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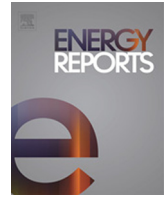
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Performance analysis of a 11.2 kWp roof top grid-connected PV system in Eastern India



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HIGHLIGHTS

- The final yield of the system is 3.67 h/d.
- PV and inverter efficiency are 13.42 and 89.83% with PR 0.78.
- System efficiency is 12.05%.

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ABSTRACT

Barren land and roof tops of buildings are being increasingly used worldwide to install solar panels for generating electricity. One such step has been taken by Siksha 'O'Anusandhan University, Bhubaneswar (Latitude 20.24° N and Longitude 80.85° E) by installing a 11.2 kWp grid connected solar power system during February, 2014. This PV system is tilted at an angle of 21° on the top floor of a 25 metre height building. This system was installed. This paper presents the results of this grid connected photovoltaic system which was monitored between September 2014 to August 2015. The entire electricity generated by the system was fed into the state grid. The different parameters of the system studied include PV module efficiency, array yield, final yield, inverter efficiency and performance ratio of the system. The total energy generated during this period was found to be 14.960 MWh and the PV module efficiency, inverter efficiency and performance ratio were found to be 13.42%, 89.83% and 0.78 respectively.

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1. Introduction

The solar photovoltaic systems have been installed in various parts of the globe for power generation where the grid connectivity is neither feasible nor possible due to inaccessible locations. Generation of electricity through solar photovoltaic (PV) system is clean, reliable and environment friendly. Solar PV systems have the potential to become a major source of electricity generation in future due to rapid reduction of fossil fuel. Electricity generation through solar PV system has shown an impressive growth around the globe with an annual total new addition of 50 GW during 2015. China added the highest of 15.2 GW while India added 2 GW during 2015 among the top ten solar power producing countries (Renewables, 2016). The global PV installed capacity at the end of 2015 was estimated as 227 GW as compared to 3.4 GW in 2004. This shows a tremendous growth of solar PV installation for power generation over the last ten years. During

2015, India occupied 5th position in the world by adding 4% (2 GW) of solar PV installation resulting a total capacity over 5 GW (Renewables, 2016). India's rooftop solar installation expanded recently due to consumer awareness and incentives provided by Jawaharlal Nehru National Solar Mission of Ministry of New and Renewable Energy, Govt of India with a projection of 100 GW solar installation by 2022. As a result in many urban areas, rooftop solar systems have been installed and the power generated is utilised for own use and the surplus power is fed to the grid. Installation of solar photovoltaic system on the surface is not always possible due to constraints of land. Hence, the roof top area can be utilised successfully for generation of electricity by installing solar PV system. Initiatives have been taken by Government and non-Government organisations to install solar power generation system over the roof top of all the public office buildings, private houses and institutions to tackle recent power crisis. The rooftop solar power generation system will not only resolve the power crisis, but also reduce the harmful effects of greenhouse gases which are produced by fossil fuel based energy generation system. A significant part of the solar energy can be utilised for promoting grid connected solar photovoltaic power

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Nomenclature

A_m	PV module area, m ²
E_{AC}	AC energy output, kWh
E_{DC}	DC energy output, kWh
$E_{AC\ d}$	Monthly average daily total ac output, kWh
$E_{DC\ d}$	Monthly average daily total dc output, kWh
P_{DC}	DC power output, kW
P_{AC}	AC power output, kW
G_{STC}	Total solar radiation under standard test condition, kW/m ²
G_t	Total in-plane solar irradiance, W/m ²
$G_{i.ref}$	Reference irradiance, W/m ²
H_t	Total mean daily in-plane solar insolation, kWh/m ² /day
Y_f	Final yield, h/d
Y_{Fd}	Daily final yield, h/d
Y_r	Reference yield, h/d
Y_a	Array yield, h/d
Y_t	Temperature corrected reference yield, h/d
η_{temp}	Temperature corrected efficiency, %
CUF	Capacity utilisation factor, %
$P_{pv rated}$	Rated power of PV system
β_{ref}	Temperature coefficient of power
T	Cell temperature, °C
η_{STC}	PV efficiency at standard test condition
η_{PV}	PV module efficiency, %
T_a	Ambient temperature, °C
L_s	System loss, h/d
L_c	Capture loss, h/d
L_{ct}	Thermal loss, h/d
L_{cm}	Miscellaneous loss, h/d
PR	Performance ratio
η_{sys}	System efficiency, %
$\eta_{sys.d}$	Daily system efficiency, %
η_{inv}	Inverter efficiency, %

systems of varying sizes as per the need. Many studies have been conducted on grid connected roof top PV systems in different parts of the globe. In India, [Sharma and Chandel \(2013\)](#) conducted a performance study of 190 kWp grid interactive solar photovoltaic power plant in Punjab and observed that the final yield, reference yield and performance ratio varies from 1.45 to 2.84 kWh/kWp-day, 2.29 to 3.53 kWh/kWp-day and 55% to 83% respectively. The average annual energy yield of the plant is 812.76 kWh/kWp with a system efficiency of 8.3%. In another study conducted by [Mondol et al. \(2006\)](#) it was found that, for a 13 kWp roof mounted grid connected PV system, the monthly average daily PV, system and inverter efficiencies varied from 4.5% to 9.2%, 3.6% to 7.8% and 50% to 87% respectively while performance ratio ranged from 0.29 to 0.66. A techno economic study of a 1 kWp grid connected PV system conducted by [Tarigan and Kartikasari \(2015\)](#) in Indonesia found that the system technically can meet the basic electrical need of a household. This system injected about 1 MWh/year to the grid with a PR of 72% and reduced 1296 kg CO₂. The payback period of this system estimated as 17.6 years after which the system will make profit.

[Pundir et al. \(2016\)](#) made a comparative study of performance of a grid connected solar PV power system in IIT Roorkee and found that the generation cost of electricity from the system is 8.50 INR per kWh without subsidy with a performance ratio of 63.68% having capacity factor of 8.77%. The payback period of this system is found to be 7.5 years and this system is eco friendly and good for environment as it reduced 2464 ton of CO₂ per annum.

In another study conducted by [Peerapong and Limmeechokchai \(2014\)](#) made a comparative study of three types of grid connected solar photovoltaic power plant namely solar residential roof top (11.04 kW), integrated ground mounted roof top (330 kW) and utility scale (38.5 MW) in Thailand found that the lowest cost of electricity of \$0.27/kWh was with the utility scale solar system. The cost of electricity with residential solar roof top and ground mounted roof top system were \$ 0.46/kWh and \$0.29/kWh respectively. They concluded that the new feed in tariff schemes of Govt for residential, integrated ground mounted and utility scale with installed capacity larger than 1 MW are reasonable for investment and make the investor feasibly profitable for the whole life time of a project. In this pursuit, a 11.2 kWp grid connected solar photovoltaic system has been installed on 17th February, 2014 and operating since then on the roof top of a constituent institute of Siksha 'O'Anusandhan University. The present study has been undertaken to study its performances with respect to final yield, performance ratio and system efficiency and compare these parameters with the results of earlier researchers.

2. Location and meteorological data

The on-grid system is installed on the roof top of a constituent institute of Siksha 'O'Anusandhan University, Bhubaneswar, India. The global horizontal solar irradiance data were collected from the local automatic weather station located at Bhubaneswar which records solar irradiance at 1 min interval over the entire month and year including night hours. The cell temperature was recorded by HDE infrared thermometer (Range: –32 °C to 380 °C) at 15 min interval which averaged hourly from 6.00 to 18.00 h during the monitored period from Sept 2014 to Aug 2015. The ambient temperature was recorded by using laboratory thermometer. Other meteorological data like monthly mean wind velocity, relative humidity and rain fall were collected from local metrological observatory. The monthly mean rainfall, ambient temperature, wind speed, humidity and inplane solar irradiance are presented in [Table 1](#).

[Table 1](#) shows that the maximum inplane solar irradiation is observed during February to April 2015 and minimum is found during August 2015. Maximum humidity varying from 79% to 87% observed during July to Oct 2015 while maximum wind speed of 2.25 m/s found in May 2015. The highest rainfall occurred during Sept 2014 (400 mm) followed by July and Aug 2015.

3. PV system

The 11.2 kWp PV system has forty number of solar modules with a total area of 77.6 m². Twenty modules are connected in series to make an array and two such arrays are arranged in parallel. The Waaree modules WS 280 (each of 280 W capacity) having 72 solar cells made up of polycrystalline silicon are used in the PV system. The modules are free from any effect of shades and are fixed with a tilt angle of 21° facing south at an azimuth angle of 0°. The entire PV systems are mounted on metal frames supported by concrete pillars. The surface of the PV modules was cleaned with water at an interval of 15 days throughout the monitoring period in order to eliminate the soiling loss.

A 3-phase transformer based inverter, Solivia model SOL 11.0-1TR3-E4 was used to convert DC to AC which was then fed directly into the state grid. The inverter has a rated efficiency of 95.6%. The PV module and inverter specifications are given in [Table 2](#).

Table 1
Meteorological observations of the site.

	Amb Temp	Humidity	Rainfall (mm)	No of rainy days	Wind speed (m/s)	Global horizontal irradiance	Solar irradiation in plane of array (kWh/m ² /d)
Sept, 14	27.9	87	400	20	0.94	3.98	4.21
Oct	26.95	81	129	10	0.92	3.76	4.67
Nov	24.45	67	0	0	0.64	4.01	4.93
Dec	20.8	66.5	0	0	0.69	3.75	4.96
Jan, 15	21	67	15	2	0.81	3.70	4.62
Feb	24.75	66.5	9	1	0.89	4.49	5.42
March	28.65	65.5	24.8	3	1.25	5.04	5.46
Apr	30.65	69	84	6	2.08	5.42	5.43
May	33	70	15	5	2.25	5.23	4.93
June	31.15	75	75	13	1.86	4.48	4.26
July	28.7	79.5	252	18	1.33	3.49	3.82
Aug	28.7	79	284	16	1.36	4.11	4.01
Total	326.70	873	1317.8	94	15.03	51.444	56.71
Average	27.23	72.75	109.82	–	1.25	4.287	4.73

Table 2
PV module and inverter specifications.

PV module		Inverter (transformer based)	
Parameters	Specification	Parameters	Specification
Type of module	Polycrystalline	Model	SOLVIA 11 EU G4 TR (Make: Delta)
P_{max}	280 W	Input (DC)	
I_{mp}	8 A	Nominal power, W	11 600
V_{mp}	35 V	Voltage range, V	420–900
I_{sc}	8.68 A	Nominal current, A	19.5 A @600 V
V_{oc}	43 V	Maximum current, A	29
Temperature Coefficient of P_{max}	−0.47%/°C	Output (AC)	
Nominal operating cell temperature (NOCT)	47 ± 2 °C	Voltage range, V (3-phase)	3 × 400 V
Module area, m ²	1.94	Nominal current, A	16 A per phase
No. of modules	40	Nominal frequency, Hz	50
Efficiency	14%	Efficiency, %	95.60
Weight/module, kg	29	Weight, kg	39

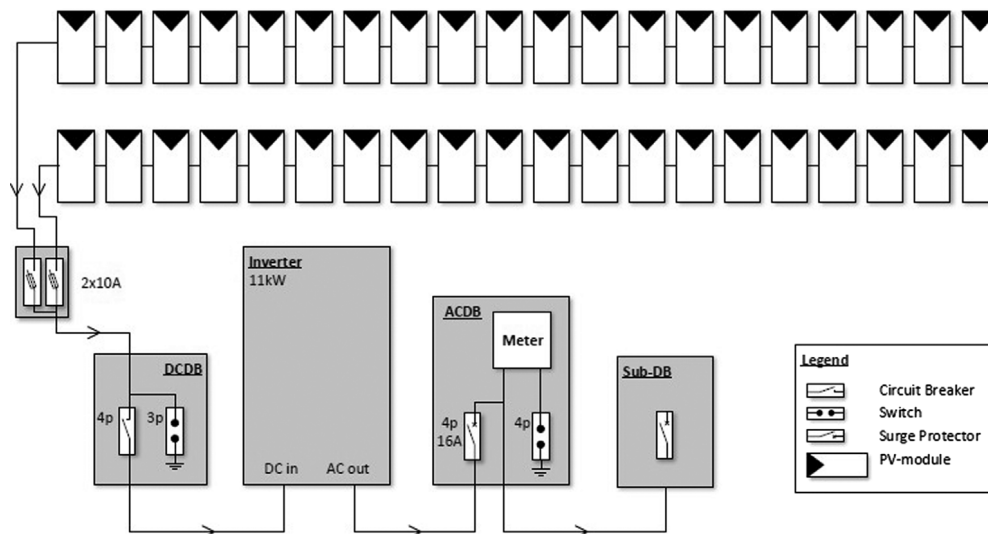


Fig. 1. Schematic layout of installed system.

3.1. Integration of PV power with grid

The output of solar PV system is fed into the inverter which converts DC into AC and then supply to the state grid after synchronisation. In case of grid failure, or low or high voltage, solar PV system will be disconnected from the grid. With a 15 min interval, the data logger records the input voltage and current fed to the inverter and the energy going out of the inverter. The schematic lay out of the system is shown in Fig. 1 and the installed system is shown in Fig. 2.

3.2. Monitoring and data acquisition

The data acquisition system consists of a Wattmon (multi-purpose data logger and automation device) that is used to log and monitor data. It is a built-in web server and local data storage that is easily accessible via a local LAN or remotely through the internet. The Voltage and current are measured at 1 min interval by the Wattmon data acquisition system. Wattmon (multi-purpose data logger and automation device) is used to log and monitor data. It is a built-in web server and local data storage that is easily accessible via a local LAN or remotely through the internet. Data is logged in



Fig. 2. View of 11.2 kWp rooftop grid interactive solar PV system.

CSV files. A new CSV file is created every day, and data is stored at one-minute intervals which is averaged in 15 min and stored in custom server. Data was recorded on 15 min intervals via an SD card and read directly in a computer.

4. Performance analysis

The International Electro Technical Commission (IEC) published the International standard IEC 61724 in 1998 which describes few parameters for evaluating the performance of the photovoltaic systems (Photovoltaic, 2010). This standard has been accorded by Bureau of Indian Standards (BIS) in 1998. To analyse the electrical performance of the present grid connected PV system, some parameters like array yield, final yield, reference yield, capture loss, system loss, performance ratio etc. were studied by computing the actual data collected during the assessment period of 12 months from 1st September 2014 to 31st August 2015 in accordance with IEC 61724.

4.1. Array yield

The array yield is defined as the ratio of energy output from a PV array over a particular period (day, month or year) to its rated power and is given by Ayompe et al. (2011)

$$Y_a = \frac{E_{DC}}{P_{pv, rated}} \quad (1)$$

4.2. Final yield

The final yield is defined as the ratio of net daily, monthly or annual AC energy output of the entire PV system which was supplied by the array to the rated power of the installed PV array. The daily final yield is given by Ayompe et al. (2011)

$$Y_{fd} = \frac{E_{AC, d}}{P_{pv, rated}} \quad (2)$$

4.3. Reference yield

The reference yield Y_r is defined as the total daily inplane solar irradiation H_t (kWh/m²) divided by the reference irradiation G_{i-ref} (1 kW/m²). It is given by Ayompe et al. (2011).

$$Y_r = \frac{H_t}{G_{i-ref}} = \frac{H_t \text{ (kWh/m}^2\text{)}}{1 \text{ kW/m}^2} \quad (3)$$

This yield represents the number of peak sun-hours per day (h/d).

4.4. PV module efficiency

The instantaneous PV module efficiency is given by Ayompe et al. (2011)

$$\eta_{pv} = \left(\frac{P_{DC}}{G_t * A_m} \right) * 100. \quad (4)$$

As a function of temperature, it can be represented as Skoplaki and Palyvos (2009), Evans and Florschuetz (1977) and Dubey et al. (2013)

$$\eta_T = \eta_{T-ref} [1 - \beta_{ref} (T - T_{ref})] \quad (5)$$

where,

η_{T-ref} = Efficiency of PV module at reference temperature

β_{ref} = the temperature coefficient of power

T_{ref} = Reference temperature

T = the cell temperature and is given by

$$T = T_{amb} + \frac{(NOCT - 20) G_t}{800}$$

where, T_{amb} is the ambient temperature, NOCT is Nominal operating cell temperature of module declared by the manufacturer and G_t is the total inplane solar irradiation. One can reach in nominal incident condition under an irradiance of 800 W/m² and ambient temperature of 20 °C (Mulcué-Nieto and Mora-López, 2014).

4.5. Inverter efficiency

The instantaneous inverter efficiency is given by Ayompe et al. (2011)

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \quad (6)$$

and the monthly inverter efficiency ($\eta_{inv, m}$) is calculated by

$$\eta_{inv, m} = \left(\frac{E_{AC, d}}{E_{DC, d}} \right) * 100\%. \quad (7)$$

4.6. System efficiency

The instantaneous PV system efficiency is given by Ayompe et al. (2011) and Drif et al. (2007)

$$\eta_{sys} = \eta_{pv} * \eta_{inv} \quad (8)$$

and system efficiency is represented by

$$\eta_{sys, d} = \frac{E_{AC, d}}{H_t * A_m} \quad (9)$$

4.7. Performance ratio

Performance ratio (PR) indicates the overall effect of losses on the rated output due to PV module temperature, inverter inefficiency, wiring mismatch, soiling or component failure. It is a dimensionless quantity. Generally PR values are greater in winter than in summer because of losses due to PV module temperature. Normally PR varies from 0.6 to 0.8 depending on the location, solar irradiance and climatic conditions. It does not represents the amount of energy produced because a system with low PR in high solar irradiation area may produce more energy than a system with high PR in a low solar irradiation location (Marion et al., 2005).

Performance ratio is defined as the ratio of the energy fed to the grid (final yield) to the energy that the system could have

produced at DC rated power for the number of peak sun hours per day (reference yield) and is expressed as

$$PR = \frac{Y_F}{Y_R} \quad (10)$$

It is also defined as the ratio of the PV system efficiency to its efficiency at STC and is given by [Ayompe et al. \(2011\)](#) and [Drif et al. \(2007\)](#).

$$PR = \frac{\eta_{sys}}{\eta_{STC}} = \frac{E_{AC}}{G_t} \frac{G_{STC}}{P_{DC,STC}} = \frac{E_{AC}}{G_t \eta_{STC}} \quad (11)$$

where

$$\eta_{sys} = \frac{E_{AC}}{A_a G_t} \quad \text{and} \quad \eta_{STC} = \frac{P_{DC,STC}}{A_a G_{STC}}$$

The PR indicates how close a PV system approaches ideal performance during real operation and allows comparison of PV system independent of location, tilt angle, orientation and their nominal rated power capacity.

The performances of solar PV system studied by different researchers at various places are presented in [Table 3](#).

4.8. Capacity utilisation factor

The capacity utilisation factor (CUF) is defined as the ratio of actual annual energy generated by the PV system ($E_{AC,a}$) to the amount of energy the PV system would generate if it is operated at full rated power for 24 h per day for a year and is denoted by [Ayompe et al. \(2011\)](#) and [Vasisht et al. \(2016\)](#).

$$CUF = \frac{E_{AC,a}}{P_{PV,rated} * 24 * 365} \times 100 \quad (12)$$

where $E_{AC,a}$ is the annual ac energy output, kWh.

$P_{PV,rated}$ is the rated PV power, kW.

The capacity factor for a grid connected PV system is also represented by

$$CUF = (\text{Peak sun hours/day})/24 \text{ h/day.}$$

If a system delivers full rated power continuously, its CUF would be unity i.e. 100%. CUF is dependent on the location of the PV system. The higher the capacity factor, the better the PV system. The capacity utilisation factor of all roof top solar PV system in India is 16%–17%. CUF is location specific and it is 13%–15% in Massachusetts (USA) and 19% in Arizona (USA) ([23](#)).

4.9. Energy losses

The different losses in a PV system include array capture loss, system loss, soiling and degradation losses.

A. Capture loss (L_c)

Capture losses are divided into two types:

A.1 Thermal Capture loss (L_{ct}).

A.2 Miscellaneous capture loss (L_{cm}).

A.1 Thermal Capture loss and effect of cell temperature on loss

The thermal capture loss L_{ct} is due to the PV module operation at temperature higher than the 25 °C. The electrical behaviour of PV system has strong influence on cell temperature thereby affecting the final yield.

The instantaneous temperature loss is the difference between the real power and the hypothetical power produced if the cell were working at 25 °C and is given by [Mulcué-Nieto and Mora-López \(2014\)](#)

$$L_{temp,inst} = -\gamma (T_c - 25) \quad (13)$$

where T_c = cell temperature

γ = Coefficient of temperature.

The study conducted in Colombia suggested the maximum temperature loss by the following empirical relation

$$L_{temp,max} = 0.492 T_a - 4.405. \quad (14)$$

This study suggested that for each 2 °C increase in the average ambient temperature of the place, the maximum losses increase approximately by 1% ([Mulcué-Nieto and Mora-López, 2014](#)).

A.2 Miscellaneous Capture loss

Miscellaneous Capture loss (L_{cm}) includes cable loss (Joule effect of wiring), shading effect, degradation losses and mismatch losses.

Capture loss is denoted as [Drif et al. \(2007\)](#)

$$\text{Capture loss}(L_c) = L_{ct} + L_{cm} \quad (15)$$

$$L_{ct} = \sum_{day} I_{ct} \quad (16)$$

where

$$I_{ct} = Y_r - Y_T \quad (17)$$

$$Y_T = Y_r [1 - \gamma (T_c - 25)] \quad (18)$$

$$L_{cm} = \sum_{day} I_{cm} \quad (19)$$

where Y_r = corrected reference yield

T_c = Cell temperature

Capture loss is also represented by [Ayompe et al. \(2011\)](#).

$$L_c = Y_R - Y_A \quad (20)$$

where Y_R = Reference yield and Y_A = Array yield.

B. System losses (L_s)

This losses is due to conversion of DC into AC by inverter and are given by [Kymakis et al. \(2009\)](#).

$$L_s = Y_a - Y_f. \quad (21)$$

Loss in inverter is calculated by

$$L_{inv} = 1 - \frac{E_{AC}}{E_{DC}}. \quad (22)$$

The losses in the inverter (L_{inv}) depend on DC input power and voltage, DC input power and voltage fluctuations, inverter temperature and grid voltage. Hence, it is very complex to access the losses of the inverter. Conversion losses have been reported in a wide range between 13% ([Mondol et al., 2006](#)), 9.62%–17.7% ([Baltus et al., 1997](#)), 6.3%–16.8% ([Alonso-Abella et al., 2005](#)). For good inverters the losses can be taken as 5% ([Hegedus and Luque, 2011](#)).

C. Total loss

$$\text{Total loss is given by } L_T = L_c + L_s = Y_R - Y_F. \quad (23)$$

5. Results

5.1. Results for yields

The performance results of the PV system is discussed in this section. The monthly average solar radiation on the tilted PV array indicates that the solar radiation is minimum during August 2015 (4.01 kWh/m²/d) and maximum in March (5.46 kWh/m²/d). The annual mean of monthly cell temperature varies from 27.49 to 39.94 °C ([Table 4](#)). The annual average monthly final, reference and array yields are 3.67, 4.73 and 4.09 h/d respectively. The highest final yield of 4.65 kWh/kWp/day was observed during March 2015

Table 3

Performance summary of some selected grid connected PV systems.

Reference	Location	PV type	System size (kWp)	Final yield (kWh/kWp/day)	PV module efficiency (%)	Inverter efficiency (%)	Performance ratio (%)
Ayompe et al. (2011)	Dublin, Ireland	Mc-Si		2.40	14.9	89.20	81.50
Pietruszko and Gradzki (2003)	Poland	a-si		–	6.0	93.00	80.00
Kymakis et al. (2009)	Crete, Greece	P-Si		1.96–5.07	15.0	–	67.36
Chokmaviroj et al. (2006)	Thailand	–		2.91–3.98	12.0	92.16	70.00
Mondol et al. (2006)	Dublin, Ireland	–	3.056	1.69	7.60	75.00	0.6–0.62
Cucumo et al. (2006)	Italy	P-Si		3.40	7.95	98.00	–
Drif et al. (2007)	Spain	Isofoton I-106	2.5	1.60	5.71	87.03	49.00
Sharma and Chandel (2013)	India	P-Si	190	2.23	–	–	74.00
Okello et al. (2015)	South Africa	P-Si	3.2	4.90	13.72	88.10	64.30
Sidrach-de-Cardona and Lopez (1999)	Spain	–	2.0	3.80	8.50	88.00	64.00
Present study	India	P-Si	11.2	3.67	13.42	89.83	78.00
Wittkopf et al. (2012)	Singapore	P-Si		3.12	11.80	–	81.00
Al Ali and Emziane (2013)	Abu Dhabi	a-Si/ P-Si	142.5	–	–	94.80	–
Vasisht et al. (2016)	India	P-Si	20	4.1	13.71	–	85.00
Pundir et al. (2016)	India	P-Si	1816	–	8.76	–	63.58
Kamalapur and Udaykumar (2011)	India		50				55–89
Kumar and Nagarajan (2016)	India	Mc-Si	80	4.45	15.53	–	83.2
Padmavathi and Daniel (2013)	India		3 MWp	3.75			0.70
Shukla et al. (2016)	India	c-Si/a-Si	110	2.67–3.36		93.5–97.5	71.6–79.5
Sundaram and Babu (2015)	India		5 MWp	4.81	6.08	88.2	–
Kumar and Sudhakar (2015)	India	P-Si	10 MWp	1.96–5.07	13.3	97.0	86.12

due to clear sky during this month except only three days of cloud and rain. The lowest final yield of 2.75 kWh/kWp/day was during December 2014 due to lowest energy production during this month. The annual average final yield was 3.67 kWh/kWp/day i.e. 1339.55 kWh/kWp per year for the PV system which is significantly higher. The final yield of the present study is higher than that of Spain, Italy, Ireland, Singapore and some of earlier studies in India (Table 3). This is because of higher average daily inplane irradiance of 4.73 kWh/m²/day as compared to 2.9 kWh/m²/day (Ireland), 3.26 kWh/m²/d (Spain), about 1.0 kWh/m²/day (Italy) and 4.6 kWh/m²/d in Singapore. This is also higher than that of earlier studies conducted in India during 2013 due to its lower irradiance varying from 2.30 to 3.53 kWh/m²/day (Sharma and Chandel, 2013).

The mean hourly variation of cell temperature and DC power production with solar irradiance is shown in Figs. 3 and 4. It is seen that with increase in intensity of solar radiation, the cell temperature increased linearly ($R^2 = 0.939$). Higher value of the linear correlation coefficient (R^2) indicates fairly closeness between the values. Also, the DC power production varies with variation of solar irradiance. It increases with increase in solar irradiance and vice versa.

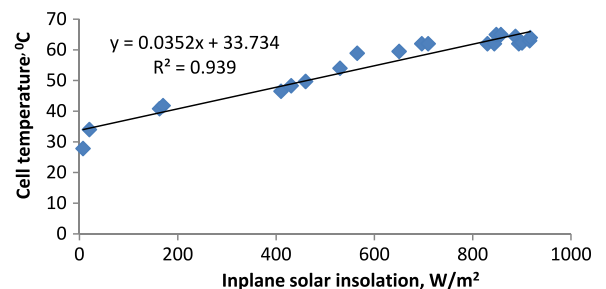


Fig. 3. Effect of inplane solar insolation on cell temperature (15.04.2015).

5.2. Results for performance ratio and module efficiency

The performance of the PV system is graded on the basis of (i) Capacity Utilisation Factor (CUF) and (ii) Performance Ratio (PR). PR is a measure of the quality of a PV system independent of its location while CUF mainly dependent on GHI of the location of the PV system and module efficiency and hence it depends on the location. The PR, CUF and module efficiency varies with weather condition of the location. The monitored period is divided into

Table 4
Average monthly performance parameters of 11.2 kWp grid connected solar PV system for 2014–15.

Month	Cell temp T_c	Energies		Yields		Losses			
		E_{dc} (kWh/d)	E_{ac} (kWh/d)	Y_f (h/d)	Y_r (h/d)	System loss (L_s) (h/d)	Capture loss (L_c) (h/d)	Total loss ($L_s + L_c$) h/d	
Sep, 14	33.82	42.78	36.27	3.24	4.21	3.82	0.58	0.39	0.97
Oct, 14	33.52	36.18	31.56	2.82	4.67	3.23	0.41	1.44	1.85
Nov, 14	31.38	51.47	42.16	3.76	4.93	4.60	0.83	0.33	1.17
Dec, 14	27.78	32.58	30.83	2.75	4.96	2.91	0.16	2.05	2.21
Jan, 15	27.49	46.18	43.20	3.86	4.62	4.12	0.27	0.49	0.76
Feb, 15	32.37	59.27	49.15	4.39	5.42	5.29	0.90	0.13	1.03
Mar, 15	36.33	55.74	52.08	4.65	5.46	4.98	0.33	0.48	0.81
Apr, 15	38.28	52.21	48.76	4.35	5.43	4.66	0.31	0.77	1.07
May, 15	39.94	52.58	48.13	4.30	4.93	4.69	0.40	0.24	0.64
June, 15	37.14	40.29	38.05	3.40	4.26	3.60	0.20	0.66	0.86
July, 15	34.07	37.02	33.70	3.01	3.82	3.31	0.30	0.51	0.81
Aug, 15	34.33	43.50	38.78	3.46	4.01	3.88	0.42	0.12	0.54
Total	406.45	549.8	492.7	43.99	56.71	49.09	5.10	7.62	12.72
Mean	33.87	45.82	41.06	3.67	4.73	4.09	0.43	0.64	1.06

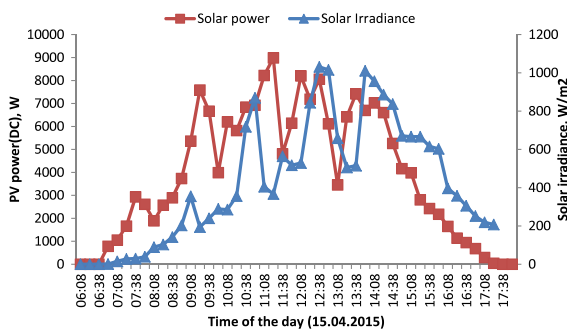


Fig. 4. Solar power production vs. solar irradiance (15.04.2015).

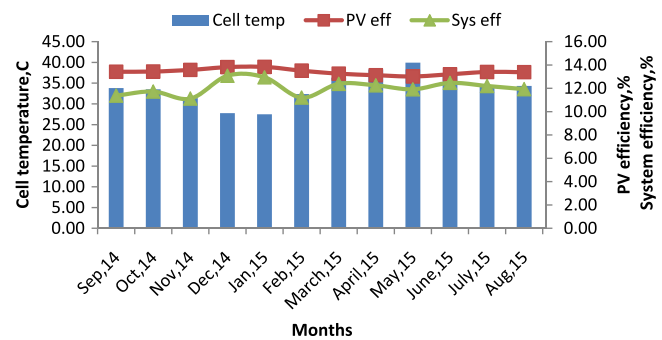


Fig. 5. Effect of cell temperature on PV efficiency.

three seasons such as winter (Nov–Feb), summer (March–June) and rainy (July–Oct). The variation of performance of the PV system in regard to PR and module efficiency during this three seasons are discussed below.

(a) Winter

The highest PR of 84% was observed during February 2015. The average PR during winter season was found to be 74.25%. The PR varies from 0.56 to 0.84 during winter and the lowest PR of 0.56 obtained during December due to lowest final yield of 2.75 h/d. The maximum PV module efficiency of 13.84% was observed in January 2015 at cell temperature of 27.49 °C and this is 98.85% of rated efficiency. This is mainly due to the cooling of module surface by cold winds of the north thereby lowering the ambient temperature and preventing module surface to reach higher temperature.

(b) Summer

The average PR during this season was found to be 83% which is higher than that of winter. The higher PR during summer is mainly due to the higher final yield varying from 3.40 to 4.65 h/d. The module efficiency varies from 13.02% to 13.25% during this season. The lowest module efficiency of 13.02% was observed in May 2015 and may be due to highest cell temperature of 39.94 °C.

(c) Rainy

The average PR during this season was found to be 75.5% while the module efficiency varies from 13.39% to 13.44%. Comparatively lower PR during this season may be due to maximum number of rainy and cloudy days (64 days) during this season. The higher PR of 86% observed during Aug 2015 and this may be due to higher final yield of 3.46 h/d during this month.

The annual mean monthly PR of the system is 78% which means 22% of the incident solar energy is not converted to useable energy due to losses or defects in components. It is observed that, the efficiency of PV module decreased with increase in cell

temperature (Fig. 5). The minimum PV efficiency of 13.02% was observed due to highest cell temperature of 39.94 °C during May, 2015 while highest efficiency of 13.84% observed at lowest cell temperature of 27.49 °C in January 2015 (Table 5).

5.3. Results for inverter and system efficiency

The annual monthly average value of inverter efficiency and system efficiency were found to be 89.83% and 12.05% respectively. The system efficiency of the present study (12.05%) is higher than the previous studies conducted in India on roof top SPV system which is only 8.32%–8.77%. The mean module efficiency is 95.85% of its rated efficiency while the inverter efficiency is 93.96% of its rated efficiency. This indicates both the modules and the inverter works satisfactorily during the monitored period.

5.4. Results for capacity utilisation factor and energy production

The annual monthly average CUF of the PV system was found to be 15.27% and this is higher than some of the previous studies conducted in India on roof top SPV system which is only 9.27%–13.85%. The highest CUF (19.38%) is observed in March 2015 due to highest AC energy production of 1614.54 kWh while the lowest (11.47%) in December 2014 for lowest energy generation of 955.80 kWh. The CUF varies from 16.07% to 17.91% during January to May, 2015 which well agrees the range of most of the roof top solar PV system in India which is 16%–17%. The lower CUF from September to October, 2014 and from June to August, 2015 are due to higher number of rainy days (Table 1) and lower energy production during these months. Energy generation depends on cell temperature and it is seen that with increase in cell temperature, the energy generation increased (Fig. 6). At lower

Table 5
Average monthly module, inverter and system efficiencies, PR, CF and energy supplied to grid during 2014–15.

Months	Module efficiency (%)	Inverter efficiency (%)	System efficiency (%)	Energy supplied to Grid (kWh)	CUF	PR
Sep, 14	13.42	84.79	11.38	1088.13	13.49	0.77
Oct, 14	13.44	87.24	11.72	978.50	11.74	0.60
Nov, 14	13.58	81.91	11.12	1264.74	15.68	0.76
Dec, 14	13.82	94.64	13.08	955.80	11.47	0.56
Jan, 15	13.84	93.55	12.94	1339.28	16.07	0.84
Feb, 15	13.51	82.92	11.21	1376.10	18.28	0.81
March, 15	13.25	93.44	12.39	1614.54	19.38	0.85
April, 15	13.13	93.39	12.26	1462.86	18.14	0.80
May, 15	13.02	91.54	11.92	1492.00	17.91	0.87
June, 15	13.20	94.44	12.47	1141.42	14.15	0.80
July, 15	13.40	91.02	12.20	1044.63	12.54	0.79
Aug, 15	13.39	89.13	11.93	1202.05	14.43	0.86
Total	161.00	1078.01	1735.55	14960.05	183.28	9.31
Mean	13.42	89.83	12.05	1246.67	15.27	0.78

Table 6
Green house gasses reduction by 11.2 kWp PV system.

	GHG from coal fired thermal power plant	Emission per kWh of electricity (g/kWh)	Total annual reduction for 14960 kWh (kg)	Reference
CO ₂		980	14660.8	Vasisht et al. (2016)
SO ₂		1.24	18.55	Tarigan and Kartikasari (2015)
NO _x		2.59	38.75	-do-
Ash		68	1017.28	-do-

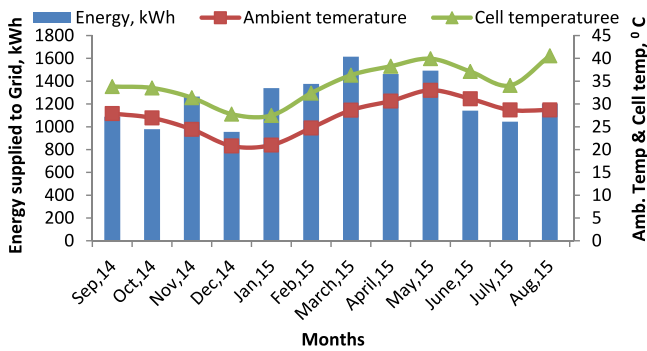


Fig. 6. Month wise variation of energy generation with cell temperature.

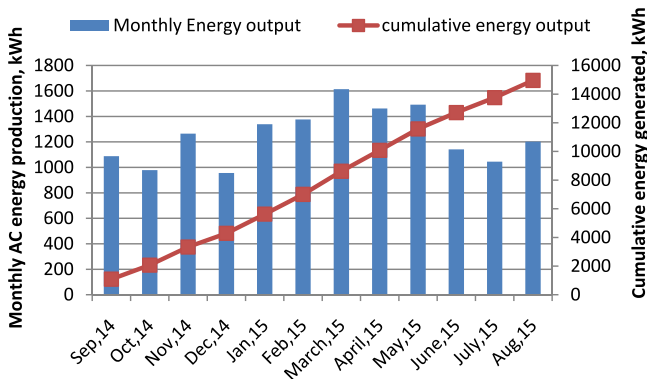


Fig. 7. Month wise energy injected to grid.

cell temperature in December, the lower energy of 955.8 kWh is produced. The annual mean of monthly energy generation comes to be 1246.67 kWh and total energy injected to grid is 14960.05 kWh during the monitored period (Fig. 7).

5.5. Environmental benefit

Power generation from PV system or any other renewable resources would result in positive impact on environment. Coal based thermal power plant releases huge amount of green house gasses (GHG) like carbon dioxide (CO₂), nitrogen oxide (NO_x), sulphur dioxide (SO₂) and ash. It is estimated that the installed PV system (11.2 kWp) in SOA University has caused a reduction of about 14661 kg CO₂, 18.55 kg SO₂ and 38.75 kg NO_x from the atmosphere per annum (Table 6).

6. Conclusions

The 11.2 kWp grid connected PV system installed on the roof top of a constituent institute of Siksha 'O'Anusandhan University Bhubaneswar, India was monitored during September 2014–August 2015 and its monthly and annual performance parameters were studied. The performance of the PV system was compared with that of other grid connected PV systems installed across the globe. The salient findings from this study are summarised below.

- i. The yearly average final yield of the present system is 3.67 h/d (1339.55 kWh/kWp/year) which is higher than the final yield of all other studies referred in Table 3 except that of South Africa and some studies in India.
- ii. The average PV and inverter efficiency were found to be 13.42% and 89.83% respectively. The PV efficiency of the present study is higher than most of the studies referred in Table 3 while its inverter efficiency is higher than that of Ireland, Spain and South Africa.
- iii. The overall system efficiency was found to be 12.05% with annual supply of 14.960 MWh to the grid.
- iv. The annual mean performance ratio was found to be 0.78 which is higher than that of the studies conducted in Greece, Thailand, Ireland, Spain, South Africa, and many studies in India.

- v. The installed PV system in SOA university has caused a reduction of about 14.661 tone of CO₂ from the atmosphere per annum.
- vi. Looking into the overall performance of the installed roof top solar PV system, it is found to be a feasible solution for power supply in eastern India and such PV system can successfully be installed in off-grid remote locations of Odisha and other states.

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