Simulation-Based Performance Assessment of a Grid Connected Rooftop Photovoltaic System in a Coastal Urban Environment

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Abstract. This paper present a simulation based performance evaluation of a 5.45 kWp grid-connected rooftop photovoltaic system intended for a coastal urban location in Mumbai, India. The system was modeled using PVsyst 8.0.20 with Meteonorm 8.2 climatic data. The site receives an annual global horizontal irradiations of 1813.8 kWh/m^2 resulting in generation of 7518 kWh of energy generation and 5058.5 delivered to the grid. The overall performance ratio is 0.686, indicating stable operation in coastal urban areas. Seasonal variation shows lower output during monsoon season due to lower irradiation. According to Loss analysis, thermal effects are the most important performance-limiting factor. The results demonstrate the technical feasibility and reliable performance of rooftop solar PV systems.

Keywords: Monofacial photovoltaic system; Bifacial photovoltaic system; Coastal climatic conditions; PVsyst simulation; Performance ratio; Energy yield; Direct Current distribution box (DCDB); Alternating Current distribution box (ACDB).

1 Introduction

The growing electricity demand and the environmental issues have made grid-connected photovoltaic (PV) systems to be a crucial part of the sustainable urban energy infrastructure. Modularity, scalability, and direct grid interfacing with minimal operation complexity are essential in the development of the PV installation, particularly in the institutional and rooftop applications[1],[2],[3]. For technical validation and economic planning control, accurate prediction of the PV system performance before installation is essential. PVsyst is a popular simulation tool used in the detailed model of the transposition of irradiance, thermal behavior, effect of shading and system losses, allowing realistic estimation of the annual energy yield and performance indicators[4], [5], [6]. The unique climatic features of the coastal urban setting, like the high ambient temperature, humidity, and a seasonal variation in irradiation because of the monsoon patterns, are observed in the city of Mumbai. These play a great role in determining module operating temperature and system efficiency. Thus, the site-specific assessment is based on the simulation which requires site-

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specific analysis to determine the anticipated system performance in realistic operating conditions. In this paper, the performance of a 5.45 kWp grid-connected rooftop PV system that is proposed to be installed at Sardar Patel College of Engineering in Mumbai is explored using the PVsyst 8.0.20[7]. Some of the key performance parameters that include annual yield, specific yield, performance ratio, and loss component are evaluated to determine the suitability of the system to be deployed in the tropical seas coasts[8].

2 System description

2.1 Site location and climatic condition

The proposed photovoltaic system is located at the rooftop of a building at Sardar Patel College of Engineering, Andheri, Mumbai, India (19.12^0 North latitude and 72.84^0 East longitude) at an elevation height of about 19 m above mean sea level. Mumbai is in a tropical coastal climate with high solar availability, high ambient temperature and seasonal differences due to the monsoon. The location and near-shading scene produced in PVsyst for the selected rooftop is given in Fig. 1.

Fig. 1. Site location and climatic characteristics of the proposed photovoltaic system at Sardar Patel College of Engineering, Mumbai.

Meteorological inputs used for the simulation were retrieved from the Meteonorm 8.2 database (the data set from 1996 to 2015). The site has an annual global horizontal irradiation of about 1813.8 kWh/m^2 and the average annual ambient temperature is 27.87^0C [9], [10]. The coastal climate leads to high levels of humidity and high running temperatures of the modules, especially during summer months. In addition, monsoon conditions, i.e., from June to August, result in reduced solar irradiation because of increased cloud cover. Considering these climatic characteristics and the favourable rooftop exposure as shown in Fig. 1, the site is technically suitable for grid connected photovoltaic deployment[11].

2.2 Overall system configuration

The proposed photovoltaic system is located at the rooftop of a building at Sardar Patel College of Engineering The electrical configuration of the proposed 5.45 kWp grid-connected rooftop photovoltaic system is shown in Fig. 2. The entire power flow from solar panels to utility grid and local load is shown in the diagram making the system layout easy to understand. The system is constructed from 10 photovoltaic modules, in series to one string. These modules convert solar radiation that falls on them into direct current (DC) electricity. The generated DC power is first passed into a DC Distribution Box (DCDB) which offers protection in the form of fuses, surge protection devices and isolation switches. The DCDB guarantees the safe collection and control of the power before it actually passes on to the inverter. From the DCDB, the power is supplied to the grid tied inverter. The inverter has a critical role in the process of converting the DC power to the alternating current (AC) power which can be synchronized with the grid and used for local consumption. It also performs maximum power point tracking (MPPT) to make sure the best energy extraction is made from the PV modules under different irradiance and temperature conditions.

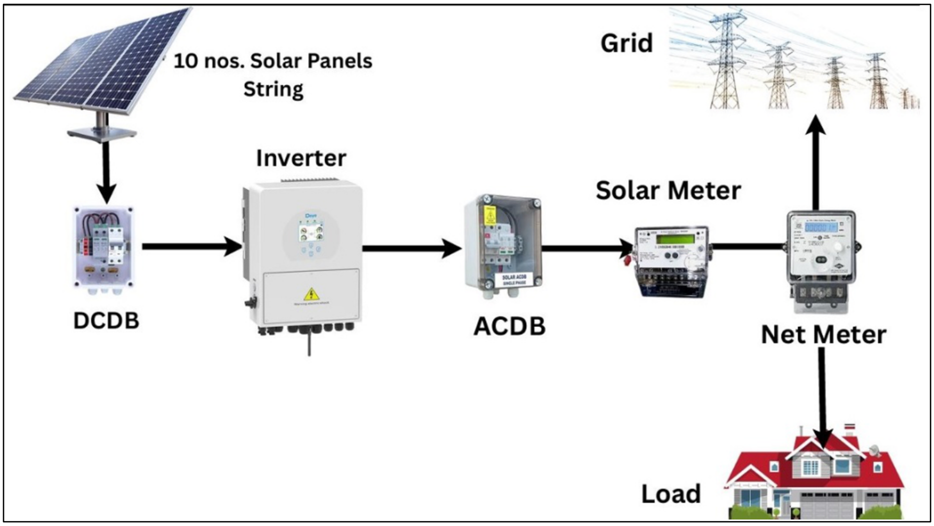

Fig. 2. Electrical configuration of the proposed 5.45 kWp grid-connected rooftop photovoltaic system showing power flow from PV modules through DCDB, inverter, ACDB, metering system, and grid interface.

The AC output of the inverter is then connected to the AC Distribution Box (ACDB). The ACDB has circuit breakers and protective devices in order to protect the system from faults and over-current conditions. After being passed through the ACDB, the energy generated is measured by a solar generation meter, which measures the total energy that is generated by the PV system. The electricity then passes through a net meter which measures exported and imported energy between the building load and the utility grid. When the generating solar supply is more than the load demand of the building, the extra energy supply is exported to the grid. Conversely when the solar generation is not sufficient (e.g. at night) electricity is purchased from the grid to fulfill the load demand. The Fig. 2 illustrates how the system is very much in the standard grid-connected rooftop configuration typically used for institutional & residential installations. This arrangement is to ensure safe operation, compliance with regulations and efficient use of energy under normal conditions of operation of urban environment.

2.3 Near Shading and iso-shading analysis

Near shading effects were analyzed using three-dimensional shading scene and iso-shading analysis tools of PVsyst. The iso-shadings diagram for the selected array orientation (fixed plane with a tilt angle of 19.12^0 and azimuth angle of 0^0) is given in Fig. 3. The diagram shows the interaction between the path of the sun and the obstacles around the building throughout the year, showing potential shading of the beam in terms of the solar height & azimuth.

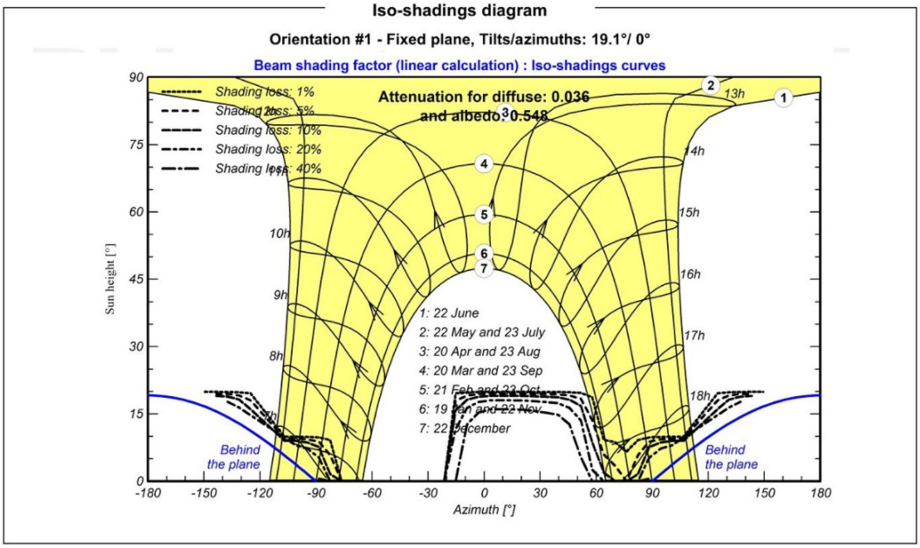

Fig. 3. Iso-shadings diagram showing near-shading effects for the proposed photovoltaic system

The shaded areas show restricted obstruction mainly during early morning hours and late afternoon hours of low solar elevation and the central area of the sun path is relatively free of obstruction. The annual beam shading loss estimated by the linear shading calculation is about 1%, which indicates that there is little shading effect on the system performance. Diffuse and albedo attenuation factors are quite low, and confirm a favorable rooftop exposure for the chosen site. This analysis has shown that the near shading effects have a negligible effect on annual energy production, and confirms the suitability of where the rooftop will be deployed for photovoltaic use. Incorporation of iso-shading analysis[7], [12]

2.4 Near Shading and iso-shading analysis

The orientation and tilt of the photovoltaic array has been determined using the orientation management module of PVsyst as shown in Fig. 4. A fixed tilted plane configuration was used for the simulation. The PV array is oriented towards the south direction with an azimuth angle of 0^0, and a tilt angle of 19.12^0 which closely correspond to the site latitude and is also suitable to ensure accurate estimation of incident irradiation and improve the reliability of the simulated performance results for maximizing energy yield in a year under local climatic conditions. PVsyst's built in optimization tools were employed to examine the effect of tilt and orientation on annual incident irradiation. The chosen tilt angle gives a transposition factor of 1.07 approximately and a global incident irradiation on the plane of the collector of about 1813.8 kWh/m^2/year[12], [13].

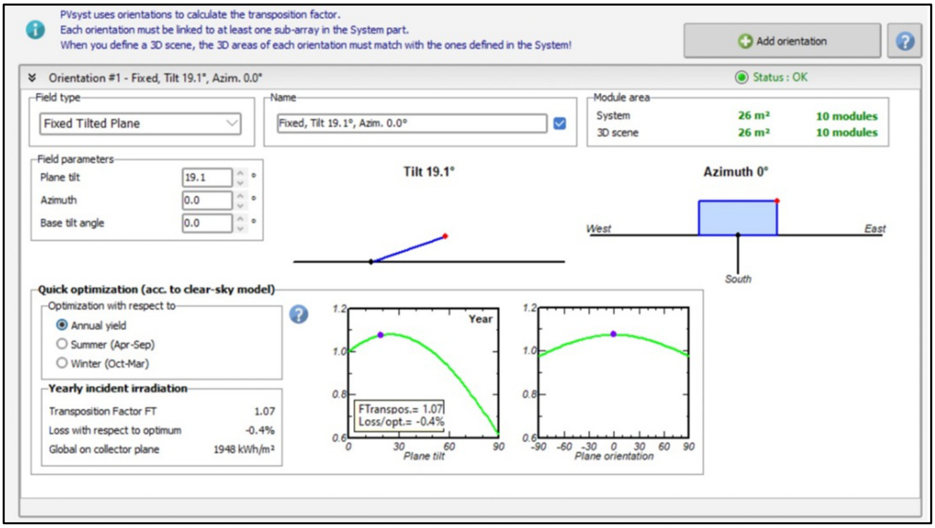

Fig. 4. Orientation and tilt optimization of the photovoltaic array using PVSyst

2.5 PV array and inverter specification in PVSyst

The PV array and inverter configuration for the simulation is shown in Fig. 5. The system is made up of 10 numbers of 545Wp (monofacial) photovoltaic modules combined in a string. The total installed DC capacity is equal to 5.45 kWp with a total module area of about 26 m^2. To interface the PV array to the utility grid, one 5 kW grid connected inverter is chosen. The electrical compatibility between the PV array and inverter was confirmed by using PVsyst sizing tools. Voltage limit at various temperature conditions, current ratings at standard test conditions (STC) and range of inverter operation were carefully checked to ensure safe and reliable operation. The chosen configuration operates within allowable voltage limits even in a low temperature open circuit. The DC to AC ratio of about 1.09 guarantees an efficient utilisation of the inverter without any significant power clipping [17], [18]. For clarity the key technical specifications of the PV array and inverter are summarised in Tables 1 &2.

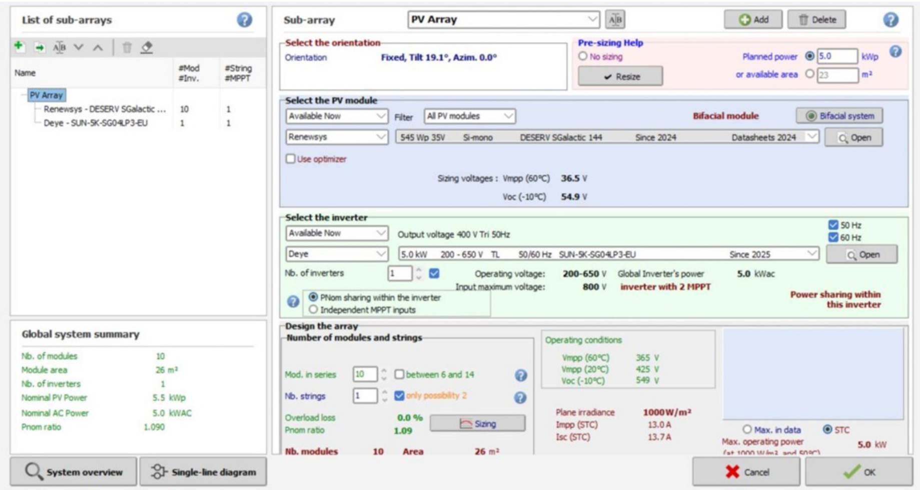

Fig. 5. PVsyst-based sizing and configuration of the photovoltaic array and inverter

Table 1. PV Array specification.

Parameters	Values	Parameters	Values
Module Manufacturer	RenewSys	Total Installed Capacity	5.45 kWp
Module Model	DESERV SGalactic 144	Total Module Area	26 m²
Module Type	Bifacial, Mono-Si	Vmp (20°C)	42.5 V
Rated Power (Pmpp)	545 Wp	Voc (-10°C)	54.9 V
Number of Modules	10	Plane Irradiance (STC)	1000 W/m²
Modules in Series	10	Impp (STC)	13.0 A
Number of Strings	1	Isc (STC)	13.7 A

Table 2 Inverter Specification.

Parameters	Values	Parameters	Values
Manufacturer	Deye	Maximum Input Voltage	800 V
Model	SUN-5K-SG04LP3-EU	Number of Inverters	1
Nominal AC Power	5.0 kW	Number of MPPT Inputs	2
Output Voltage	400 V (3-phase)	Power Sharing	Within inverter
Frequency	50/60 Hz	DC-to-AC Ratio	1.09
Operating Voltage Range (MPPT)	200 – 650 V	Maximum AC Operating Power	5.0 kW

2.6 Simulation approach

The performance of the proposed rooftop photovoltaic system was analyzed by using the software tool PVsyst version 8.0.20, which is very popular software for design and performance prediction of photovoltaic systems. PVsyst allows detailed modeling of solar resource availability and electrical configuration and specification of system losses, so that realistic estimates of annual energy yield and performance indicators can be obtained. In the present study, the global horizontal irradiation retrieved from Meteonorm was transformed to irradiation at tilted plane of PV array by using Perez transposition model. The Perez model is widely used in PV performance simulations in which the diffuse radiation components under different sky conditions are better estimated, especially in the tropical and coastal areas[11]. Thermal behavior of the modules has been modeled with the data from the ambient temperature and incident irradiance. Since the operating temperature of the module has a great influence on output voltage and efficiency, power variation with temperature was implemented in the simulation. Elevated temperatures usually decrease module efficiency because of higher internal resistance and lower open circuit voltage [19], [20], [21].

3 Result and Discussion

3.1 Monthly energy performance analysis

The tailored monthly simulation results for the suggested 5.45 kWp grid connected rooftop PV system are displayed in Table 3. The solar irradiance, ambient temperature, array energy production, grid injected energy and performance ratio of each month are all compiled in the table. Annual global horizontal irradiations (GlobHor) of 1813.8 kWh/m^2 indicate that the Mumbai Site has good solar potential. During summer month of March through May higher irradiations values are recorded. Because there is more cloud cover during the monsoon season (June to August), radiation levels drastically decrease. The selected tilt angle of 19.1° improves solar energy capture, as evidenced by the fact that the incident irradiation on the tilted plane (GlobInc) is higher than the horizontal value.

Table 3 Monthly and annual energy balance and performance parameters of the proposed photovoltaic system

	GlobHor	DiffHor	T_Amb	GlobInc	GlobEff	EArray	E_Grid	PR
	kWh/m²	kWh/m²	°C	kWh/m²	kWh/m²	kWh	kWh	ratio
January	152.4	44.03	24.74	189.6	184.3	713.1	508.6	0.666
February	163.8	42.05	25.84	191.5	186.8	671.2	484.2	0.620
March	194.9	70.68	28.21	209.4	203.0	750.4	532.6	0.635
April	202.5	77.90	29.01	202.1	195.5	736.0	519.2	0.645
May	208.1	90.31	30.24	195.6	188.1	750.6	523.3	0.680
June	132.7	88.96	28.88	123.6	117.2	532.4	327.2	0.761
July	96.1	72.10	28.08	90.2	84.7	396.8	201.3	0.775
August	109.7	82.68	27.83	106.0	100.2	461.6	261.4	0.768
September	126.3	82.06	27.68	128.4	122.4	540.9	341.7	0.744
October	149.9	78.99	29.41	164.6	158.4	652.3	440.6	0.701
November	143.7	56.02	28.17	172.6	167.2	665.9	466.1	0.683
December	133.7	52.46	26.21	165.1	160.2	647.0	452.1	0.693
Year	1813.8	838.24	27.87	1938.7	1868.1	7518.0	5058.5	0.686

The slight variation between GlobEff and GlobInc suggests that optical losses and shading are negligible. The seasonal pattern of energy generation at the array level (EArray) is comparable to that of irradiation. March through May sees the highest energy production, while the monsoon months see the lowest output. After taking system losses into consideration, the annual energy delivered to the grid (E_Grid), which represents realistic operating conditions, is 5058.5 kWh. With an average of 0.686 per year, the performance ratio (PR) remains comparatively constant throughout the year. The main cause of the slight drops in PR during the warmer months is the higher module temperature, which lowers efficiency. Overall, the findings demonstrate that the system operates reliably in coastal climates, with seasonal variations mostly due to variations in temperature and solar irradiation[22], [23].

3.2 Comparison with reported rooftop PV System in India.

The comparison presented in Table 4 indicates that the performance of the proposed Mumbai rooftop system falls within the range reported for similar installation in India. While the performance ratio slightly lower than some inland installation, this variations can be attributed to higher ambient temperature and costal climate conditions. Overall the results demonstrate consistency with published rooftop PV performance data across different India Regions[14], [15], [16].

Table 4 Comparison with reported Rooftop PV systems in India

Locations	System Size	Specific Yield (kWh/kWp/yr)	Performance Ratio (PR)	Study Type
Northern India [14]	10	~1440	0.75	Field Measurement
Eastern India [15]	11.2	~1500	0.77	Grid-Connected Rooftop
Multi City India [16]	5-50	1400-1600	0.70 – 0.80	PVsyst based analysis
Mumbai (Present study)	5.45	~1380	0.69	Coastal Rooftop PVSyst based

3.3 Monthly irradiation and daily energy output behavior.

The variations in solar energy received on the tilted PV surface over the course of the year are shown in Fig. 6. It averages 5.311 kWh/m^2/day. The months of February through April, when the sky is largely clear, have the most solar availability. In June and July, monsoon clouds and rainfall result in notable decreases in values. As the weather improves starting in September, solar radiations gradually rise[24], [25].

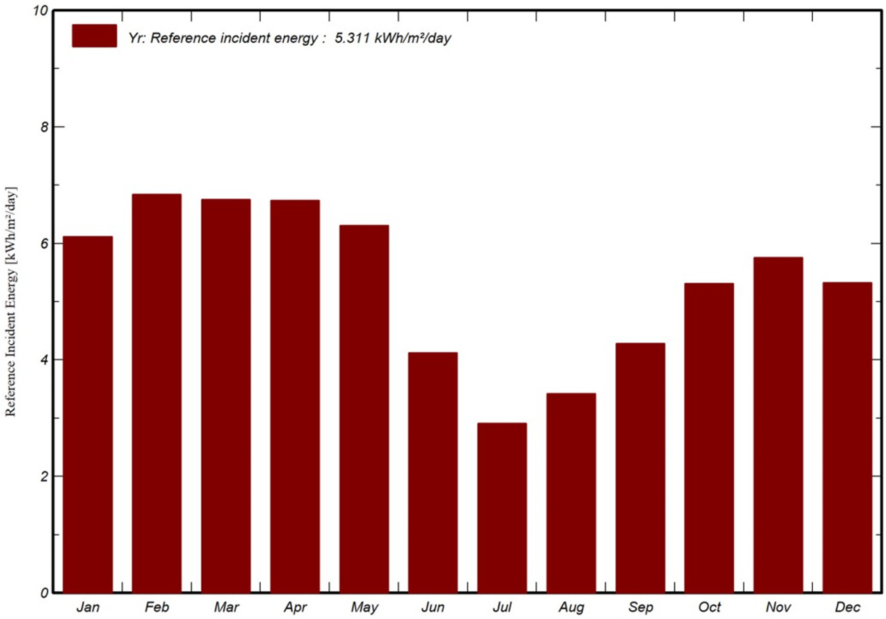

Fig. 6. Monthwise Reference Incident Energy on collecter plate (kWh/m^2/day)

3.4 Daily energy generation profile of the Photo voltaic system

The system's daily energy output over full year is shown in Fig. 7. The average daily generation from January to May is between 22 and 24 kWh. This is indicative of steady performance in the first half of the year. Between June and August, when output varies significantly, there is a noticeable variation. Production is below 10 kWh/day on a number of days during this time, with some values falling as low as 3-5 kWh/day. There is noticeable increase in the frequency of these dips compared to prior months. By the end of the year, the daily output ranges between 18 and 22 kWh/day, having steadily stabilized after August. The seasonal variation in daily energy generation over the course of the year is clearly depicted in the figure[24], [25].

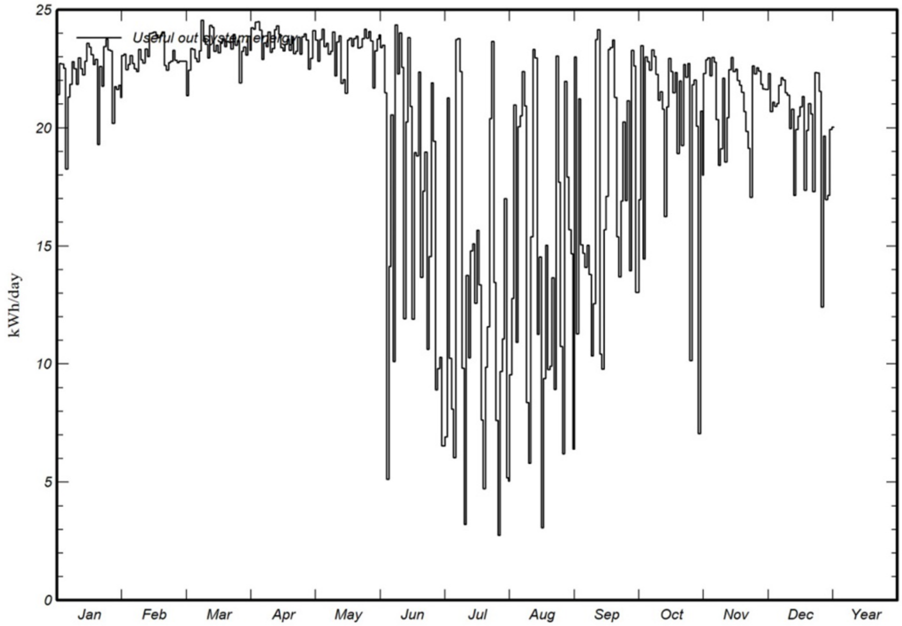

Fig. 7. Daily output energy profile (kWh/day)

3.5 Monthly Performance Ratio (PR) analysis

Fig. 8 shows how the performance ratio (PR) changes over the year. The average PR is 0.686. It is lowest in the February month at about 0.62 and highest in July month at around 0.77. The slightly lower values in the summer months are mainly due to higher panel temperature, which reduce efficiency of the system. During the monsoon season, even though sunlight is lower, the panels operate at cooler temperatures, which helps improve the PR[26].

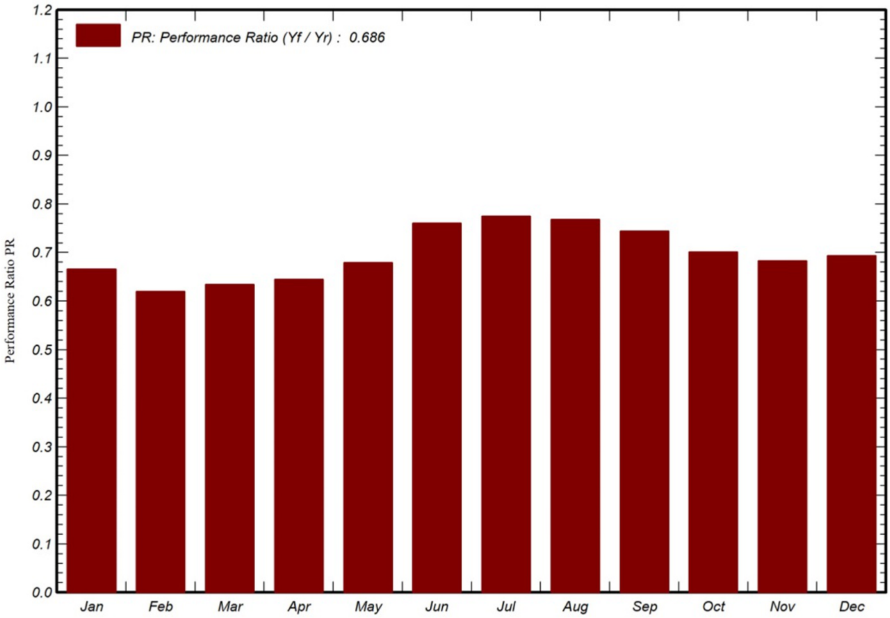

Fig. 8. Performance Ratio (Monthwise)

3.6 Daily Input–Output Relationship of the PV System

Fig. 9 shows how the daily solar energy received by the panels affects the energy produced by the system. As the sunlight increases from about 1 to 7.5 kWh/m^2/day, the daily output also increases from around 3 kWh to nearly 24-25 kWh. The data points follow a clear upward pattern, showing that the system respond properly to changes in the sunlight. At very high sunlight level, the output increases more slowly, mainly due to system limits and temperature effects. Overall the figure 9 clearly shows that the more sunlight result in more energy generation[27].

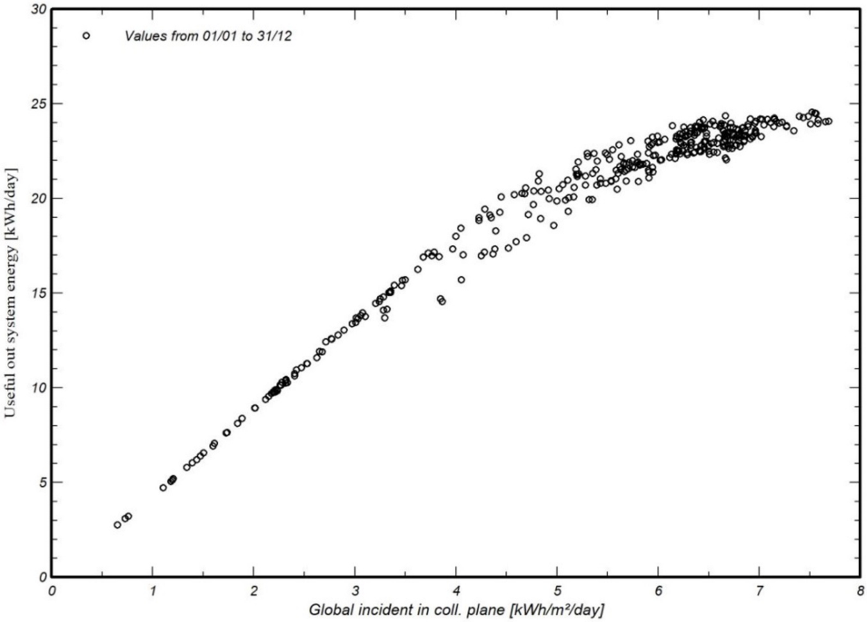

Fig. 9. Daily Input- output Energy of Solar PV panels

3.7 Normalized energy production and loss distribution

Fig. 10 depicts the normalized energy output per installed kWp for the 5.45 kWp system. The inverter's annual useful energy (Yf) is 3.67 kWh/kWp/day. Collection losses at the array level (Lc) are 1.53 kWh/kWp/day, while system losses due to the inverter (Ls) are relatively low at 0.11 kWh/kWp/day. Higher normalized production is observed from February to April, exceeding 4 kWh/kWp/day, while lower values occur in June and July due to reduced solar availability. The figure clearly shows that the majority of losses occur at the PV array level, with inverter losses being minimal. Overall, the system has a consistent performance with predictable seasonal variation[6], [28].

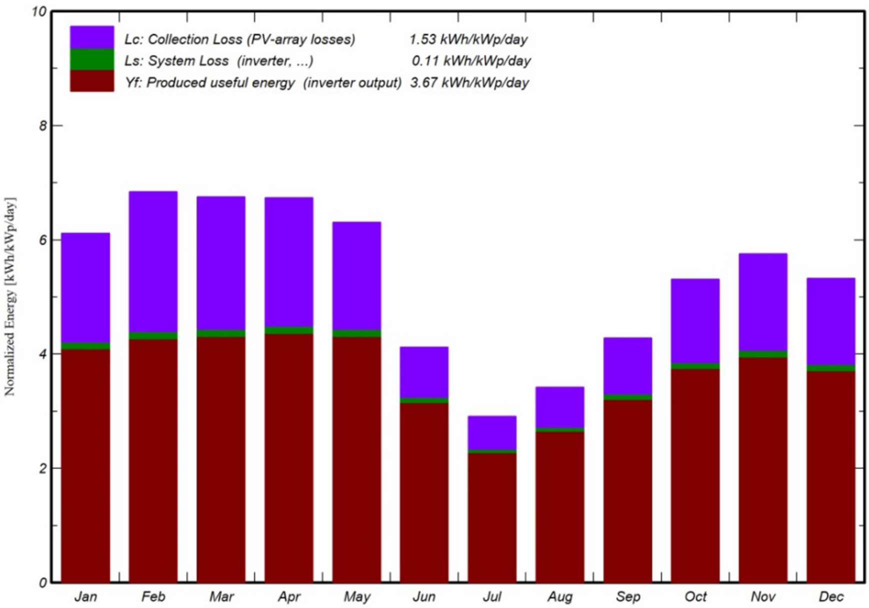

Fig. 10. Normalized Energy in terms of production and losses (Monthwise)

3.8 Normalized production and loss factor distribution

Fig. 11 displays the normalized production and loss factors for the 5.45 kWp system. Annually, 69.1% of the available solar energy is converted into useful inverter output (Yf). Collection losses at the PV array level account for 28.8%, while system losses caused by the inverter account for only about 2%. The useful energy fraction remains relatively constant throughout the year, with slightly better performance observed during the monsoon season due to reduced thermal stress. The majority of losses occur on the array side, which is primarily affected by temperature and inherent module characteristics, while inverter losses are minimal. Overall, the figure demonstrates that the system is efficient, with a predictable and stable loss distribution across different seasons[28].

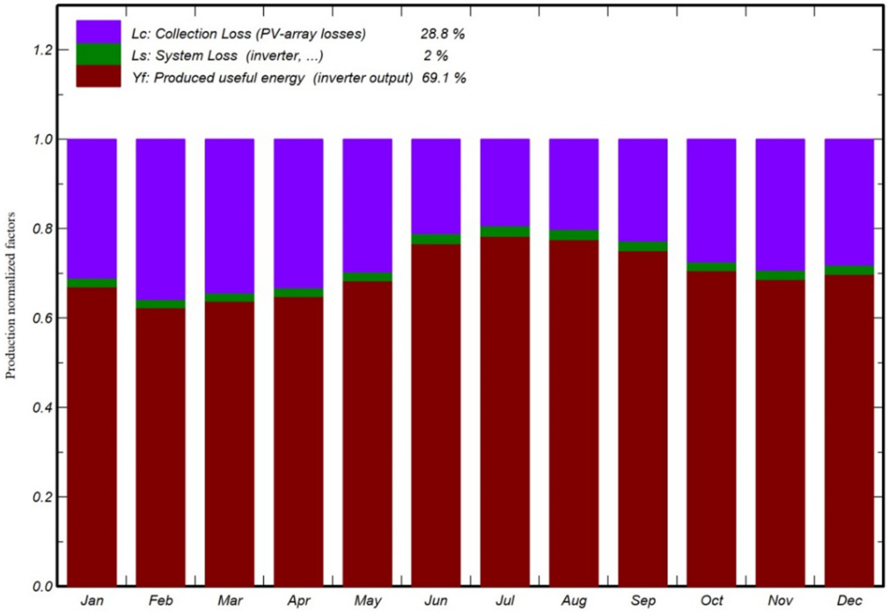

Fig. 11. Production normalized factor (Monthwise)

3.9 Overall performance assessment under coastal conditions

The simulation results show that the proposed 5.45 kWp rooftop PV system is reliable in Mumbai's coastal climate. Despite high ambient temperatures and seasonal monsoon variations, the system maintains a consistent energy generation rate and an adequate performance ratio. Thermal losses are the primary limiting factor, with shading and inverter losses remaining relatively low. Overall, the findings show that properly designed rooftop PV systems can perform well even in tropical coastal environments.

3.10 Loss diagram and energy flow analysis

Fig. 12 shows the annual loss diagram for the simulated PV system. The site receives 1814 kWh/m² of global horizontal irradiation, which increases by 6.9% after tilt adjustment, yielding an effective collector irradiation of 1868 kWh/m². Shading and incidence angle losses remain low, at 1.2% and 2.4%, respectively. With a module efficiency of 21.19%, the array generates a nominal energy of 10,227.2 kWh. The main reductions are due to temperature loss (7.9%), mismatch loss (2.0%), and wiring loss (1.1%), resulting in 9,110.5 kWh at the array output. Inverter operation causes an additional 2.4% loss. Finally, 7,303.1 kWh are available at the inverter output, with 5,058.5 kWh exported to the grid. The diagram clearly shows that temperature effects are the most significant loss factor, with shading and inverter losses remaining relatively low[12], [28]

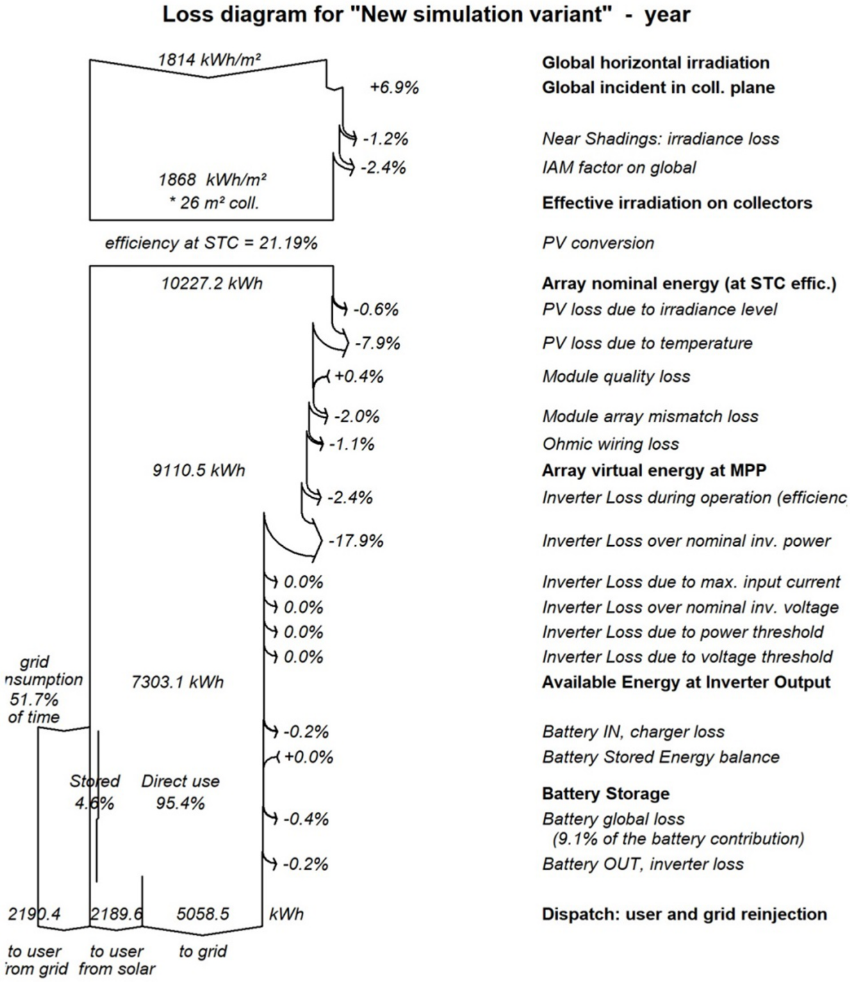

Fig. 12. Annual loss diagram of overall system

Conclusion

The results show that the proposed 5.45 kWp rooftop PV system operates reliably under Mumbai's coastal conditions. The system generates 7303.1 kWh annually at the inverter output, with 5058.5 kWh exported to the grid, and has an annual performance ratio of 0.686. Monsoon cloud cover and temperature effects have the greatest influence on seasonal variations, with thermal losses accounting for the vast majority of the total reduction. Overall, the study shows that a well-designed rooftop PV system can give reliably and practically performance in tropical coastal environments also this study can be extended to similar buildings and scaled to large capacity for wider deployment.

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Disclosure of Interests. The authors declare that they have no competing interests relevant to the content of this article..

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