.88 kWh/kWp (Y_f) in May, with lower yields in January and December.

- Simulation outputs: These include meteorological data, efficiency metrics, losses, performance ratio, energy production, carbon emission balance, and financial evaluation. It evaluates energy production, efficiency, and the economic feasibility of cleaning strategies while considering system design and operational challenges.

- Soiling impact: Dust and particulate matter accumulation caused a 7.5% power loss over 11 days without cleaning, with daily soiling losses averaging 0.7%. Scenario-based cleaning analyses revealed summer losses of 70 kWh/day and winter losses of 45 kWh/day.

- Innovative approach: The study employed advanced monocrystalline PV technology from two manufacturers and a dual seasonal tilt for energy optimization. Real-time performance monitoring using SCADA systems facilitated a detailed analysis of soiling losses across two string configurations, highlighting a 7.6% current loss in one string due to dust accumulation.

- Practical implications: This research provides actionable insights into optimizing PV systems through adapted cleaning schedules, efficient resource allocation, and better integration of advanced monitoring systems. It underscores the economic and technical benefits of mitigating soiling in dusty environments.

2. Methodology and working of the work

The methodology for assessing the technical and economic impact of soiling on a grid-connected PV system involves defining research objectives, selecting an experimental site, and gathering inputs like PV capacity, configuration, and technology type for accurate simulation is shown in figure 1. The PV system is executed on the site, and a comparative analysis is performed. Key performance parameters are analyzed under varying conditions using real-time string monitoring through SCADA. Soiling losses are identified by deviations in current values, with one string cleaned regularly to track dust accumulation. The impact of techno-economic factors on soiling losses is assessed, considering climate and cleaning cost-efficiency.

3. Site selection and meteorology profile

The selected site for the solar PV system is in Maudaha, Uttar Pradesh, India (25.91°N, 79.92°E) at an altitude of 111 m and UTC+5.5, with an albedo of 0.20 as shown in figure 2 [31]. The Clearness Index (CI) and solar radiation vary throughout the year, peaking in March and November with a CI of 0.632. The highest solar radiation occurs in May, reaching 6.58 kWh/m^2/day. From June to August, CI values drop to 0.414 and 0.405 in July and August, reducing solar radiation to 4.6 and 4.28 kWh/m^2/day, respectively [32, 35]. Seasonal temperature variations with solar radiations for the site are shown in figure 3.

4. Solar PV system design criteria and specifications of system element

The proposed grid-connected solar PV power plant performance is analysed according to the parameters. It can be evaluated using several parameters representing different time frames and efficiencies. The daily energy output ($E_{ac/d}$) refers to the total electrical energy generated by the PV system in a single day, typically measured in kilowatt-hours (kWh). It can be affected by factors like sunlight availability and system efficiency.

$$E_{ac/d} = \sum_{0}^{24} E_{(ac/h)} \tag{1}$$

The monthly energy output ($E_{ac/m}$) aggregates the daily energy outputs over a month, offering insight into how the system performs over a longer period while considering seasonal variations.

$$E_{ac/m} = \sum_{0}^{30} E_{ac/d} \tag{2}$$

The annual energy output ($E_{ac/y}$) represents the total energy generated by the system over an entire year, helping to assess long-term performance and potential savings.

$$E_{ac/y} = \sum_{0}^{365} E_{ac/d} \tag{3}$$

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The reference yield (Y_r) is the theoretical maximum energy output if the system operates under ideal conditions, calculated based on solar irradiation and reference PV irradiation.

$$Y_r = \frac{\text{PlaneI radiance total } (T_h)}{\text{Reference PV irradiance } (G_{\text{pvo}})} \tag{4}$$

In contrast, the array yield (Y_a) measures the actual energy output of the PV array, normalized by the installed capacity, and helps gauge the efficiency of the solar modules.

$$Y_a = \frac{\text{DC energy output } E_o \text{ (kWh)}}{\text{Nominal array power } P_n \text{ (kWp) at STC}} \tag{5}$$

The final yield (Y_f) indicates the net energy delivered to the grid or load, accounting for system losses, and is normalized by the installed capacity.

$$Y_f = \frac{\text{Net energy output } NE_{\text{pv}}}{\text{Nominal array power } P_n \text{ (kWp) at STC}} \tag{6}$$

The PV module efficiency (η_{pv}) quantifies how effectively the solar modules convert sunlight into electricity, with higher values indicating better performance.

$$\eta_{\text{pv}} = \frac{P_{\text{dc}}}{G_s \times A_{\text{pv}}} \times 100 \tag{7}$$

Array capture loss (L_a) represents the energy losses due to shading, soiling, and module mismatches, while system loss (L_s) accounts for energy losses between the PV array and the final usable output, such as losses in the inverter or wiring.

$$L_a = Y_r - Y_a \text{ (kWh/kWp)} \tag{8}$$

$$L_s = Y_a - Y_f \text{ (kWh/kWp)} \tag{9}$$

The performance ratio (PR) compares the actual energy output to the theoretical output under ideal conditions, with higher values reflecting better efficiency to evaluate the overall system performance.

$$\text{PR} = \frac{Y_f}{Y_r} \times 100 \tag{10}$$

Lastly, the Capacity Utilization Factor (CUF) measures the effectiveness of the system by comparing the actual

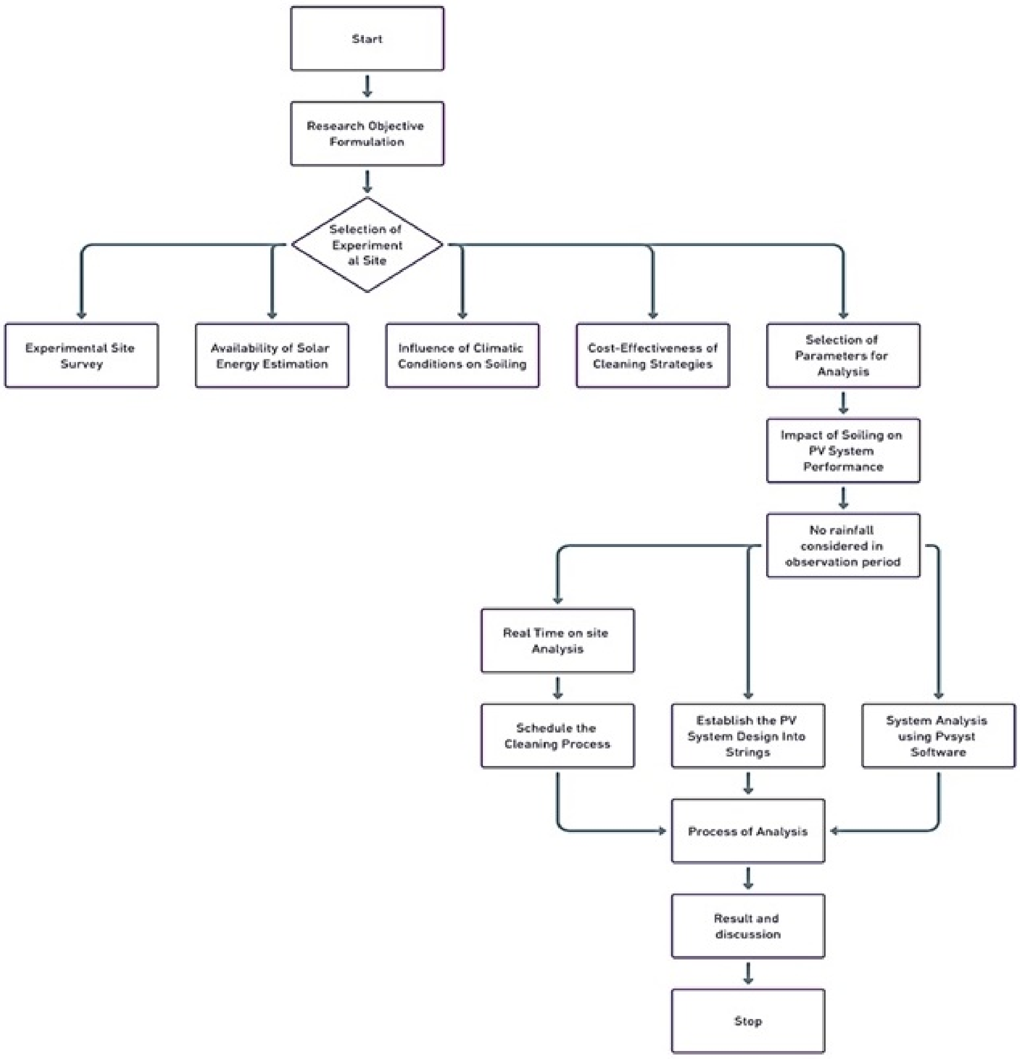

Figure 1. Methodology of the work.

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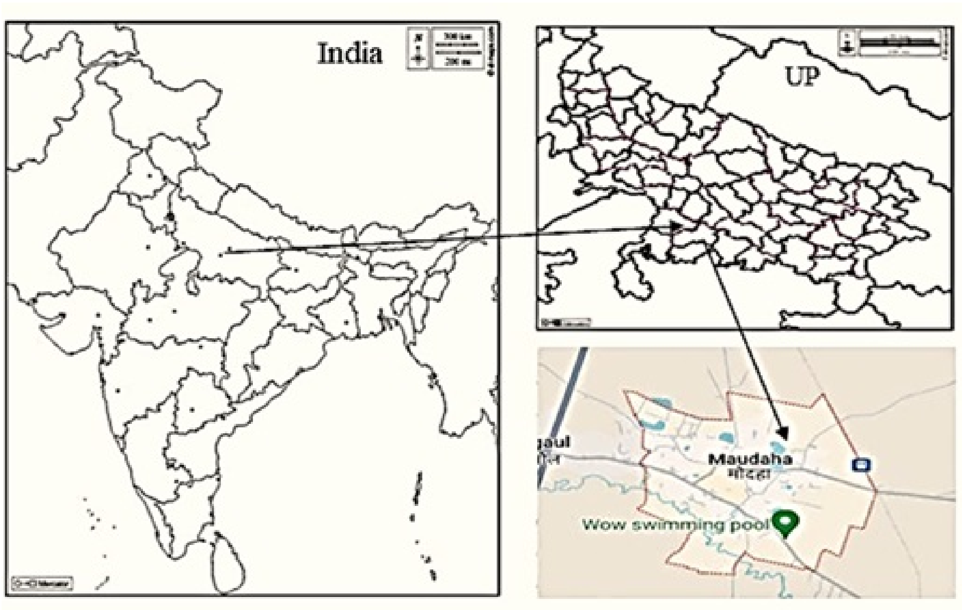

Figure 2. Site map Selected for the SPV system design and analysis [31].

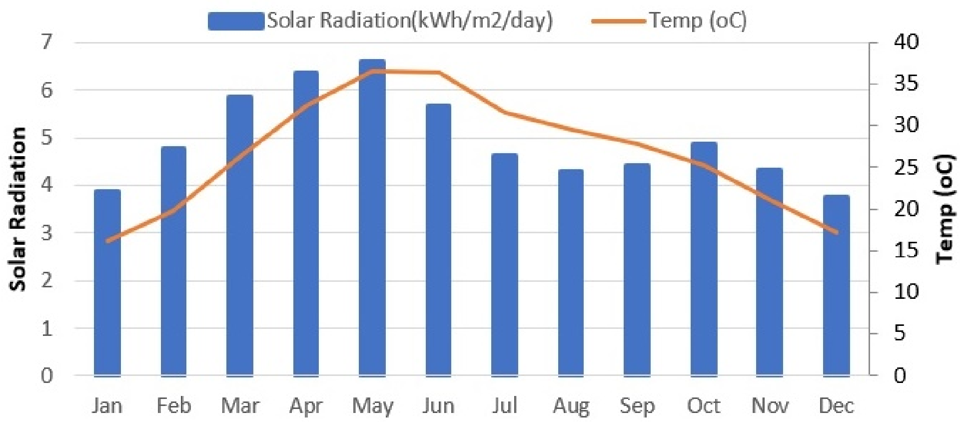

Figure 3. Solar radiation and temperature at considered site [32].

energy output to the maximum potential energy output over a given time period, expressed as a percentage.

$$\text{CUF} = \frac{E_a}{P_n \times t} \times 100 \tag{11}$$

These parameters collectively help in understanding the system's performance, efficiency, and long-term energy generation potential [36, 37, 38, 39, 40]. The working and schematic layout of the SPV system is shown in Fig. 4 (a). The detailed component specifications for the SPV plant are given in Table 1. The proposed system uses monocrystalline PV panels, an inverter with 95% efficiency and a 15-year lifespan, and a three-phase double-fed transformer for efficient power transfer. The system includes String Combiner and Monitoring Boxes (SCB-SMB) to aggregate PV strings, simplify wiring, and improve reliability. High-voltage switchgear protects equipment by isolating faulty circuits and maintaining continuous power flow. A Supervisory Control and Data Acquisition (SCADA) system monitors voltage (V), current (I), and power (P) for the SPV plant.

5. SPV system simulation results and analysis

The simulation uses PVsyst software, which models the PV system's performance based on configuration and environmental parameters. The parameters addressed in Table 2 are summarized in Table 3 based on the simulation. The system's schematic layout is shown in figure 5. The SPV System simulation results, performance analysis, optimization of energy yield, and loss analysis are described below for performance [39, 40, 41, 42, 43].

- System design and simulated structure

The PVsyst simulation obtained that the installed capacity of the grid-connected solar plant would be 14.92 MWp for obtaining the maximum output of 10 MWac. The simulation model is designed to consist of two strings of different PV panels whose numbers are obtained as 42,580 Hanwa Solar modules (13.41 MWp) and 4,560 Waaree modules (1.505 MWp).
The PV panels are arranged in 2,357 strings of 20 mod-

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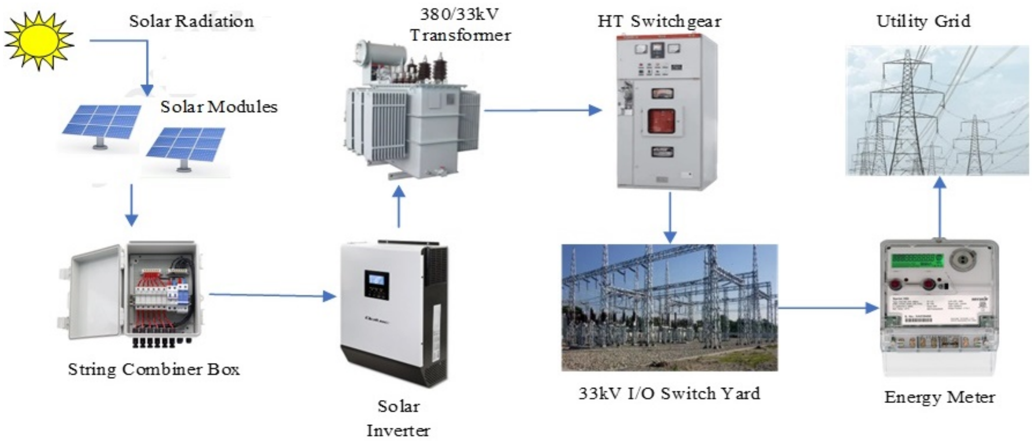
ules each and connected to ten 1000 kW-C inverters. The considered seasonal tilt adjustments are 10° tilt in summer and 30° tilt in winter.

- Energy production, seasonal performance and System yield

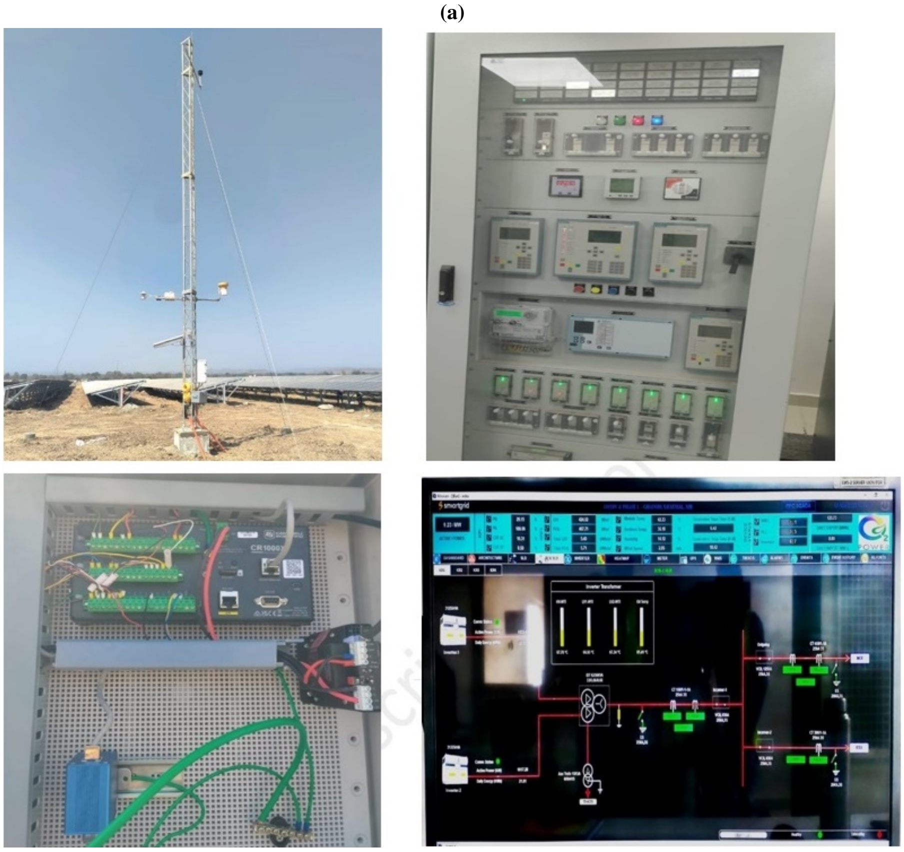
The Annual energy production of Grid connected solar PV plant is obtained as 22,651.44 MWh, with a specific yield of 1,518 kWh/kWp/year. During the Spring (April-May) season, due to high irradiance and longer days, the maximum generation is received at 2418 MWh/-month. This time duration observes peak array yield (6.50 kWh/kWp) and final yield (5.88 kWh/kWp). The reduced solar availability during the winter (January-December) season results in lower energy generation, 1723 MWh/month. A similar reduction is observed for array yield (3.57 kWh/kWp) and final yield (3.26 kWh/kWp). The high range of heat availability in the summer (June-July) season reduces the energy production efficiency of 1822 MWh/month, with a final yield of 4.35 – 4.93 kWh/kWp.

- Performance metrics

The Performance Ratio (PR) was obtained between 72.6% and 75.7% from simulation software, with an average Performance Ratio of 74.26%, indicating efficient energy conversion. The Capacity Utilization Factor (CUF)represents peak values at 20.3% in April-May and



(a)



(b)

Figure 4. (a) Working & schematic arrangement of solar PV power generation system [33].(b) Monitoring arrangement of Solar PV power generation system.

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Table 1. Solar PV system design and analysis addressed in recent literatures.

Authors	Year	Location	Capacity (kWp)	Final yield (h/d)	PR (%)	CUF (%)	Ref.
Shukla et al.	2024	India	50	3.90	75.90	17.70	[44]
Shukla et al.	2024	India	1000	4.50	76.91	14.07	[45]
Lagouch et al.	2024	Algeria	5000	4.94	72.30	20.60	[46]
Herbazi et al.	2022	Morocco	2	4.72	78.13	19.71	[47]
Bansal et al.	2022	India	9000	–	70.76	18.40	[48]
Ramanan et al.	2019	India	1	4.31	78.99	17.99	[49]
Sahouane et al.	2019	Algeria	28	4.42	–	18.58	[50]
Raghoebarsing et al.	2017	Suriname	27	3.70	74.50	15.50	[51]
Emmanuel et al.	2017	Kenya	600	–	57.40	13.97	[52]
Sharma et al.	2017	India	2.18	3.75	78.00	15.27	[53]
Dobaria et al.	2016	India	5.05	4.49	74.00	–	[54]
Kumar et al.	2016	India	80	4.45	83.20	18.26	[55]
Shukla et al.	2016	India	110	2.67–3.36	71.6–79.5	–	[56]
Shiva Kumar et al.	2015	India	10000	1.96-5.07	86.12	17.68	[57]
Sharma et al.	2013	India	190	2.23	74.00	–	[58]

Table 2. Characteristic details of components used in hybrid energy generator system.

System element	Parameters	Ratings	Ref.
Solar Modules (SPV)	Panel Rating	335 W	[34, 59, 60, 61, 62, 63, 64]
	Cell Category	Monocrystalline	
	Temperature coefficient	−0.300	
	Operating temperature	43.00 °C	
	SPV panel efficiency	21%	
	Life span	25 Years	
String Combiner Box	Number of Strings	2985 strings (approx.)	[65, 66, 67, 68, 36, 37]
	Total current	15 A/str	
	Total voltage	1000 V (approx.)	
	Fault current	Defined per system design	
	Number of inputs	12-24 (typical per box)	
Solar Inverter (SI)	CR Rated Power	1 kW	
	Relative capacity	100%	
	Efficiency	95%	
	Life span	15 years	
HT Switchgear	Rated Voltage	33 kV	
	Rated current	350 A	
	Life span	25 years	
SCADA System	Monitoring Parameters	Voltage, Current, Power	
	Communication protocol	Modbus, IEC 61850	
	Data storage	Cloud/Local Server	
	Life span	15 years	
Grid Connectivity	Rated Capacity	30 kV I/O	
	Transformer rating	10 MVA (approx.)	
	Power factor	> 0.95	
	Life span	25 years	

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Table 3. Simulation results for SPV system design.

Category	Details	Values
System design	Installed capacity	14.92 MWp
	Maximum output	10 MWac
	Hanwa solar modules	42,580 (13.41 MWp)
	Waaree solar modules	4,560 (1.505 MWp)
	String configuration	2,357 strings (20 modules/string)
	Inverters	10 × 1000 kW-C
Energy production & yield	Annual energy production	22,651.44 MWh
	Specific yield	1,518 kWh/kWp/year
	Peak monthly generation (April-May)	2,418 MWh
	Lowest monthly generation (January)	1,723 MWh
Performance metrics	Performance ratio (PR)	72.6% – 75.7% (Avg:74.26%)
	Capacity utilization factor (CUF)	Peak:20.3% (April-May); Lowest: 14.4% (January)
Loss analysis	Inverter losses (L_s)	0.31 kWh/kWp (Winter); 0.62 kWh/kWp (May)
	Array capture losses (L_a)	0.93 – 0.95 kWh/kWp (Winter); 1.94 kWh/kWp (May)
Efficiency variations	Efficiency (cooler months)	Peak:15.70% (December-January)
	Efficiency (warmer months)	Drop to 11.64% (May)
	Reference yield	Peak:209.3 kWh/kWp (May)
	Highest energy yield	162.06 kWh (May)
Probability distribution	P50 output	22.65 GWh/year
	P75 output	21.80 GWh/year
	P90 output	21.03 GWh/year
Tilt adjustments	Summer tilt	10°
	Winter tilt	30°
Summarized PVSyst simulation results for energy and losses		
	Array nominal energy (STC)	29164 MWh
Losses	Degradation losses	1475 MWh
	Temperature losses	3520 MWh
	Mismatch losses	960 MWh
	Ohmic wiring losses	448 MWh
	Inverter losses	537 MWh
	AC ohmic losses	323 MWh
	Transformer losses	425 MWh
Available energy at inverter output		22373 MWh
Energy injected into grid		22028 MWh

drops to 14.4% in January due to tinier sunshine hours as shown in figure 6.

- Loss analysis

System losses (L_s), primarily from inverter inefficiencies, range from 0.31 kWh/kWp in winter to 0.62 kWh/kWp in May. Array capture losses (L_a) are lowest in winter (0.93 – 0.95 kWh/kWp) and highest in May (1.94 kWh/kWp) due to higher temperatures.

- Efficiency variations

Due to lower temperatures, PV efficiency peaks at 15.70% in cooler months (December-January). However, higher solar irradiance from April to June boosts the reference

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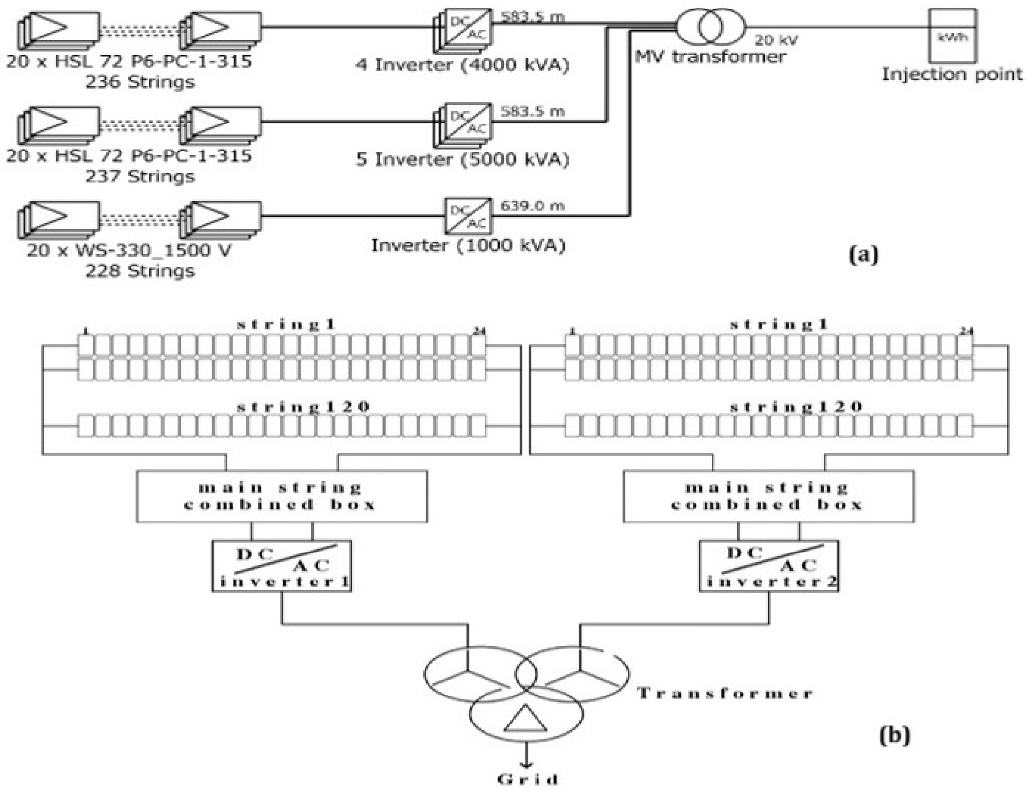

Figure 5. (a) Single-line diagram. (b) Typical plant layout of considered SPV generation system in two strings.

yield, peaking at 209.3 kWh/kWp in May, though efficiency drops to 11.64% due to heat. Despite this, May achieves the highest energy yield at 162.06 kWh.

- System output

The daily input-output data and system output power distributions are illustrated in Appendix 1 with a single-line diagram of the proposed system. The DIO diagram shows a correlation between solar radiation (kWh/m^2/day) and system output energy (MWh/day), The output power distribution graph shows most energy output within lower to mid-power ranges, with occasional peaks during optimal conditions. These figures collectively highlight the system's efficiency, variability, and reliability throughout the year, influenced by solar availability, cloud cover, and temperature.

- Probability distribution for total energy generation

The Probability Distribution Function graph shows the prospect of realizing various energy production levels considering meteorological and system variations, as shown in Appendix 1. P50:22.65 GWh/year (most probable output), P90:21.03 GWh/year (90% chance of achieving this output), P75:21.80 GWh/year (75% probability level). The bell-shaped curve peaks at P50 and indicates variability due to factors like irradiance,

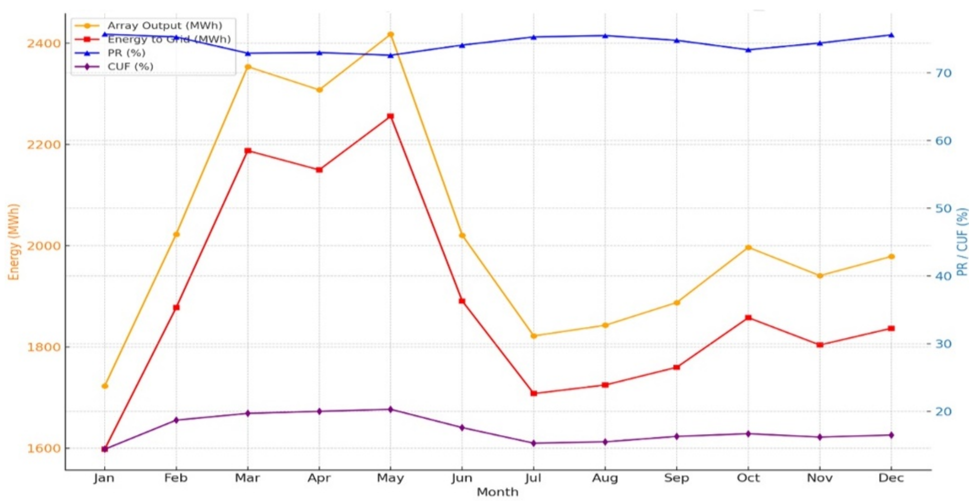

Figure 6. Array energy output, energy into grid, performance ratio and capacity utilization factor.

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temperature, and system losses. The P90 value defines a conservative lower bound, offering insight into system reliability and risk.

6. Performance analysis of SPV plant for soiling and environmental impact for 12 days cleaning schedule

The schematic of the proposed grid-connected PV system is shown in Fig. 5 (b), with the system sizing results discussed in the previous section. These simulated results were applied to the grid-connected SPV plant at the selected location. It consists of two-panel strings, String A and String B. The system uses SCADA to assess current and power losses due to soiling and environmental factors. Table 4 also outlines the performance parameters used for estimating soiling losses. A manual cleaning schedule was implemented from April 15 to April 26, 2024, where String A was cleaned daily, while String B remained uncleaned. SCADA monitoring revealed output deviations caused by dust accumulation. A comparative analysis of the 12-day cleaning schedule is shown in figure 7. On Day 1, no deviations were observed in current or power. By Day 2, current dropped by 1.1% and power by 1.3%. On Day 4, losses increased to 3.2% (current) and 3.4% (power). By Day 8, deviations reached 6.3% (current) and 6.1% (power), peaking on Day 11 with 7.6% (current) and 7.5% (power). After cleaning on Day 12, deviations returned to 0.0%, highlighting the effect of soiling and the cleaning effectiveness, as shown in figure 7.

7. Discussion and comparative analysis

The similar works including a comparative discussion that clearly connects the findings with relevant studies reviewed in the literature. The results of our 14.92 MWp utility-scale PV plant have been evaluated against several existing installations across diverse geographies, particularly those with comparable climatic or operational conditions.

The present system recorded an average PR of 74.26%, which is in line with findings from similar studies. For example, Shukla et al. (2024) reported a PR of 76.91% for a 1 MWp installation in Lucknow, while Dobaria et al. (2016) observed a value of 74% in Rajkot. These similarities highlight the reliability and consistency of well-executed system designs under Indian climatic conditions [51, 52, 53, 54]. Interestingly, our PR is also comparable to international benchmarks, such as the 74.5% reported in Suriname (Raghoebarsing et al 2017) and data from Adrar, Algeria (Sahouane et al., 2019), which suggests that current system performance meets global standards for optimized installations [47, 48, 49, 50].

The Capacity Utilization Factor (CUF) in the present analysis ranged between 14.4% and 20.3%, which places it within the expected performance band for high-efficiency solar PV systems. These results are on par with results from Tamil Nadu (17.99%, Ramanan et al., 2019), Gujarat (18.4%, Bansal et al., 2022), and even Reggane in Algeria (20.6%, Lagouch et al., 2024). Such comparisons reinforce that present results make effective use of available solar resources, particularly given the seasonal variability typical of subtropical climates [46,

Table 4. Performance parameters consider for estimation of soiling loss.

	Aspect	Observation
Cleaning Schedule and	Study period	15-Apr-24 to 26-Apr-24
monitoring period	Initial condition (Day-0)	Both strings cleaned thoroughly with water
	Day-1	Currents of both strings are almost identical,
	Subsequent days	String A: Cleaned daily
		String B: Left uncleaned until Day-10
Data collection	Current monitoring	Daily current output recorded for each string
and analysis	Performance comparison	String A (cleaned daily) with String B (uncleaned) daily over 10 days
	Soiling loss trend	Calculation of power and current losses based on deviation between the strings
Results and	Initial findings (Day-1)	Identical current outputs after initial cleaning
analysis	Performance over 10 days	Significant deviation in current String A and String B by Day-10
Quantifying	Power loss	7.5% reduction in power output for String B over 11 days
soiling losses	Daily power drop	0.7% per day for uncleaned modules (String B)
Implications and	Soiling loss trend	Consistent decrease in performance for uncleaned String B
trend analysis	Daily deviation	Increasing current deviation highlights impact of dust and soiling on PV module efficiency

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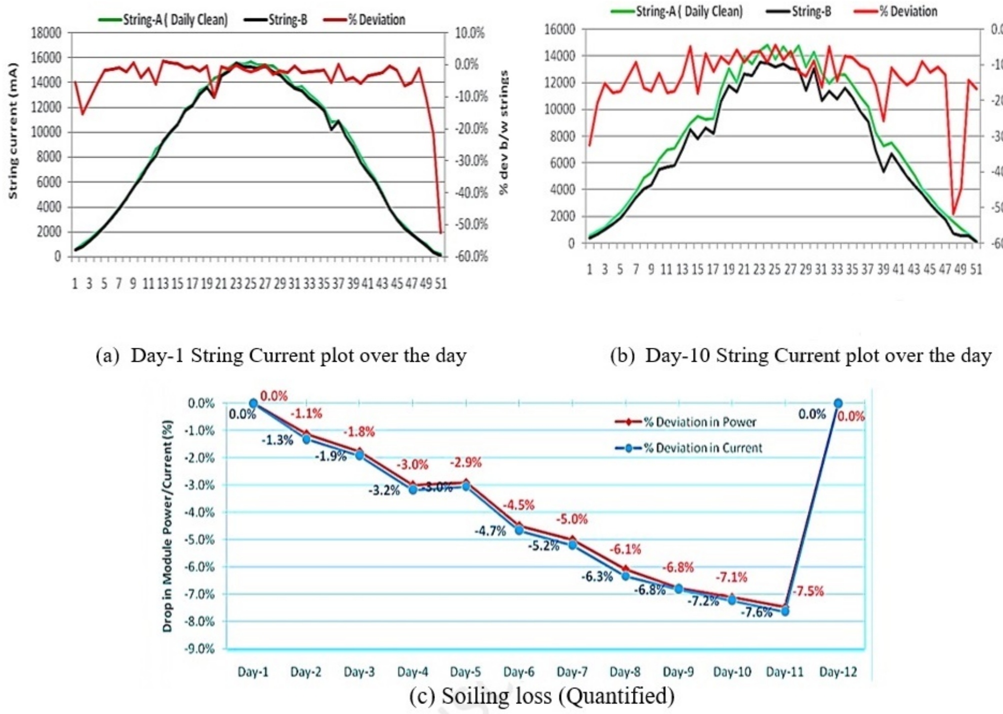

(a) Day-1 String Current plot over the day

(b) Day-10 String Current plot over the day

(c) Soiling loss (Quantified)

Figure 7. Day-wise monitoring and responses for comparative cleaning.

47].

In terms of energy generation, our system produced 22,651 MWh annually, translating to an average daily final yield of approximately 4.16 hours. This figure is notably higher than the 3.9 h/day reported by Shukla et al. (2016) and closely matches yields from other large-scale systems such as those in Adrar (4.42 h/day, Sahouane et al., 2019) and Tamil Nadu (4.31 h/day, Ramanan et al., 2019) [49, 50, 56]. This further validates that our system design is well-aligned with local solar irradiance conditions and demonstrates effective optimization.

The consistent PR (74.26%) and CUF (up to 20.3%) indicate stable generation, aiding grid reliability. Soiling losses of up to 7.5% stress the need for predictive maintenance and cleaning schedules. For policymakers, these findings support region-specific cleaning guidelines and incentives. The high final yield (4.16 kWh/kWp/day) confirms the potential of PV in subtropical regions. For developers and investors, the observed performance gains post-cleaning highlight the value of monitoring and optimized O&M to improve ROI.

This study, conducted at a site in North India with two PV technologies and fixed seasonal tilts, offers scope for expansion across diverse climates, advanced tracking systems, and additional PV types. Future work may include longer-term soiling studies; detailed lifecycle cost analysis, energy storage integration, and enhanced modelling using high-resolution sensors and dynamic environmental variables.

8. Conclusion

This paper presented a 10 MW (AC) grid-connected solar PV system in Maudaha, Uttar Pradesh, spans 75 acres and leverages advanced PV technology with seasonal tilt adjustments for year-round optimization. The entire system is executed in three stages firstly proposed SPV model is simulated. Later on, onsite execution is presented; The SCADA application is used for manual monitoring of soiling impact. The simulation of the grid-connected solar PV system using PVsyst reveals an installed capacity of 14.92 MWp and a maximum output of 10 MWac. The summarized conclusion points are as below.The system integrates over 47,000 solar modules, combining two different brands Hanwa and Waaree across a 75-acre site. This dual-module setup not only enhances overall capacity but also allows for useful comparisons in performance under the same conditions. Annual energy generation is projected at 22,651 MWh, which reflects a strong match between system design and the solar resource profile of North India. The energy output translates to roughly 6.2 kWh per square meter per day. The average performance ratio (PR) is around 74.26%, indicating efficient conversion and minimal energy losses. The capacity utilization factor (CUF), ranging from 14.4% to 20.3%, captures seasonal variation but remains within expected norms for the region. Losses are well-managed overall. System-level losses are just 0.46 kWh/kWp, and array-level losses are slightly higher at 1.44 kWh/kWp, mainly due to shading and temperature effects typical in large-scale PV systems. Seasonal trends in performance-measured through various yield and efficiency indicators-show consistent energy delivery across months, confirming the reliability of the design under changing weather and solar conditions.

Authors contributions
All authors contributed equally to the conception, design, execution, and writing of this work. All authors read and approved the final manuscript.

Availability of data and materials
The authors declare that the data supporting the findings of this study are available within the paper.

Conflict of interests
The authors assert that they do not have any identifiable conflicting financial interests or personal relationships that might be perceived to influence the work presented in this paper.

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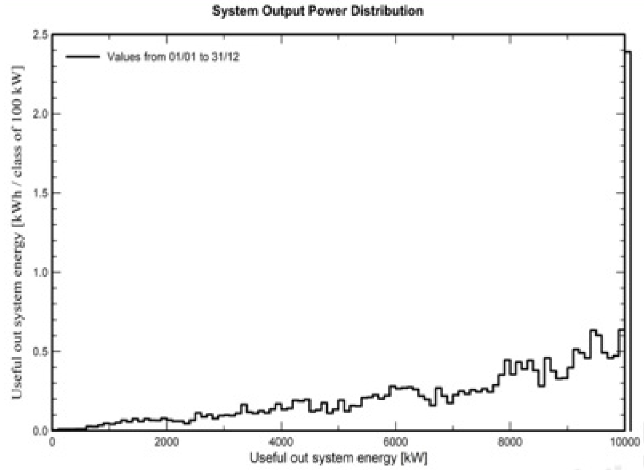
Appendix



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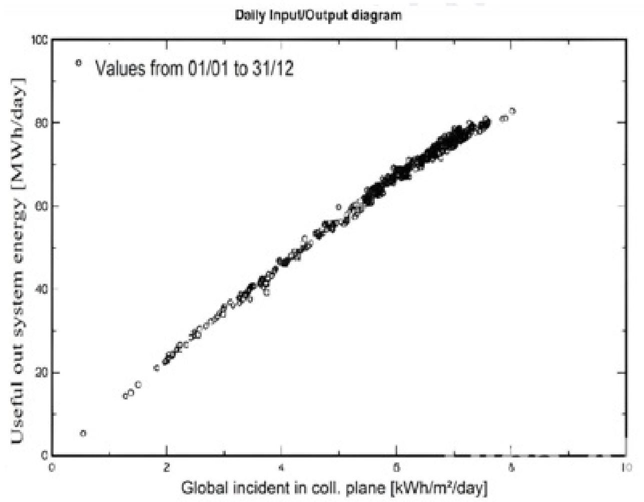

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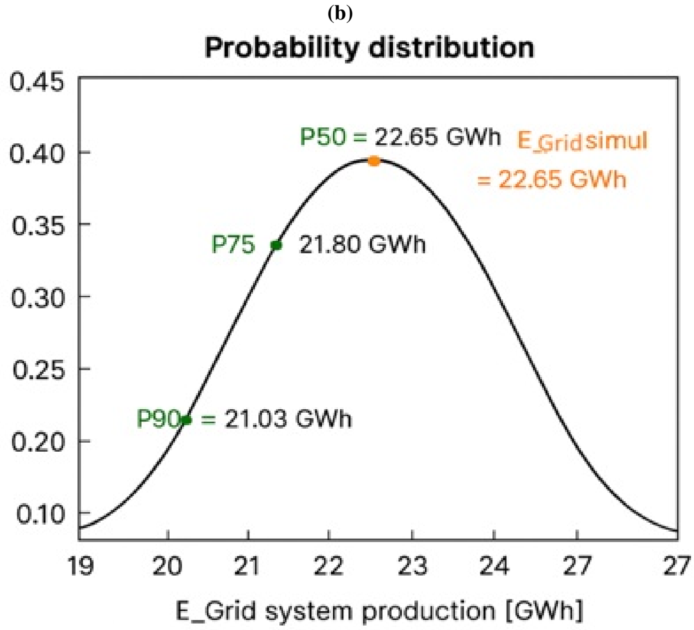

(c)

Appendix 1. (a) System output power distribution of proposed system, (b) Daily input/output diagram, (c) Probability function.

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