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Performance Analysis of a Rooftop Solar Power Integration: A Case Study of an Educational Campus

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Abstract: -. This research work examines performance of a rooftop solar plant at the Government Engineering College in Bharuch, Gujarat, India, comprising 417 solar panels and 8 inverters. Data from January 2016 to December 2020 was analyzed monthly and yearly, focusing on one year's data. Key parameters evaluated include array yield, reference yield, final yield, performance ratio, Photovoltaic module efficiency, system losses, inverter efficiency, and capacity factor. Peak solar radiation and average temperature reached 192.7 W/m^2 and 31.6^{0}C in May. Annual reference yield totaled 214104.26 kWh, with actual yield at 172090.48 kWh, resulting in a performance ratio of about 80.28%. January saw the lowest performance ratio at 73.22%, while May peaked at 86.74%. Average daily efficiencies for the photovoltaic module, system, and inverter were 11.96%, 11.67%, and 97.63% respectively. The yearly average daily performance ratio and capacity factor were 80.28% and 19.92% respectively. System losses ranged from 0.04 to 0.12 hours per day (h/d), while capture losses varies from 0.19 to 1.23 h/d, averaging 0.17 h/d and 0.69 h/d respectively. This research emphasis solar energy's potential for India's sustainable development and emphasizes the need for ongoing research and innovation.

Keywords: Inverter efficiency, Photovoltaic (PV), PV module efficiency, Performance analysis, Performance ratio

I. INTRODUCTION

Solar energy has rapidly expanded in India, promoting energy security and sustainability. In order to address the nation's growing energy needs in a clean and localized manner, solar panels convert sunshine into electricity [1]. The promotion of solar electricity across the country has been greatly aided by government programs like the Grid Connected Solar Rooftop projects and Solar Park [2]. With a total commissioned capacity of 70.10 GW, India holds the fifth-largest global position in solar power deployment as of June 30, 2023. This capacity is made up of 2.51 GW of off-grid projects, 10.37 GW of rooftop projects, and 57.22 GW of ground-mounted projects. Among the many renewable energy sources, solar energy stands out as being extremely sustainable and beneficial for both the environment and the economy, especially for emerging nations like India [3]. India demonstrated its commitment to solar energy development as seen by the fact that as of March 31, 2024, it has installed 81.81 GW of grid-tied solar energy (MNRE, 2024). In order to address issues like grid synchronization, power quality, and energy storage, technological developments are being made with an emphasis on improving control algorithms, monitoring systems, and energy management techniques.

In India, rooftop solar systems that are connected to the grid and can either supply power at regulated pricing or be used for self-consumption present a substantial research opportunity. This study could encourage new ideas, shape public policy, and accelerate the transition to sustainable energy sources. India's energy landscape may be reshaped and the effects of climate change mitigated with interdisciplinary collaboration and knowledge exchange [4]. Gujarat has 13,544.28 MW of installed rooftop solar capacity as of March 31, 2024, more than any other state in India. This state's robust infrastructure, ample solar potential, and effective utility services are its main contributing factors.

The operating performance of a rooftop solar plant in Bharuch, Gujarat, India, is assessed in this research. It evaluates performance metrics, examines efficiency trends in monthly and annual statistics, and highlights the importance of continuing solar energy research for India's sustainable development.

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II. Materials and Methodology

A. Type of Solar Panel

Solar panels are vital components in converting sunlight into electricity, utilizing semiconductor materials in a p-n junction configuration. Monocrystalline panels offer high efficiency and durability, suitable for residential and commercial installations, while polycrystalline panels provide a cost-effective solution for large-scale projects. Amorphous Silicon (a-Si) panels offer flexibility and lightweight design, catering to unconventional applications. Cadmium Telluride (CdTe) panels hold promise for efficient energy generation, and Copper Indium Gallium Selenide (CIGS) panels offer high efficiency and flexibility. Biohybrid solar panels integrate biological components for sustainable energy production, advancing renewable energy technology. Our institution uses polycrystalline panels, chosen based on factors like efficiency, space availability, and budget.

B. Solar Installation process

A solar energy project was initiated at the Government Engineering College, Bharuch, by the Gujarat Energy Development Agency (GEDA) in collaboration with Topsun Company. The institute is situated in Bholav near old National Highway No. 8 at a Latitude and Longitude angle of 21.7° North and 73° West respectively with an altitude of 18 m above Mean Sea Level (MSL), where an average wind speed is of 2.5 km/h. All these factors allow to harness solar energy efficiently through the installation of photovoltaic (PV) modules on rooftops. This project aligns with the institution's commitment to sustainable energy practices. Following is the outlined step-by-step procedure for installing a solar rooftop system at our institution.

1 Series Interconnection of SPV Modules

Topsun Company methodically executed the series interconnection of SPV modules to form strings, ensuring optimal performance and reliability. Each module was equipped with an integrally fitted junction box containing positive and negative polarity cables (4 mm^2). The interconnection involved connecting the positive cable of one module to the negative cable of the adjacent module using MC4-type connectors[9]. This arrangement facilitated the formation of 16 such strings, with a total of 26 modules interconnected in series per string. The SPV plant is designed with a ballasted flat roof installation method in which 417 polycrystalline PV modules are configured with a fixed tilt angle of 15 in north-south orientation facing south. The SPV modules are positioned according to the standard rules of shading analysis so that modules should receive uninterrupted sunlight in peak sun hours all over the year[10]. Also, modules are placed at optimal inter-row spacing to avoid shading caused by the panels themselves.

2 Interconnection of SPV Module Strings to String Inverters

High-quality cables and connectors were used by the company to connect the series strings of SPV modules to the DC distribution board (DCDB) and string inverters. Specifically, they employed 1Cx 4 cables made of copper with XLPO insulation and no armor. The used MC4 connectors had a rating of 1000 VDC (IEC) and a rated current of 30A, ensuring compliance with safety standards. Eight 12.5 kWp string inverters (Solivia 15TL) were deployed to convert the DC power produced by the solar array into usable AC power.

3 Installation of AC Combiner Boxes (ACCB/ACDB)

The installation of AC Combiner Boxes (ACCB/ACDB) was smoothly incorporated in the project. These boxes, important for distributing AC power, were mounted on MS stands welded to the rooftop MMS, ensuring there was at least 500 mm of space above the ground. This careful installation made sure the AC combiner boxes worked well and persisted a long time[12].

4 Installation of DC Distribution Boxes (DCDB)

Topsun Company`s solar-mounted structure exemplifies excellence in design and installation. DC distribution boxes (DCDBs) were strategically installed on walls, optimizing space and facilitating efficient power distribution to string inverters. This setup reflects meticulous planning and execution, ensuring easy maintenance and inspections.

C. Methodology for performance analysis

To evaluate the effectiveness of the grid-connected PV system, ongoing measurements are conducted. Performance metrics including performance ratio (PR), reference yield (Y_R), final yield (Y_F), array yield (Y_A), and capacity factor (C_F) are calculated according to the definitions outlined in the IEC Standard 61.724 [17]. The production of electrical energy by PV systems is affected by both solar radiation and ambient temperature. PV modules are designed to operate optimally under Standard Test Conditions (STC), which include 1000 W/m2 irradiance, 25°C ambient temperature, and 1.5 air mass. There is a direct correlation between solar radiation and panel output power, while ambient temperature, and thus module temperature, demonstrate an inverse relationship with output power. Equation (1) is employed to calculate the output power of PV modules based on radiation and cell temperature[13].

$$P_{PV} = P_{Peak}\left(\frac{G_t}{G_{Standard}}\right)[1-\alpha_T(T_{Cell}-T_{Standard})] \quad (1)$$

P_{PV} stands for the module output power, while P_{Peak} indicates the peak power of the PV module, G_t stands for the total irradiance on the module surface, αT represents the module temperature coefficient, T_c denotes the cell temperature, and $T_{standard}$ represent the standard value under standard test conditions (STC).

Cell temperature is defined in reference [14], [15] and can be calculated by using equation (2).

$$T_{cell} = T_{amb} + \frac{(NOCT-25)G_t}{1000} \quad (2)$$

Within this equation, T_{amb} represents the ambient temperature, while NOCT stands for the nominal operating cell temperature, set at 45°C for the cells in use. This NOCT denotes the temperature achieved by the PV cell operating in an open circuit configuration under particular conditions, which include 1000W/m^2 irradiance, an ambient temperature of 25°C, a wind speed of 6.7m/s, and an air mass (AM) of 1, the system functions. Typically, the NOCT value is provided by the manufacturer.

The inverter plays a crucial role in converting the DC power generated by the PV array into AC power for distribution to the grid. However, losses occur during the DC/AC conversion process due to factors such as cables, electronic components, and transformers[16]. The AC output power of the inverter is determined by subtracting these losses from the DC power at its input. Furthermore, the efficiency of the inverter is calculated using equation (3).

$$\eta_{inv} = (P_{DC} - P_{loss})/P_{DC} \quad (3)$$

In this study, η_{inv} represents the efficiency of the inverter, P_{DC} denotes the DC power output from the PV array, and Ploss stands for the losses incurred during the DC/AC conversion. The manufacturer specified an inverter efficiency of 98% for the equipment used in this research, as outlined in Table 2. However, for analysis purposes, a slightly conservative estimate of 97.5% was adopted.

The hourly electricity generation from the PV system was calculated using a specific equation (4).

$$E_h = G_t A_m \eta_m C_m \quad (4)$$

G_t denotes the hourly irradiance on the module surface, Am represents the area of the PV module, ηm stands for module efficiency, and Cm indicates the number of modules. Equations (5-7) are used to calculate daily, monthly, and annual energy production.

$$E_d = \sum_{i=1}^{24} E_{h,i} \quad (5)$$

$$E_m = \sum_{i=1}^{N_d} E_{d,i} \quad (6)$$

$$E_a = \sum_{i=1}^{365} E_{d,i} \quad (7)$$

$E_{h,i}$ denotes the electricity production of the system in the ith hour of the day, while $E_{d,i}$ indicates the electricity production of the system on the ith day. N_d represents the number of days in the month.

To evaluate the effectiveness of the grid-connected PV system, ongoing measurements are conducted. Performance metrics including performance ratio (PR), reference yield (Y_R), final yield (Y_F), array yield (Y_A), and capacity factor (C_F) are calculated according to the definitions outlined in the IEC Standard 61.724 [17].

A Yield Calculation

Array yield is determined using equation (8), This is expressed as: [18]

$$Y_A = \frac{E_{DC}}{P_{PVrated}} \quad (8)$$

The daily array yield ($Y_{A,d}$) and monthly array yield ($Y_{A,m}$) are provided as per [19]and calculated utilizing equation (9).

$$Y_{A,D} = \frac{E_{DC,D}}{P_{PVrated}} \quad \text{and } Y_{A,m} = \frac{1}{N}\sum_{d=1}^{N} Y_{A,d} \quad (9)$$

The final yield is computed by dividing the AC energy (E_{AC}) generated by the entire solar PV plant during a designated time frame (day, month, or year) by the peak power rating of the PV plant at Standard Test Conditions (STC)[18], [19]. This metric facilitates comparison among similar PV systems installed within specific (same or nearby) geographical regions. Daily final yield is determined using equation (10).

$$Y_{F,d} = \frac{E_{AC,d}}{P_{PVrated}} \quad (10)$$

The reference yield is obtained by dividing the total in-plane solar insolation (Gt) in kWh/m^2 by the array reference irradiance (1000 W/m^2). This metric represents the number of peak sun hours per day and is detailed in [20], calculated using equation (11).

$$Y_R = \frac{G_t[kWh/m2]}{1\ [kWh/m2]} \quad (11)$$

B The Performance ratio

The performance ratio of the PV plant explains the correlation between the actual and theoretical energy outputs [21], signifying the proportion of energy available for export to the grid post-energy loss deduction. The performance ratio (PR) is computed using equation (12).

$$\mathrm{PR} = \frac{\mathrm{Y_F}}{\mathrm{Y_R}} \quad (12)$$

Where Y_F represents the actual yield in kWh, which is the energy exported to the grid by the PV plant, and Y_R denotes the reference yield, indicating the calculated nominal output of the plant[22]. The performance ratio (PR) is usually within the range of 55% to 94%.

C Loss calculations

Array capture losses (L_c) denote the portion of total radiation not captured by the photovoltaic modules, calculated as the difference between the reference yield (Y_R) and the actual array yield (Y_A) (Equation (13)) [23].

$$L_C = Y_R - Y_A \quad (13)$$

System losses (L_s) encompass losses that arise in the system components during the conversion of DC power to AC power and its integration into the grid. These losses are determined by the difference between the actual array yield (Y_A) and the finally measured yield (Y_F) (Equation (14)).

$$L_s = Y_A - Y_F \quad (14)$$

D Efficiency calculations

The instantaneous PV module efficiency (η_{PV}) was computed according to equation (15), as described in [18][24].

$$\eta_{PV} = \left(\frac{P_m}{I_t A_m}\right) 100 \quad (15)$$

In equation (15), P_m represents the module output power, I_t (W/m^2) denotes the total in-plane solar insolation, and A_m stands for the module area. The module efficiency, which is dependent on cell temperature and provided in [8], can be calculated using equation (16).

$$\eta_{PV} = \eta_{PV,STC}[1 - \Upsilon(T_{cell} - T_{ref})]$$

(16)

The instantaneous PV module efficiency at Standard Test Conditions ($\eta_{PV,STC}$) is determined by the efficiency of the PV module at STC_γ, the temperature coefficient of power, the reference temperature (T_{ref}) set at 25°C, and the cell temperature (T_{cell}) calculated using Eq. (2). The instantaneous inverter efficiency (η_{inv}) is calculated using Eq. (17), where it represents the ratio of the instantaneous AC output power (P_{AC}) to the DC input power (P_{DC}) [15].

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \quad (17)$$

The monthly inverter efficiency was determined using Eq. (18), which calculates the ratio of the total monthly AC energy (E_{AC}) supplied to the grid to the monthly total DC energy (E_{DC}) at the inverter input [25].

$$\eta_{inv,m} = \frac{\sum_{d=1}^{N} E_{AC,d}}{\sum_{d=1}^{N} E_{DC,d}}$$

(18)

The instantaneous system efficiency (η_{sys}) illustrates the proportion of the total irradiance (I_t) received by the PV modules that are converted into DC or AC electrical energy [22]. It was calculated using Eq. (19).

$$\eta_{sys} = \left(\frac{P_{AC}}{I_t A_m}\right) \quad (19)$$

In Eq. (19), I_t represents the total radiation on the tilted surface, while Am denotes the area of the module. Additionally, this value can be computed using Eq. (19), where η_{pv} stands for the PV array efficiency and η_{inv} represents the inverter efficiency.

$$\eta_{sys} = \eta_{PV}\eta_{inv}$$

(20)

Furthermore, the method for calculating the annual system efficiency was provided in equation (21).

$$\eta_{sys,a} = \left(\frac{E_{AC,a}}{A_m \sum_{d=1}^{365} G_{t,d}}\right)$$

(21)

G_t (Wh/m^2) represents the total radiation received on the inclined surface over a specified period of time.

E Capacity factor

The capacity is determined by dividing the annual AC energy output of the system by the maximum energy it could produce if operating at rated power continuously throughout the year. [13], [15], [18]. It is defined in Equation (22).

$$CF = 100\frac{E_{AC,a}}{P_{PV\ rated} * 8760}$$

(22)

III. Results and discussions

The performance results of the PV system are discussed in this section. Table 1 presents the solar plant`s performance metrics over a year, with total AC generation reaching 172090.48 kWh. Monthly variations in energy production reveal peak performance in May at 16250.40 kWh and lowest in January at 12167.80 kWh. May showcases optimal conditions for solar energy. January's lower output may be influenced by weather or operational factors.

Table 1 Month-wise measured Energy

	Measured Energy	
Months	**DC (kWh)**	**AC (kWh)**
January	13105.54	12167.80
February	15182.59	12907.66
March	16192.35	14781.98
April	16640.68	15855.70
May	16338.65	16250.40
June	16154.23	15930.06
July	15210.47	15736.00
August	14993.87	14890.42
September	14256.13	14664.28
October	13145.36	13877.98
November	12552.81	12749.96
December	13105.54	12278.24

Bharuch City experienced its peak average temperature in May, reaching 31.6°C, while the lowest average temperature was observed in January at 22°C. Figure 1 illustrates the monthly variation in generation alongside ambient temperature changes. Additionally, the highest number of sun hours occurred in April, while the lowest were recorded in August.

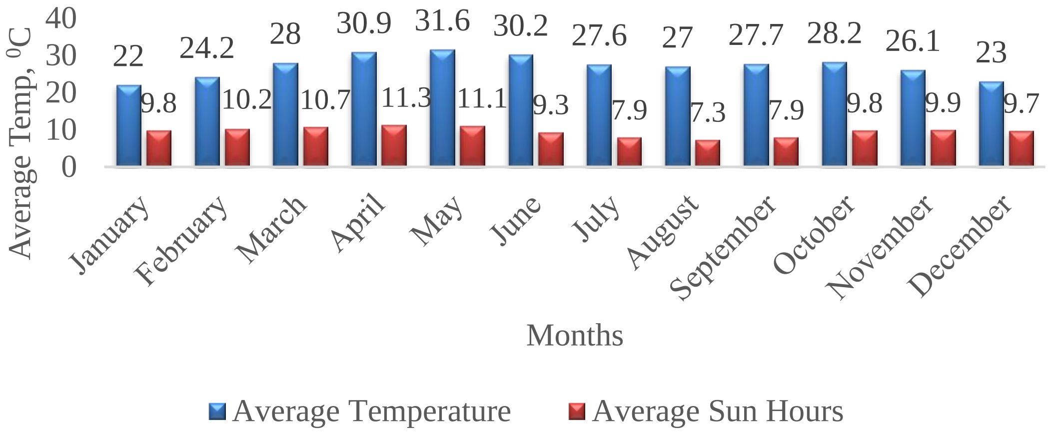

Figure 1 Month-wise Average temperature variation with Average sun hours.

Figure 2 presents the solar plant's performance metrics over a year, with total AC generation reaching 172090.48 kWh. Monthly variations in energy production reveal peak performance in May at 16250.40 kWh and lowest in January at 12167.80 kWh. May showcases optimal conditions for solar energy. January`s lower output may be influenced by weather or operational factors.

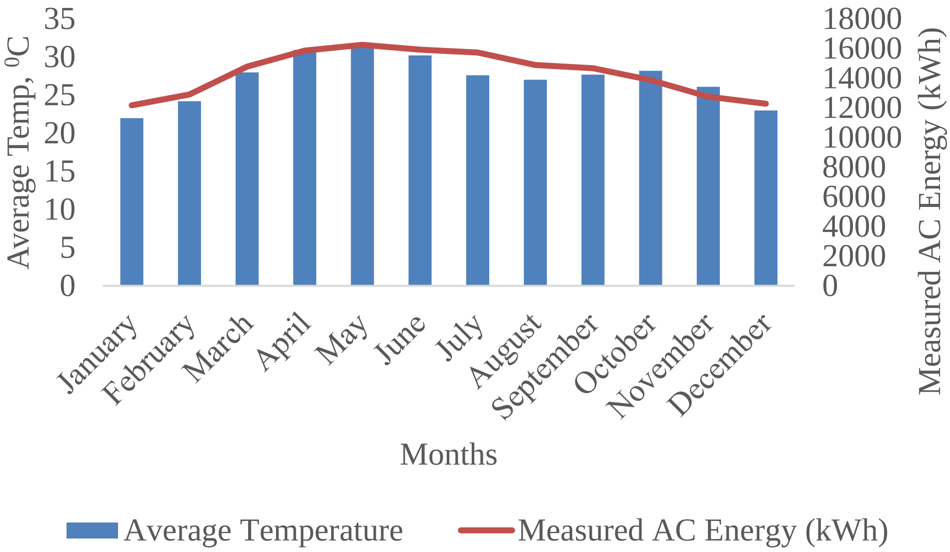

Figure 2 Monthly AC Power Generation and Maximum Temperature Recorded

Figure 3 illustrates mean hourly solar radiation levels (W/m²) for Bharuch City throughout the year, showcasing peak values in spring and early summer, notably May (231.26 W/m²) and April (224.92 W/m²), and lowest levels in December (149.31 W/m²). The mean annual solar radiation is 181.39 W/m², informing decisions on solar energy system design, installation, and performance optimization by highlighting seasonal variations in solar energy availability.

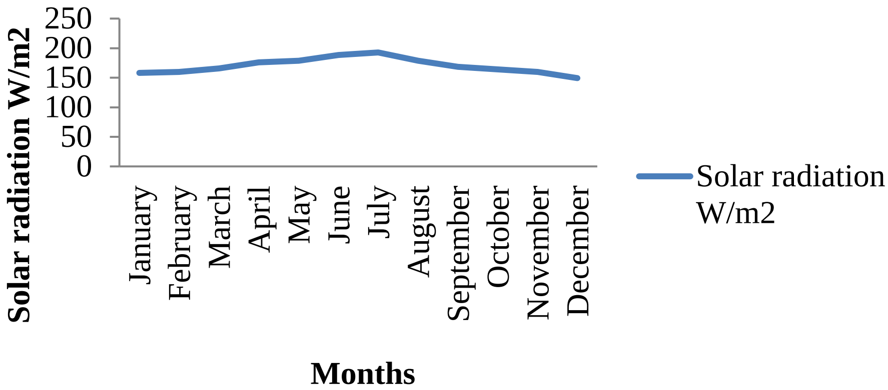

Figure 3 Mean monthly solar radiation of Bharuch City

Table 2 summarizes the system`s performance dynamics throughout the year, showcasing seasonal variations in Yield Factor, Reference Yield, and Performance Ratio. The plant's annual reference yield is calculated at 214104.26 kWh, while the actual annual yield is 172090.48 kWh, resulting in a performance ratio of approximately 80.28%. January records the lowest Performance Ratio at 73.22%, while May shows the highest at 86.74%. System losses range from 0.04 h/d to 0.12 h/d, with capture losses averaging 0.69 h/d. These figures underscore the dynamic nature of system losses across operational periods.

Table 2 Computing Final Yield, Reference Yield, and Performance Ratio

Months	**YF (kWh/kW)**	**YR (kWh/kW)**	**PR (%)**
January	12167.80	16619.19	73.22
February	12907.66	16765.11	76.99
March	14781.98	17423.33	84.84
April	15855.70	18458.42	85.90
May	16250.40	18734.52	86.74
June	15930.06	19770.66	80.57
July	15736.00	20229.41	77.79
August	14890.42	18734.52	79.48
September	14664.28	17684.73	82.92
October	13877.98	17244.87	80.48
November	12749.96	16765.11	76.05
December	12278.24	15674.38	78.33

Table 3 summarizes monthly energy data and efficiency metrics for both AC and DC outputs. The PV arrays achieved an average annual efficiency of 12.05%, ranging from 10.93% in January to 12.91% in May. The inverter maintained a high average efficiency of 97.65%. System efficiency fluctuated between 10.65% and 12.61%, while the annual capacity factor reached 20.19%. Monthly variations in energy production correlate with solar irradiance and ambient temperature changes. Despite fluctuations, the system demonstrates consistent performance, highlighting reliability and efficiency in photovoltaic operations.

Table 3 Monthly generated and energy efficiencies

Months	**DC Energy (kWh)**	**AC Energy (kWh)**	**η_{PV} (%)**	**η_{inv} (%)**	**η_{sys} (%)**	**PR (%)**	**CF (%)**
January	12498.21	12167.80	10.93	97.36	10.65	73.22	16.90

February	13105.54	12907.66	11.37	98.49	11.19	76.99	17.93
March	15182.59	14781.98	12.67	97.36	12.34	84.84	20.53
April	16192.35	15855.70	12.75	97.92	12.49	85.90	22.02
May	16640.68	16250.40	12.91	97.65	12.61	86.74	22.57
June	16338.65	15930.06	12.02	97.50	11.72	80.57	22.13
July	16154.23	15736.00	11.61	97.41	11.31	77.79	21.86
August	15210.47	14890.42	11.80	97.90	11.56	79.48	20.68
September	14993.87	14664.28	12.33	97.80	12.06	82.92	20.37
October	14256.13	13877.98	12.02	97.35	11.70	80.48	19.27
November	13145.36	12749.96	11.40	96.99	11.06	76.05	17.71
December	12552.81	12278.24	11.64	97.81	11.39	78.33	17.05

IV. Conclusion

From January 2016 to December 2020, the 100 kWp rooftop PV power plant at Government Engineering College, Bharuch, Gujarat, India, showed robust productivity, generating a total of 172,090.48 kWh. Peak production occurred in May with 16,250.40 kWh, while January saw the lowest output at 12,167.80 kWh. Output closely follows ambient temperature and solar radiation levels, peaking in May. Operational efficiency is evident with system losses averaging 0.17 h/d and capture losses at 0.69 h/d. Annual PV array efficiency averages 12.05%, reaching 12.91% in May and dropping to 10.93% in January. The inverter maintains an impressive 97.65% average efficiency. Overall system efficiency ranges from 10.65% to 12.61%. The plant achieves a performance ratio of approximately 80.28%, with January at 73.22% and May at 86.74%. The calculated annual capacity factor of 20.19% highlights the plant`s reliability and efficiency as a renewable energy source.

V. Acknowledgement

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VI. Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

VII. Nomenclature

ACRONYMS		**ABBREVIATION**	
ACCB	AC combiner box	A_m	PV module area, m^2
ACDB	AC Distribution box	a-Si	Amorphous Silicon
CIGS	Copper Indium Gallium Selenide	C_m	Number of modules
CU	Copper	E_a	Annual electric energy production
DCDB	DC Distribution box	E_d	Daily electric energy production
GEDA	Gujarat Energy Development Agency	$E_{d,i}$	Electricity production of the system on the i^{th} day
GW	Gigawatt	E_h	Hourly electric energy production
IEC	Importer Exporter Code	$E_{h,i}$	System's electricity production in the ith hour
km/h	kilometer per hour	E_m	Monthly electric energy production

kW	kilowatt	G_t	Total irradiance on the module surface, W/m^2
kWp	kilowatt peak	I_t	Total in-plane solar insolation
MC4	Multi Connect, 4 millimeter	L_c	Array capture losses, kWh/kW
MMS	Module Mounting Structure	L_s	System losses, kWh/kW
MNRE	Ministry of New & Renewable Energy	N_d	Number of days in the month
MS	Mild Steel	$\eta_{PV,STC}$	PV module efficiency at Standard Test Conditions, %
MSL	Mean Sea Level	η_{sys}	Instantaneous system efficiency, %
NOCT	Nominal operating cell temperature	P_{AC}	AC output power, kWh
PV	Photovoltaic	P_{DC}	DC power output, kWh
SPV	Solar PhotoVoltaic	P_{loss}	Power loss, kWh
STC	Standard Test Conditions	P_{peak}	Peak Power of the PV module, kWh
TEL	Topsun Energy Limited	P_{PV}	Module output Power, kWh
TL	Transformer loss	T_{amb}	Ambient temperature, °C
XLPO	Cross Linked polyolefin	T_c	Cell temperature, °C
		Tref	Reference temperature, °C
		$T_{Standard}$	Standard value of temperature
		Y_A	Array yield, kWh/kWp
		$Y_{A,d}$	Daily array yield, kWh/kWp/day
		$Y_{A,m}$	Monthly array yield, kWh/kWp/month
		Y_F	Final yield, kWh/kWp
		Y_R	Reference yield, kWh/kWp
		α_T	Module temperature coefficient
		η_{inv}	Efficiency of the inverter
		η_m	Module efficiency

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