frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 22 March 2023
DOI 10.3389/fenrg.2023.943207

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Process and Energy Systems Engineering, a section of the journal Frontiers in Energy Research

RECEIVED 13 May 2022
ACCEPTED 10 March 2023
PUBLISHED 22 March 2023

CITATION
Sharma R, Goel S and Lenka SR (2023), Pragmatic analysis of solar photovoltaic system design in an institutional building in eastern India.
Front. Energy Res. 11:943207.
doi: 10.3389/fenrg.2023.943207

Pragmatic analysis of solar photovoltaic system design in an institutional building in eastern India

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PV systems connected to the grid are primarily designed to generate clean energy to fulfil the rising energy demand. To predict the performance and efficacy of PV systems, several installation aspects are employed, such as location, local meteorological data, orientation, optimal tilt angle, varying losses, and energy yield estimation. Siksha 'O' Anusandhan Deemed to be University, Bhubaneswar (Latitude 20.24°N and Longitude 80.85°E) has taken one such initiative by installing a 13 kWp rooftop grid-connected solar photovoltaic system in one of its institutional buildings. The solar PV system is fixed at an angle of 21° and is installed on the rooftop of a 25-m height building. The measured performance characteristics were analysed and compared to those of PVSyst software to determine its feasibility in campus buildings. From the result, the annual electricity supplied to the grid is 17.79 MWh, final yield of 3.80 h/d, reference yield of 4.62 h/d and performance ratio of 0.82. The solar PV system installed at the institution is predicted to have reduced 17443.02 kg of CO_2, 22.07 kg of SO_2, and 46.1 kg of NOx from the atmosphere per year. The lebelised cost of energy (LCOE) of the installed PV system is 9.408 INR/kWh with a payback of 9.8 years. This study provides the techno-economic feasibility of installing grid-connected solar PV systems on the roof of an institutional building and help the solar installers in establishing the most efficient solar photovoltaic system's sizing and design.

KEYWORDS

solar photovoltaic system, performance study, techno-economic analysis, environmental emission analysis, soiling loss

1 Introduction

The world's energy demand has increased in all fields as a result of various developmental activities. Because fossil fuel-based technology is rapidly decreasing, it is time to harness renewable energy sources such as solar, wind, biomass, and small hydropower to overcome the energy crisis. Many countries have installed solar PV

Abbreviation: CUF capacity utilisation factor,% Diff Hor horizontal diffused radiation, kWh/m^2 E_{ac} energy injected into grid, kWh E_{ARR} MPP effective energy at the output of the array, at maxi maximum power point EArray effective energy at the output of the array, kWh GlobHor horizontal global irradiation,kWh/m^2 h/d hour/day Ht total mean daily in-plane solar insolation, kWh/m^2/day kWh kilo watt hour Lc captor loss, h/d L_{CR} array loss/incident energy ratio = Lc/Y_R L_S system loss, h/d L_{SR} system loss/incident energy ratio = Ls/Y_R MWh mega watt hour PR performance ratio PVrated rated PV power T Amb ambient temperature Y_A array yield Y_F final yield $Y_R$reference yield.

TABLE 1 Summary of some relevant studies in Institutional buildings.

Sl. no	Institution name	Findings	Size of PV plant	References
1	ITER, SOA (Deemed to be University), Bhubaneswar, India	The 13 kWp PV system is producing 17.79 MWh of electricity per year. This system is capable of saving 17443.02 kg of CO_2 emission per year	13 kW	(Present Study)
2	SUM Hospital, SOA (Deemed to be University) Bhubaneswar, India	Solar PV systems can be utilised to meet their daily energy demands due to rising electricity bills and a desire to protect the environment	120 kW	
2	OUAT, Bhubaneswar, India	The electricity generated by the PV-technology is fed into the grid systems to reduce their future electric bills	1 MW	
3	KISS, KIIT University, Bhubaneswar, India	The generation can be used to meet the daily energy demand of the institution	500 kW	
4	DAV Public School, Unit-8, Bhubaneswar, India	The generation could save 80% of their energy need from rooftop solar panels	50 kW	Odisha Renewable Energy Development Agency (2022)
5	Xavier University, Bhubaneswar, India	The generation is saving energy cost because of the installation of the Solar PV system	200 kW	Odisha Renewable Energy Development Agency (2022)
6	NIT Rourkela, Rourkela	The solar project which is connected to the Power grid will now cut down the conventional electricity by one-third	1,020 kWp	Newindianexpress (2019)
	India			
7	Manit Campus, India	A solar-based PV system with a capacity of 5 MW is expected to produce 8,000 MWh/year of electricity, resulting in a carbon reduction of 173,318 tonnes per year	5 MW	Baitule and Sudhakar (2017)
8	Jawaharlal Nehru University (JNU),India	The institution will save over 60% on energy costs because of the installation of the solar power system	500 kW	Mercomindia (2022)
9	Jamia Millia Islamia University, India	Solar PV systems can be utilised to meet their daily energy demands due to rising electricity bills and a desire to protect the environment	2.25 MW	Mercomindia (2022)
10	Amity University, India	Solar PV systems can be utilised to meet their daily energy demands due to rising electricity bills and a desire to protect the environment	1.8 MW	Mercomindia (2022)
11	Tezpur University, India	The installation of the solar power plant reduces INR 140 lakhs in the University Electricity Bill	1,000 kWp	Tezu (1994)
12	Bangalore University, India	The present solar installation will reduce 790 tonnes of CO_2 every year	495 kW	Timesofindia (2019)
13	Khatkar-Kalan, India	Performance ratio, Capacity utilisation factor and the system efficiency were 74%, 9.27%, and 8.3% respectively	190 kWh	Sharma and Chandel (2013)
14	IIT, Roorkee, India	i. The cost of energy of the system is 8.50 INR/kWh and performance ratio of 63.68%	1816 kWp	Pundir et al. (2016)
15	Zero-energy office building, Singapore	i. PR: 81%	142.5 kW	Wittkopf et al. (2012)
		ii. System efficiency: 11.2%		
		iii. Inverter efficiency: 94.8%		
		iv. Yield reduction: 18% due to high module temperature of 55–60°C		
		The average final yield: 3.12 h/d		
16	Errachidia city in Morocco	YF = 5.26 h/day, PR 82%, CF is 21.93%, levelized cost of electricity is 0.068 €/kWh and payback time is 12 years, were recorded by pc-Si solar module	5.94 kWp	Elamim et al. (2018)
17	High School of Technology in Meknes	The lebelised cost of Energy was found to be in between 0.073 and 0.082 $/kWh, payback of 11.10–12.69 years. CO_2 reduction per year is 5.01 tons/year	2 kWp	Allouhi et al. (2016)
18	Shri Vishnu Educational Society, Bhimavaram, India	i. The performance factor varies from 55% to 89%	50 kWp	Omkar et al. (2015)
		ii. Energy supplied to grid is 392.3 kWh		

(Continued on following page)

TABLE 1 (***Continued***) **Summary of some relevant studies in Institutional buildings.**

Sl. no	Institution name	Findings	Size of PV plant	References
		iii Capacity factor is between 2% and 10.7%		
19	Sawda and Azda Schools, Kuwait City	The performance ratio was less than 70%.Monthly energy yield is 104 kW·h/kWp. The annual average daily final yields of the PV systems was 4.5 kW·h/kWp/day. The total soling loss for Azda is 45.8% and for Sawda it is 42%	85.05 kWp and 21.6 kWp	Al-Otaibi et al. (2015)
20	TERI Retreat Building, India	The annual average PV and grid contribution to meet the load demand is estimated to be 53% and 47% respectively	12.8 kWp	Sharma et al. (2019)
21	Jaen University	The average annual energy production was 168.12 MWh per year, accounting for 6.40% of the total consumption of the Jaen university campus	200 kWp	Drif et al. (2007)
22	High School of Technology in Meknes	The LCOE is in the range of 0.073–0.082 $/kWh and Payback period of 11.10–12.69 years. The PV system saved 5.01 tons of CO_2 emission per year	2 kWp	Allouhi et al. (2016)
23	Kyungpook National University, the Republic of Korea	Annual electricity exported to the grid is 9,521 kWh. The annual final and array yield of p-si is 4.93 h/day and 5.12 h/day. The solar PV saved 9.7 tons of CO_2 per year	5 kWp	Owolabi et al. (2022)

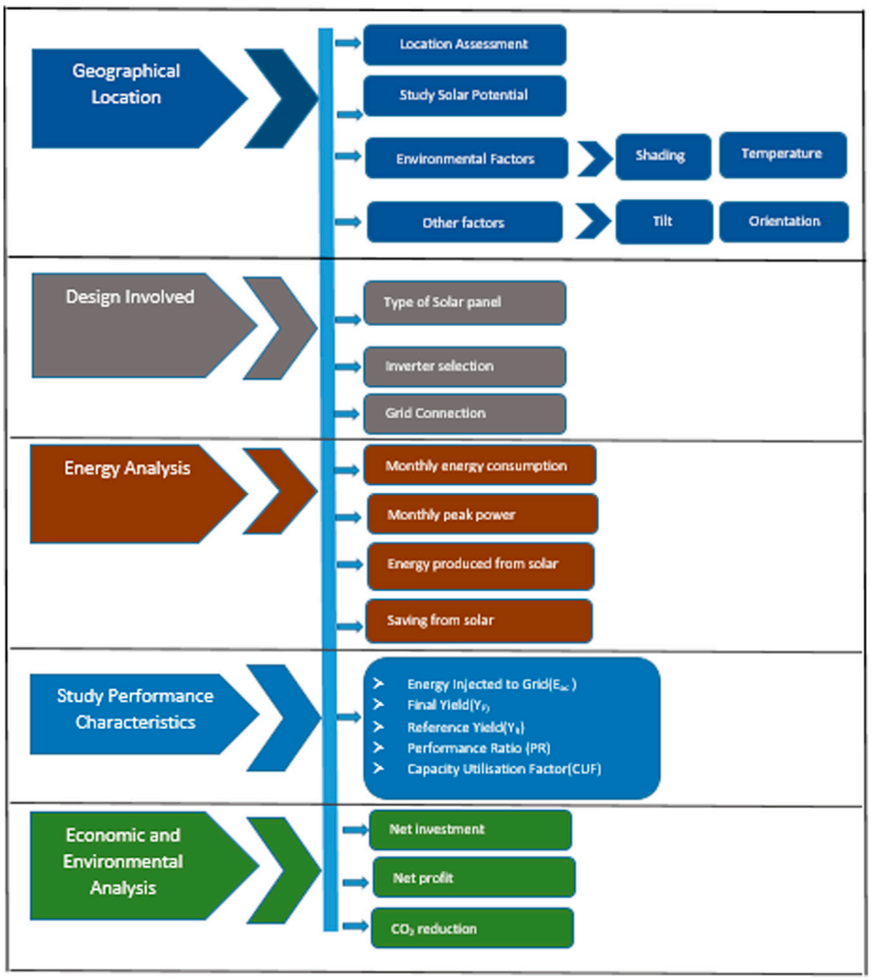

FIGURE 1
PV design methodology.

TABLE 2 Specification of PV module installed.

PV module	
Parameters	Specification
Type of module	Polycrystalline
Frame material	Anodized aluminium alloy
Pmax	325 W
Imp	8.60 A
Vmp	37.80 V
Isc	9.20 A
Voc	46.60 V
Temperature coefficient of Pmax	−0.3948%/°C
Nominal operating cell temperature (NOCT)	46 ± 2°C
Operating temperature range	−40°C–85°C
Maximum System Voltage	1500 V DC
Each module area, m^2	1.94
No. of modules	40
Solar cells per module (Units)	72
Efficiency	16.75%
Weight/module, kg	22.5

TABLE 3 Specification of inverter.

PV grid inverter	
Parameters	Specification
Model	KSG-III-20 K
Maximum PV Voltage	1000 V
Maximum Output Power	20 kW
Maximum Apparent power	22,200VA
Input (DC)	
Voltage range, V PV I_{sc}, A Maximum current, A	200 V-1000 V 45 A 37.5 A
Output (AC)	
Nominal output voltage Maximum output current, A Nominal frequency, Hz Safety level Operating ambient temperature	230 V/400 V 32.2 A 50/60 Hz Class II −25°C–+60°C

projects to produce electricity; as a result, the total installed capacity across the globe has reached 627 GW (IEA, 1974). Many Universities worldwide are making major investments to strengthen their long-term and medium-term sustainability. Odisha by its position in the globe has very good potential for almost all the renewable energy resources (Sharma and Goel, 2017) (Goel and Sharma, 2021). An assessment indicated that Odisha has a feasible renewable energy potential of 27,728 MW. The state of Odisha is located at 17.49′N −22.34′N latitude and 81.27′E–87.29′E longitude and receives a good amount of solar radiation of approximately 5.5 kWh/m^2 for over 300 days a year (Government Of Odisha, 2023). Many rooftop solar power plants of various capacities have been installed in various government buildings, residential schools, hostels, and public health centres to meet the power deficit of the state. Additionally, many institutions have installed grid-interactive rooftop solar power plants. If the institution plans a large power plant to meet the load demand of the entire campus, a pre-feasibility study must be conducted in terms of its viability. However, academic solar projects can solve the energy demand of the campus, thereby generating revenue by selling excess electricity to the grid. The novelty of this paper is that no such study has been conducted in an institutional building in Eastern India, which is the first of its kind in the known literature. In Odisha, there has been no investigation on the installation of solar PV in an academic institution. This requires a large construction area and a large investment. In addition to this, the accumulation of dust over a solar panel situated over a 25 m high building was studied, which is new of its kind in any of the institutional buildings in eastern India. Despite the feasible potential of solar energy in Odisha, the implementation of the rooftop photovoltaic system in institutional buildings faces various challenges. A large-scale project necessitates a significant financial commitment as well as a longer timeframe to execute. During this period, changes in the inflation rate will have an influence on the investment. Similarly, the government's renewable energy subsidy looks to be modest in comparison to the project's investment. However, the institute's insufficient budget makes it difficult to implement such a large scale project without the Govt. subsidy and a low-interest loan.

Better solar irradiance, climatic conditions, geotechnical considerations, topography, bearing strength of soil, environmental factors (soiling loss and shading loss), availability of grid supply, and land accessibility are important factors to consider when choosing a location (IFC, 2015). When evaluating solar potential, special emphasis should be placed on minimizing the shadowing impact, as this reduces the efficiency of the system (Sathyanarayana et al., 2015).

Some of the relevant studies along with the salient findings and place of study are presented in Table 1.

2 Methodology

This study investigates the use of open rooftop areas at academic institutions to produce sustainable energy, which can generate revenue and protect the environment. Many adjustments must be made to achieve the best balance between energy performance and cost, particularly in self-consumption estimations. The detailed methodology is shown in Figure 1.

The measured performance characteristics were studied and compared with those of the PVSyst software to determine its feasibility in campus buildings. The parameters considered for designing a grid-connected solar Photovoltaic system are the location of the study (latitude and longitude), orientation,

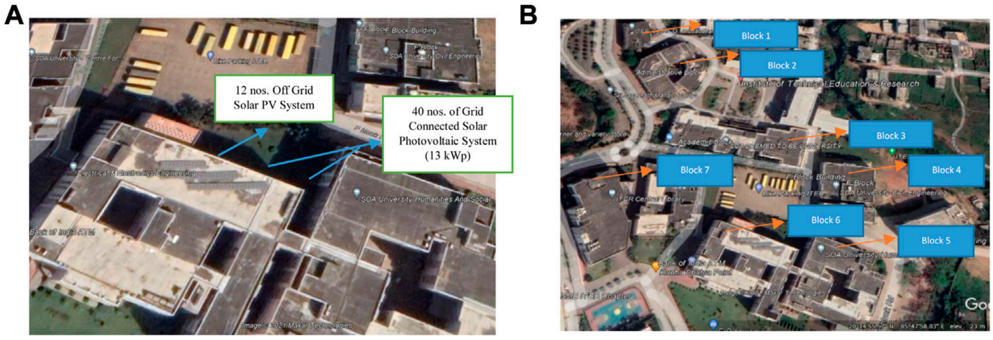

FIGURE 2
(A) Satellite image of the roof area of the building of the constituent Institute. **(B)** The roof top area found suitable for the construction.

TABLE 4 Meteorological observations of the site.

Month	Ambient Temp,°C	Humidity, %	Rainfall, mm	No of rainy days	Wind speed, m/s	Global horizontal irradiance, kWh/m²/d	Solar irradiation on plane of array, kWh/m²/d
January 19	20	71	0	0	0.9	3.70	4.62
February 19	24	69	19.2	1	1.8	4.48	5.42
March 19	27.5	76	2	1	2.4	5.04	5.46
April 19	29.5	78	24.6	3	3	5.41	5.43
May 19	30	83	55	2	4	5.23	4.93
June 19	30	86	160	9	2.9	4.47	4.26
July 19	28	92	348	16	3	3.71	3.82
August 19	27	94	299	16	2.1	4.10	4.01
September 19	27	93	467.6	16	1.8	3.98	4.18
October 19	26.5	91	324.1	8	0.8	3.75	4.28
November 19	23.5	84	3.8	1	1.1	4	4.91
December 19	20.5	80	0	0	0.8	3.74	4.76

TABLE 5 Comparison of different solar technology.

Sl. no.	Property	Monocrystalline	Polycrystalline	Thin film
1	Efficiency	High	Moderate (13%–15%)	Lowest
2	Cost	High	Moderate	Lowest
3	Area occupied per kW	Low	Moderate	Highest
4	Generation capability in diffused light	Average	Average	Better
5	High temperature performance	Poor	Poor	Better

climatic condition, photovoltaic type, its losses, and the area required for the potential site for installation. The design procedure is as follows:

- Finding the geographical location for the installation of the solar PV system.
- Selecting the right model of a PV system

TABLE 6 Monthly energy consumption and monthly electricity bill.

Month	Energy consumption, MWh	Power on hour, kWh	Minimum demand, KVA	Monthly bill amount, INR
January 19	1463.80	744	1,413.60	931,713
February 19	1642.00	744	755.20	1,207,314
March 19	1835.50	672	755.20	1,316,906
April 19	2215.30	744	755.20	26,64,813
May 19	2548.60	720	755.20	2,688,658
June 19	664.60	744	755.20	9,29,024
July 19	796.60	720	755.20	946,039
August 19	950	744	755.20	1,080,597
September 19	1117.70	744	755.20	1,149,120
October 19	1283.70	744	755.20	1,160,166
November 19	1427	744	755.20	1,176,031
December 19	1556.20	720	755.20	1,190,296
Total	17,501	8,784		16,440,677
Average	1458.42	732		

TABLE 7 Measured performance parameters of 13 kWp grid connected PV system.

Month	In-plane irradiance kWh/m^2/d	E grid (Eac), kWh	Yield, h/d		PR = Y_F/Y_R	CUF % = Eac.m/(PV_{rated} × 24 × 30/31 days)
			Y_F = Eac/PV rated	$Y_{R=}$Ht/ 1 kWp		
January 19	4.62	1554.52	3.98	4.62	0.86	16.07
February 19	5.42	1597.25	4.09	5.42	0.75	16.51
March19	5.46	1874.01	4.80	5.46	0.88	19.37
April 19	5.43	1697.96	4.35	5.43	0.80	18.14
May 19	4.93	1731.78	4.44	4.93	0.90	17.90
June 19	4.26	1324.86	3.39	4.26	0.79	14.15
July 19	3.82	1212.51	3.10	3.82	0.81	12.53
August 19	4.01	1395.23	3.57	4.01	0.89	14.42
September 19	4.18	1327.46	3.40	4.18	0.81	14.18
October 19	4.28	1551.15	3.97	4.28	0.92	16.03
November 19	4.91	1497.35	3.83	4.91	0.78	15.99
December 19	4.76	1034.88	2.65	4.76	0.55	10.69
Total	55.46	17798.97	45.63	55.46	0.82	185.98
Mean	4.62	1483.25	3.80	4.62	0.82	15.49

- Knowing the energy consumption of the institutional building
- Measured data analysis of the SPV system
- Data analysis by using PVSyst
- Comparison of the measured data with the predicted values by using PVSyst software
- Evaluation of the cost and benefit of the solar PV system

TABLE 8 Soiling loss in monsoon and non-monsoon days.

Day no	Non-monsoon period			Monsoon period		
	January-May			Jun-Oct		
	Pmax (clean)	Pmax (soiled)	Soiling loss, %	Pmax (clean)	Pmax (soiled)	Soiling loss, %
0	30.57	30.57	0	29.46	29.46	0
1	29.43	28.65	2.65	29.72	29.43	0.98
2	39.93	37.96	4.93	34.75	34.23	1.495
3	33.14	32.6	1.63	32.37	32	1.14
4	39.23	38.08	2.93	0	0	0
5	33.12	32.12	3.01	0	0	0
6	32.2	31	3.73	0	0	0
7	34.4	32.95	4.22	0	0	0
8	29.72	28.12	5.38	0	0	0
9	31.56	30.85	2.25	32.93	32.65	0.85
10	32.87	31.12	5.32	40.5	39.93	1.41
11	36.67	35.14	4.17	38.83	38.65	0.46
12	33.47	32.67	2.39	35.67	34.23	4.04
13	35.97	35.01	2.67	38.12	37.41	1.86
14	36.43	35.17	3.45	41	40.54	1.12
15	34.41	33.42	2.87	38.86	37.63	3.17
Avg			3.67			1.03

FIGURE 3
Measurement of soiling loss.

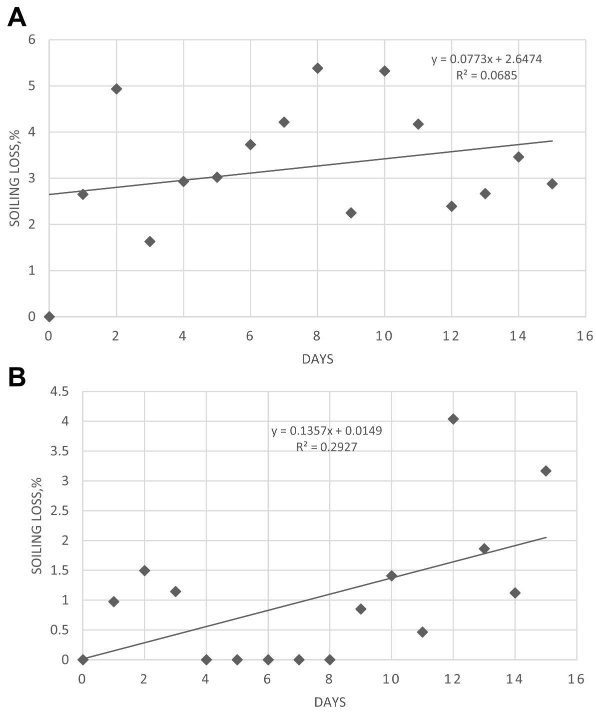

FIGURE 4
(A) Soiling loss in non-monsoon month. **(B)** Soiling loss in monsoon months.

- Environmental benefit assessment of the PV System

3 Case study

The 13 kWp grid-connected solar PV system consists of 40 nos. of solar PV modules each with 1.94 m^2 area (total area of 77.6 m^2). An array is formed by connecting twenty modules in series, and two such arrays are arranged in parallel. The Waaree modules WS 325 (each of 325 Wp capacity) having

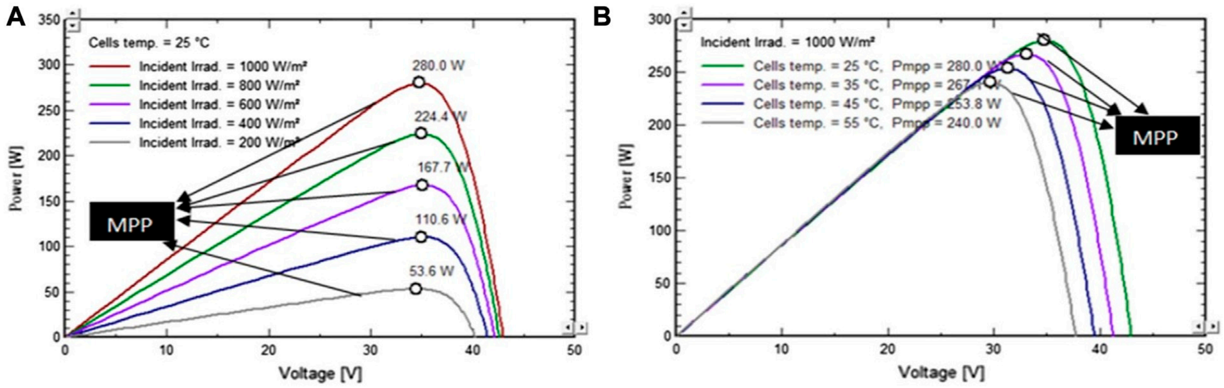

FIGURE 5
(A) P–V characteristics of PV module with the location of MPP for different irradiance levels at 25°C **(B)** P–V characteristics of the module at different temperatures at an irradiance of 1000 W/m².

TABLE 9 Performance Calculation of the PV System Balances and main results.

Month	Glob_Hor kWh/m²	Diff_Hor kWh/m²	T_Amb, °C	E_Array kWh	E_ grid kWh	PR
January	142.1	56.27	21.86	1981	1943	0.845
February	149.4	60.81	25.16	1887	1850	0.819
March	186.4	70.45	30.04	2101	2058	0.788
April	195.8	79.28	30.74	2057	2016	0.794
May	203.2	87.03	31.58	2043	2001	0.804
June	157.2	80.55	29.57	1,605	1,569	0.829
July	140.2	80.11	28.39	1,454	1,421	0.841
August	146.6	79.91	28.03	1,593	1,558	0.840
September	139.8	70.80	27.78	1,612	1,578	0.836
October	150.9	64.13	26.51	1,888	1,849	0.833
November	138.3	54.40	23.99	1,878	1,839	0.840
December	134.0	60.62	21.88	1,880	1,842	0.851
Year	1883.8	844.34	27.14	21,979	21,522	0.825

72 solar cells made up of polycrystalline silicon with an open circuit voltage (Voc) of 46.60 V and a short circuit current (Isc) of 9.20 A were used in the PV system. The modules are free from any effect of shade and are fixed with a tilt angle of 21^0 facing south at an azimuth angle of 0^0. The entire PV system is mounted on metal frames supported by concrete pillars. The surface of the PV modules was cleaned with water at intervals of 15 days throughout the monitoring period to reduce losses due to soiling. The solar panel, inverter, and battery bank should have the same input voltage (either 12 V, 24 V, or 48 V). In this case, a Kirloskar 3 Phase Solar Inverter, model KSG-III-20 K, was used to convert DC to AC, which was then fed directly into the state grid. The specifications of the PV module and the inverter are listed in Tables 2, 3, respectively.

4 Result and discussion

4.1 Weather data

The study was conducted in Siksha "O" Anusandhan Deemed to be University Bhubaneswar, India. The satellite image of the roof area of the buildings of a constituent institute in Bhubaneswar, India is shown in Figure 2A. The image was assessed on 3rd December 2021 through "Google Earth" software.

Figure 2B shows the rooftop area, which is suitable for the construction of a large-scale solar PV system. A total of 22,048 m² areas were identified for installation of the solar photovoltaic system, out of which only 101 m² of rooftop area was utilized. The remaining 21,947 m² can be used for the placement of an additional solar photovoltaic system. Solar irradiance data were used to assess the

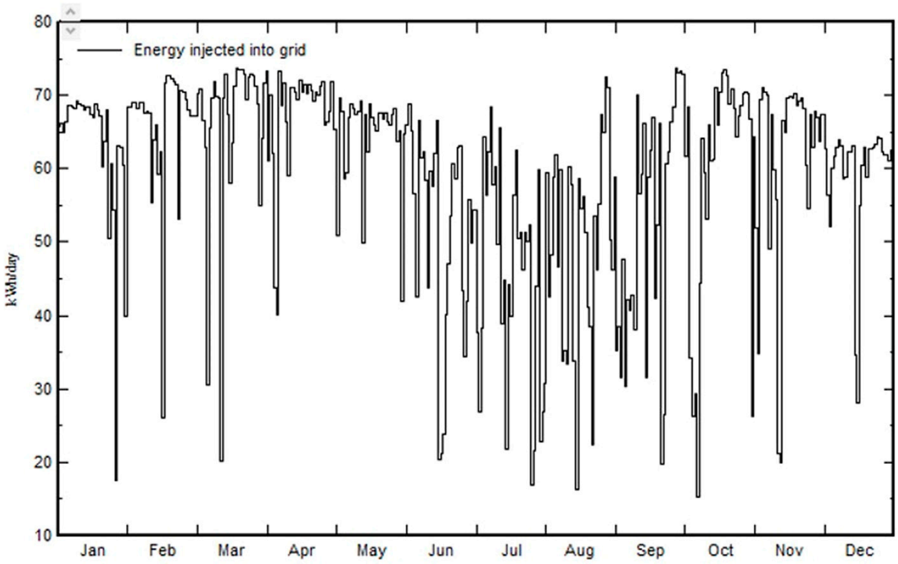

FIGURE 6
Energy injected into the grid.

TABLE 10 Normalised Performance coefficient.

	Y_R kWh/m²/day	Lc ratio	Y_A kWh/kWp/day	Ls ratio	Y_F kWh/kWp/day	L_{CR} ratio	L_{SR} ratio	PR ratio
January	5.70	0.788	4.92	0.096	4.82	0.138	0.017	0.845
February	6.20	1.017	5.19	0.103	5.08	0.164	0.017	0.819
March	6.48	1.262	5.21	0.108	5.11	0.195	0.017	0.788
April	6.51	1.233	5.28	0.107	5.17	0.189	0.016	0.794
May	6.18	1.107	5.07	0.105	4.97	0.179	0.017	0.804
June	4.85	0.737	4.11	0.092	4.02	0.152	0.019	0.829
July	4.19	0.586	3.61	0.081	3.53	0.140	0.019	0.841
August	4.60	0.651	3.95	0.086	3.87	0.141	0.019	0.840
September	4.84	0.707	4.13	0.088	4.05	0.146	0.018	0.836
October	5.51	0.823	4.68	0.096	4.59	0.149	0.017	0.833
November	5.62	0.800	4.81	0.099	4.72	0.143	0.018	0.840
December	5.37	0.706	4.66	0.093	4.57	0.132	0.017	0.851
Year	5.50	0.867	4.63	0.096	4.54	0.158	0.017	0.825

location's solar potential, as it is the key parameter that directly affects the system's energy output and is influenced by factors such as latitude, longitude, altitude, cloud cover, and air quality (Sharma and Goel, 2015; Rathod et al., 2016; Hasapis et al., 2017; Paudel et al., 2021).

The cell temperature was measured using an HDE infrared thermometer (Range: −32°C–380°C) at 15-min intervals and averaged hourly from 6.00 h to 18.00 h. A laboratory thermometer was used to record the ambient temperature. Other meteorological data, such as temperature, wind velocity, relative humidity, solar insolation, were obtained from the local meteorological department. The weather data are presented in Table 4.

From the above Table, it was seen that the maximum in plane solar irradiation was observed during the month of March while minimum was found during July. Minimum and maximum humidity varies from 69% to 94% while maximum wind speed of 4 m/s found in May 2019. The highest average ambient temperature of 30°C were observed in May, June and lowest of 20°C in the month of January. Maximum rainfall of 467.6 mm was found in the month of September 2019. Usually the solar radiation data is available for

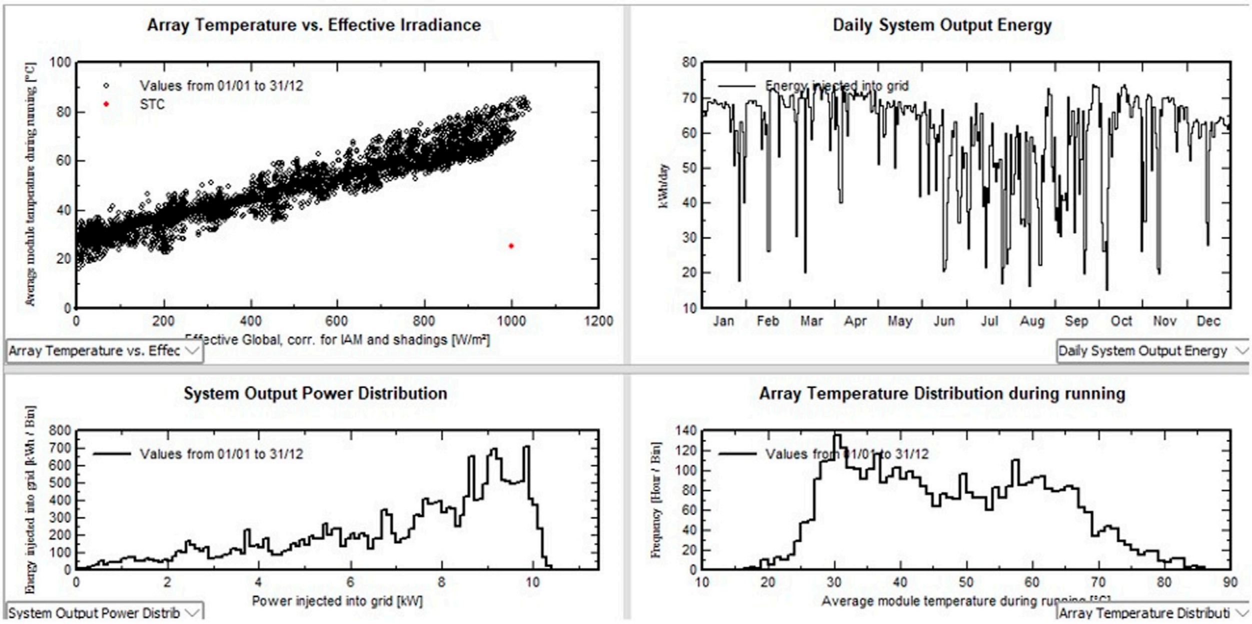

FIGURE 7
Simulation results.

TABLE 11 Various system losses of 13 kWp PV system Detailed System losses.

Month	Ohmic loss, kWh	EArr MPP kWh	Inverter loss kWh
January	24.08	1981	38.81
February	25.09	1887	37.55
March	30.05	2101	43.70
April	27.81	2057	41.81
May	25.23	2043	42.16
June	16.38	1,605	35.72
July	12.63	1,454	32.82
August	15.85	1,593	34.55
September	17.56	1,612	34.13
October	22.91	1,888	38.76
November	22.94	1,878	38.66
December	21.59	1,880	37.68
Year	262.12	21,979	456.33

the horizontal surface. Therefore, it needs to be corrected for the tilted surface.

4.2 Selecting the right model of a PV system

Solar energy has gained in popularity over the last decade. Improvements in solar technology have resulted in a reduction in panel costs. The Government of India provides various financial incentives to encourage renewable energy development. Therefore, integration technologies have become essential. A comparison of the various types of solar PV technologies is presented in Table 5.

Because polycrystalline solar panels are cheaper and more eco-friendly to produce, they are best suited for installation in large solar farms, roof-mounted arrays, traffic lights, and houses.

4.3 Estimating the energy and power consumption of the institutional building

The campus energy consumption data were studied by collecting data such as monthly energy consumption, monthly peak power, monthly electricity bills, energy produced from solar PV systems, and solar energy savings. The monthly energy consumption in MWh, Power per hour in kWh, and minimum demand for the year 2019 were collected through a personal survey, as mentioned in Table 6.

The monthly average energy consumption of the campus was 1458.42 MWh whereas the yearly total energy consumption was 17,501 MWh. The average power-on time was 732 kWh. The total electricity bill of the campus is INR 1, 64, 40,677, which is too high. Thus, switching to various solar power options can reduce the total electricity bill.

4.4 Measured performance analysis of the solar PV system

The performance parameters such as final yield, reference yield, performance ratio, capacity utilisation factor, soiling loss, shading loss, and energy generation were studied to observe the overall

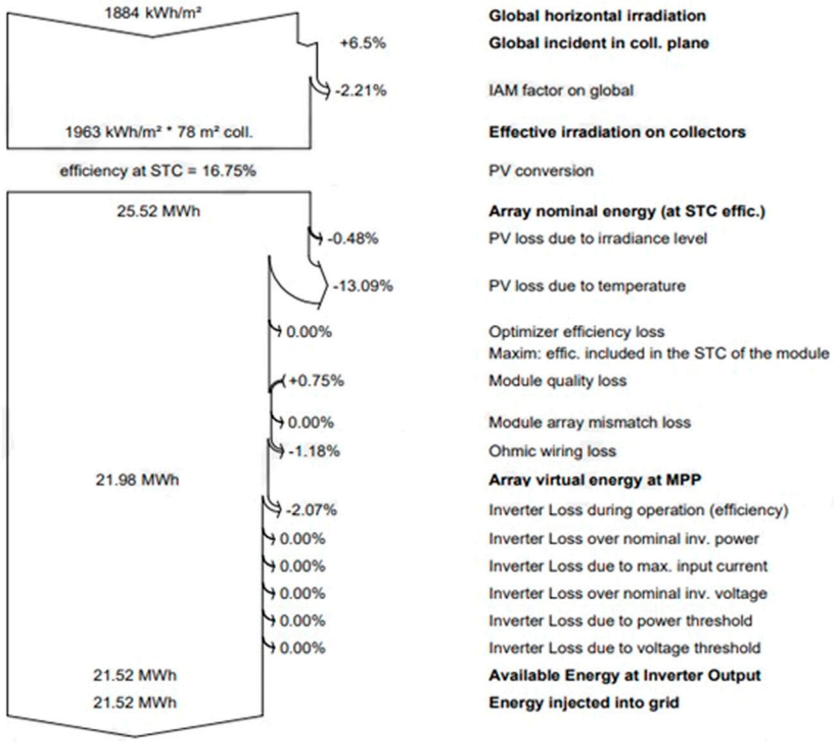

FIGURE 8
Loss diagram of the PV System.

TABLE 12 Comparison of measured and simulation parameters.

Parameters	Measured	Simulated by PVSyst
Eac (kWh)	17799	21522
Y_F, (h/d)	3.80	4.54
Y_R, (h/d)	4.62	5.50
PR	0.82	0.82

performance of the PV power plant. The measured performance parameters of the 13-kWp grid connected PV system are given in Table 7.

As the present PV system is installed on rooftop of a 5th floor building, shading loss due to adjacent buildings, trees, etc., is zero.

4.4.1 Soiling loss

As the present research site is situated in crowded localities, many traffic and construction sites are located in and around the building (where the rooftop system is mounted), causing more dust deposits on the modules. As massive construction is ongoing in and around the institutional building, the accumulation of dust over the solar panel is more, which requires frequent cleaning. The effect of dust accumulation is shown in Table 8, which is unique to our study. The measurement of soiling loss at the site of study is shown in Figure 3.

Two 50 Wp solar panels were mounted separately on the roof at a 21^0 tilt angle for soiling loss measurement, and Isc, Voc, and Pmax were measured for clean and soiled panel every day at 12 noon for 15 days. To minimize soiling loss, cleaning was performed every 15 days. Soiling loss was calculated by

$$\text{Soiling Loss (SL), \%} = \left(1 - \frac{X_{soiled}}{X_{cleaned}}\right) * 100$$

Where, $X = I_{sc}$ or P_{max} or daily energy yield in kWh, I_{sc} and P_{max} values are recorded at solar noon for soiling loss calculation.

Power and efficiency loss due to soiling can be calculated by (Goel et al., 2020)

$$\text{\% reduction in power} = \left(\frac{P_{without\ dust} - P_{with\ dust}}{P_{without\ dust}}\right) * 100$$

$$\text{\% reduction in efficiency} = \left(\frac{\eta_{without\ dust} - \eta_{with\ dust}}{\eta_{without\ dust}}\right) * 100$$

From the above table it is seen that the soiling loss was found to be 3.67%/day during non-monsoon months (January-May) while it is only 1.03%/day in monsoon months (June-October). The details of soiling loss is shown in Figure 4A, B.

4.5 Data analysis using PVSyst software

PVSyst is the most widely used simulation software tool for performance analysis of PV plants. It is capable of importing meteorological data from many sources according to the suitability of locations. This tool accurately predicts the energy

TABLE 13 Investment cost of the system. Installation costs.

Item	Quantity units	Cost INR	Total INR
PV modules			
Waaree Solar panel	40	13000.00	520000.00
Supports for modules	40	3250.00	130,000
Inverters			
Solar Inverter KSG-III-20 K	1	150000.00	150000 00
Other components			
Accessories, fasteners	1	8 0.000.00	8 0.000.00
Wiring	1	20,000.00	20000.00
Installation			
Global Installation cost per module	40	625.00	25000.00
Grid Connection	1	25000.00	25000.00
Total			950,000
Depreciable asset			880000 .00

TABLE 14 Operation and maintenance cost of the system.

Item	Total INR/year
Maintenance Salaries	144,000.00
Total (OPEX)	144,000.00
System summary	
Total installation cost	950,000.00 INR
Operating costs	144,000.00 INR/year
Produced energy	21.5 MWh/year
Cost of produced energy (LCOE)	9.408 INR/kWh

yield, performance ratio, and efficiency of a system by considering various losses. It also performs an economic analysis of the PV systems.

The two most significant factors that affect the performance of a PV system are temperature and solar irradiation. Lower irradiance results in a lower power output and temperatures above 250°C lead to reductions in the PV power output. There is also a point on the curve at which the PV module discharges the maximum power to the load for each curve. This point is referred to as the maximum power point (MPP). In addition; other factors also affect solar photovoltaic power generation. These are the losses due to shading, soiling, mismatch, and ohmic losses; the power–voltage curve of the Waaree WS 325 PV module at various levels of irradiance at 25°C is shown in Figure 5A, while Figure 5B depicts the power–voltage relationship at various cell temperatures.

The monthly performance of the PV system from PVSyst software is shown in Table 9.

The energy injected to the grid is shown in Figure 6.

The normalised performance coefficient and the simulation results are given in Table 10; Figure 7 respectively.

TABLE 15 Detail financial analysis of the system.

Financial analysis	
Simulation period	
Project lifetime 25 years start year 2019	
Income variation over time	
Inflation	0.00%/year
Production variation {aging)	0.00%/year
Discount rate	4.00%/year
Income dependent expenses	
Income tax rate	0.00%/year
Other income tax	0.00%/year
Dividends	0.00%/year
Depreciation	
Depreciable assets	880,000.00 INR
Salvage value	0.00 INR
Total redeemable	880,000.00 INR
Depreciation period	20 years
Depreciation coefficient	1.00
Financing	
Own funds	950,000.00 INR
Electricity sale	
Feed-in tariff	11.20 INR/kWh
Duration of tariff warranty	20 years
Annual connection tax	0.00 INR/kWh
Annual tariff variation	0.0%/year
Feed-in tariff decrease after warranty	0.00%
Return on investment	
Payback period	9.8 years
Net present value (NPV)	14,76,210.52 INR
Return on Investment (ROI)	155.4%

TABLE 16 Yearly net profit from the PV system.

Year	Electricity sale	Running cost	Depreciation	Taxable income	Taxes	After tax profit	Cumulative profit	%Amortized cost (%)
2019	2,41,048	1,44,000	44,000	53,048	0	97,048	−8,52,952	10.20
2020	2,41,048	1,44,000	44,000	53,048	0	97,048	−7,55,903	20.40
2021	2,41,048	1,44,000	44,000	53,048	0	97,048	−6,58,855	30.60
2022	2,41,048	1,44,000	44,000	53,048	0	97,048	−5,61,806	40.90
2023	2,41,048	1,44,000	44,000	53,048	0	97,048	−4,64,758	51.10
2024	2,41,048	1,44,000	44,000	53,048	0	97,048	−3,67,709	61.30
2025	2,41,048	1,44,000	44,000	53,048	0	97,048	−2,70,661	71.50
2026	2,41,048	1,44,000	44,000	53,048	0	97,048	−1,73,613	81.70
2027	2,41,048	1,44,000	44,000	53,048	0	97,048	−76,564	91.90
2028	2,41,048	1,44,000	44,000	53,048	0	97,048	20,484	102.20
2029	2,41,048	1,44,000	44,000	53,048	0	97,048	1,17,533	112.40
2030	2,41,048	1,44,000	44,000	53,048	0	97,048	2,14,581	122.60
2031	2,41,048	1,44,000	44,000	53,048	0	97,048	3,11,629	132.80
2032	2,41,048	1,44,000	44,000	53,048	0	97,048	4,08,678	143
2033	2,41,048	1,44,000	44,000	53,048	0	97,048	5,05,726	153.20
2034	2,41,048	1,44,000	44,000	53,048	0	97,048	6,02,775	163.40
2035	2,41,048	1,44,000	44,000	53,048	0	97,048	6,99,823	173.70
2036	2,41,048	1,44,000	44,000	53,048	0	97,048	7,96,872	183.90
2037	2,41,048	1,44,000	44,000	53,048	0	97,048	8,93,920	194.10
2038	2,41,048	1,44,000	44,000	53,048	0	97,048	9,90,968	204.30
2039	2,41,048	1,44,000	0	97,048	0	97,048	10,88,017	214.50
2040	2,41,048	1,44,000	0	97,048	0	97,048	11,85,065	224.70
2041	2,41,048	1,44,000	0	97,048	0	97,048	12,82,114	235.00
2042	2,41,048	1,44,000	0	97,048	0	97,048	13,79,162	245.20
2043	2,41,048	1,44,000	0	97,048	0	97,048	14,76,211	255.40
Total	60,26,211	36,00,000	8,80,000	15,46,211	0	24,26,211	14,76,211	255.4

TABLE 17 Greenhouse gasses reduction by 13-kWp PV system.

GHG from coal fired thermal power plant	Emission per kWh of electricity, g/kWh	Total annual reduction for 17799 kWh, kg	References
CO_2	980	17443.02	Vasisht et al. (2016)
SO_2	1.24	22.07	Tarigan and Kartikasari (2015)
NO_x	2.59	46.1	Tarigan and Kartikasari (2015)
Ash	68	1210.33	Tarigan and Kartikasari (2015)

4.5.1 Losses parameters

The main causes of losses in PV systems are thermal loss, ohmic loss, mismatch loss, soiling loss, IAM loss, degradation loss, and aging. The advantage of using the PVSyst software is the design of a PV system by considering the loss parameters of all systems. Table 11 shows the detailed losses of the 13 kWp PV system.

The PV array experienced a maximum ohmic loss of 262.12 kWh annually. The gross annual inverter loss was calculated to be 456.33 kWh. The loss diagram of the installed PV system is shown in Figure 8.

4.6 Comparison between measured data with the predicted values by using PVSyst

The comparison of measured and simulation parameters is shown in Table 12.

The measured values of the final yield, reference yield, and performance ratio were in close agreement with the results obtained from the PVSyst software. The energy supplied to the grid by the PVSyst software was much higher than that of the measured values. The annual energy supplied to the grid was 17799 kWh. The measured annual performance ratio of 82% indicates that the installation of a PV system in eastern India is much more effective for solar power generation.

4.7 Cost and benefit of the system

4.7.1 Net cash flow

The investment of the system includes installation costs and maintenance costs. The detailed investment cost of the system by PVSyst software is given in Table 13.

4.7.2 Operating costs of the system

The detailed operation and maintenance cost of the 13 kWp solar PV system is shown in Table 14.

The detailed economic analysis of the system is shown in Table 15.

4.7.3 System's net benefit

The yearly net profit from the PV system is shown in Table 16.

The yearly net profit from the PV system is calculated for 24 years, and the net cumulative profit per year is INR 14, 76,211 (Table 16).

4.8 Environmental benefit assessment of the system

Power generation from PV systems or other renewable resources has a positive environmental impact. Carbon dioxide (CO_2), nitrogen oxide (NO_x), sulphur dioxide (SO_2), and ash are among the greenhouse gases (GHG) released by coal-fired thermal power plants. The 13 kWp solar PV system installed at the institution is predicted to have reduced 17443.02 kg of CO_2, 22.07 kg of SO_2, and 46.1 kg of NOx emissions per annum (Table 17).

5 Conclusion

The performance of a 13 kWp grid-connected rooftop solar photovoltaic system installed on ITER, SOA (Deemed to be University), and Bhubaneswar was studied in 2019. The annual performance parameters were determined and compared with simulated values using the PVsyst software tool. The measured values of the final yield, reference yield, and performance ratio were in close agreement with the results obtained using the PVSyst software. The energy supplied to the grid by the PVSyst software was much higher than that of the measured values. The measured and simulated PR values were 82%. The annual electricity supplied to the grid was 17.79 MWh, final yield was 3.80 h/d and reference yield was 4.62 h/d. The solar PV system installed at the institution is predicted to have reduced 17443.02 kg CO_2/year from the atmosphere.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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