Energy Reports 1 (2015) 184–192

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Performance evaluation of 10 MW grid connected solar photovoltaic power plant in India

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ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form
28 September 2015
Accepted 15 October 2015
Available online 4 December 2015

Keywords:
Photovoltaic
SCADA system
PV syst software
SolarGIS-pvplanner
Performance ratio

ABSTRACT

The growing energy demand in developing nations has triggered the issue of energy security. This has made essential to utilize the untapped potential of renewable resources. Grid connected PV systems have become the best alternatives in renewable energy at large scale. Performance analysis of these grid connected plants could help in designing, operating and maintenance of new grid connected systems. A 10 MW photovoltaic grid connected power plant commissioned at Ramagundam is one of the largest solar power plants with the site receiving a good average solar radiation of 4.97 kW h/m^2/day and annual average temperature of about 27.3 degrees centigrade. The plant is designed to operate with a seasonal tilt. In this study the solar PV plant design aspects along with its annual performance is elaborated. The various types of power losses (temperature, internal network, power electronics, grid connected etc.) and performance ratio are also calculated. The performance results of the plant are also compared with the simulation values obtained from PV syst and PV-GIS software. The final yield (Y_F) of plant ranged from 1.96 to 5.07 h/d, and annual performance ratio (PR) of 86.12%. It has 17.68% CUF with annual energy generation of 15 798.192 MW h/Annum.

1. Introduction

Increasing demand and scarcity in conventional sources have triggered the scientist to pave way for the development of research in the field of renewable energy sources especially solar energy (Goura, 2015).

India has tremendous scope of generating solar energy. The reason being the geographical location and it receives solar radiation almost throughout the year, which amounts to 3000 h of sunshine. This is equal to more than 5000 trillion kW h. Almost all parts of India receive 4–7 kW h of solar radiation per sq meters (Sudhakar et al., 2013). India has an ambitious plan to build large grid-connected solar power plants, with a cumulative installed capacity of 20,000 MW by 2020, under the National Solar Mission (Ministry of New and Renewable Energy, 2014).

Photovoltaic modules or panels are made of semiconductors that allow sunlight to be converted directly into electricity. These modules can provide you with a safe, reliable, maintenance-free and environmentally friendly source of power for a very long time. A successful implementation of solar PV system involves knowledge on their operational performance under varying climatic condition (Makrides et al., 2010).

A 5 MW SPV power plant was designed (Besarati et al., 2013) for 50 cities of Iran, using RET screen software and the highest capacity factor was found at Bushier and lower at Anzali, i.e. 26.1% and 16.5% respectively with a mean capacity factor of 22.27%.

Elhodeiby et al. (2011) presented a performance analysis of 3.6 kW Rooftop grid connected solar photovoltaic system in Egypt. The system was monitored for one year and all the electricity generated was fed into the 220 V, 50 Hz low voltage grid to the consumer.

Studies (Pavlovic et al., 2013) were conducted in Serbia to find out possibilities of generating electrical energy through 1 MW PV power plants by taking different types of solar PV modules available and it was concluded that higher electricity is generated using CdTe solar modules.

The International Energy Agency (IEA), under photovoltaic power systems programme (PVPS) have framed a series of 13 tasks for the outreach of operation, performance and monitoring of solar photovoltaic plants under the platform of research and development. As India, not being a member of an International Energy agency, the studies and discussions on solar photovoltaic

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http://dx.doi.org/10.1016/j.egyr.2015.10.001

Nomenclature

PV	photovoltaic
PR	performance ratio (%)
CUF	capacity utilization factor (%)
Y_F	final yield (h/d)
NTPC	National thermal power corporation
V_{oc}	open circuit voltage
I_{sc}	short circuit ratio
E_A	array energy output per day
I_{dc}	DC current (A)
V_{dc}	DC voltage (V)
P_0	Nominal Power at STC
STC	standard conditions 25 °C, 1000 W/m^2; A.M. = 1.5
Y_A	array yield (h/d)
Y_R	reference yield (h/d)
H_t	total Horizontal irradiance on array plane (Wh/m^2)
G_o	global irradiance at STC (W/m^2)
η_{inv}	inverter efficiency (%)
$\eta_{sys,T}$	total system efficiency (%)
$\eta_{PV,T}$	PV module global efficiency factor (%)
L_C	array capture loss
L_{CT}	thermal capture losses
L_{CM}	miscellaneous capture losses
GlobHor	horizontal global irradiation
T Amb	ambient temperature
GlobInc	global incident in coll. Plane
GlobEff	effective global irradiance
E_{Array}	effective energy at the output of the array
E_Grid	energy injected in to grid
EffArrR	efficient E_{out} array/rough area
EffsysR	efficient E_{out} system/rough area
GHI_m	monthly sum of global irradiation (kW h/m^2)
GHI_d	daily sum of global irradiation (kW h/m^2)
DHI_d	daily sum of diffuse radiation (kW h/m^2)
T_{24}	daily air temperature (°C)
RI_d	daily sum of reflected radiation (kW h/m^2)
Shloss	losses of global irradiation by terrain shading (%)
E_{sm}	monthly sum of specific electricity produced (kW h/kW p)
E_{sd}	daily sum of specific electricity produced (kW h/kW p)
E_{tm}	monthly sum of total electricity produced (GWh)
E_{share}	percentual share of monthly electricity produced (%)

power plants as per IEC 61724 standard are not available (IEA, 2014). Hence, it is essential to document the performance of the large-scale grid-connected solar power plant installed in India.

The performance of 10 MWp grid connected solar photovoltaic power plant is carried out in this work with the following objectives.

(1) To study the seasonal variations in PV plant output from the monitored SCADA data system.
(2) To evaluate the technical performance through estimation of annual energy yield, array yield, reference yield and system losses.
(3) To compare the actual performance data with the simulated data of PVSYST and Solar GIS.

2. Description of the solar PV-GRID system

A grid-connected PV system consists of solar panels, inverters, a power conditioning unit and grid connection equipment. It has effective utilization of power that is generated from solar energy as there are no energy storage losses. When conditions are right, the grid-connected PV system supplies the excess power, beyond consumption by the connected load to the utility grid. But, in stand-alone systems batteries are used to store energy or else energy has to be directly connected to load (see Fig. 1).

2.1. Geographical location of the site

The NTPC 10 MW solar power plant is located at a longitude of 18.75″ N, latitude 79.46″ E and at an altitude of 169 m. The National Thermal Power plant (NTPC) opted this site for their construction of its 10 MW Solar Plant as it located at geographically good location where it can absorb more solar radiation for the entire year as power generated by solar plant completely depends up on its sun's insolation.

2.2. Plant layout

The total rating of the plant is 10 MW occupied over 50 acres of land. This plant area is divided into eight different blocks with each two equal blocks. Each individual block has the generating capacity of about 625 kW thus total of sixteen blocks combined to form a 10 MW generation capacity. Each block of solar panels consists of about 230 strings each and a total of 1852 strings.

These large numbers of solar panels in single block are again divided into two blocks of strings. Each string consists of 24 solar panels connected in series and about 120 of these strings are connected in parallel to a single inverter through a main string combined box. Three phases double fed primary winding transformer is used. Converted AC power from the two inverters is fed to these two primaries of the transformer. Each string consists of 24 modules in that way 16 strings are connected to one string combined box (SCB). Total 15 SCB'S are connected to one main string combined box (MSCB'S). Each inverter is connected with one main string combined box. Total 16 inverters are connected to eight transformers with each two. The output of transformer is connected directly to 33 kV grid (see Fig. 2).

The plant is installed in such a way that it is cost effective, more reliable, and more energy output. During nights when there is no power generation due to lack of solar radiation, the power is taken back from grid for internal power requirement. The power is utilized for lighting, initial starting of the batteries, control room appliances.

2.3. Tilt angle

The tilt angle of the PV array is kept as equal to the latitude of the corresponding location to get maximum solar radiation (Labed and Lorenzo, 2004). This solar plant uses modern technology for tilting of solar panels. It is designed in such a way that, manual seasonal tilt technology is used in order to absorb more solar radiation and to extract more power output. The tilting of the solar panels is arranged as follows. From November to February as it is winter season the tilt should be somewhat higher (33.75°) and from May to August the tilt is of lesser value (3.75°) as it is summer season anyhow more radiation is absorbed whatever the tilt angle may be. But, in rest of four months September, October, March and April moderate tilt angle of 18.75° is provided. The tilt angle is considered according to the geographical location of the plant.

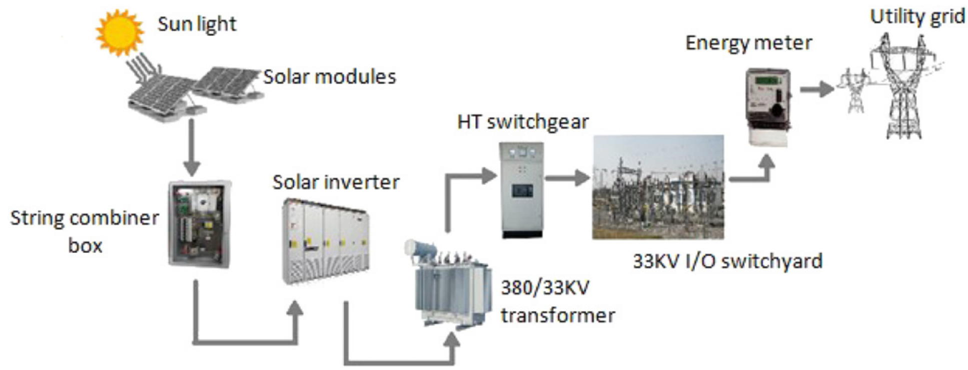

Fig. 1. Schematic diagram of NTPC 10 MW solar plant.

2.4. Specification of solar panel

The solar panels mounted at NTPC 10 MW solar power plant are of 225w_p rating and made up of polycrystalline. These panels have an efficiency of 14.06% and are of fixed type. Polycrystalline panel ratings are open circuit voltage (V_{OC}) of 36.42 V and short circuit current (I_{SC}) of 8.09 A. It has a maximum operating temperature of 43.2° centigrade. The solar panels are installed in such a way that structure to structure and leg center to center distance is at 4 m. The distance between panels (Panel to panel) is of 25 mm. Distance between grounds to lower edge of the module is 400 mm. To have a better yield panels are cleaned twice in a month.

2.5. Power conditioning units

Inverter converts DC power into AC power. The inverter power rating is 630 kW. PV voltage of 874 V and supply DC current 845 A is fed as input to inverter. The output AC voltage and current from inverter are 350 V and 1040 A respectively. The output of the inverter is synchronized automatically with same voltage and frequency as that of grid.

2.6. Power evacuation

The rated power of the transformer is 1.5 MVA and manufacture type is of Vector group DY5Y5. The primary voltage of the transformer is 385 V and secondary is directly connected to 33 kV switchyard. The current rating is given as 2.24 A/1124.70 A. The efficiency of transformer is almost 97%.

3. Methodology for performance analysis of the PV system

The performance of grid connected solar photovoltaic power plant work in this paper is divided in three stages.

(1) Manually extract the parameters of power generation through SCADA system.
(2) Compare the performance with the PVSYST software.
(3) Compare the performance with the Solar GIS.

The performance parameters are developed by International Energy Agency (IEA) (Ayompe et al., 2011) for analyzing the performance of solar PV grid interconnected system. Many performance parameters are used to define the overall system performance with respect to the energy production, solar resource and overall effect of system losses. The various parameters are the performance ratio, final PV system yield and reference yield.

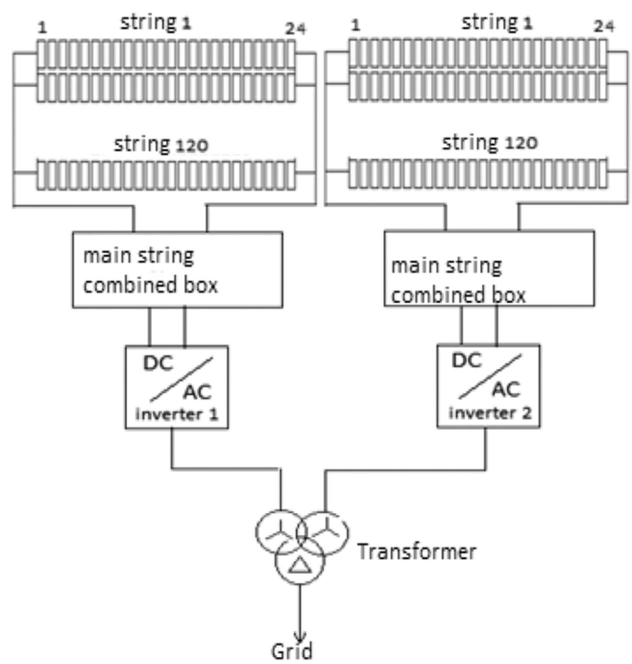

Fig. 2. Plant layout.

3.1. System parameters (Marion et al., 2005; Sharma and Chandel, 2013)

Array yield

It is equal to the time which the PV plant has to operate with nominal solar generator power P_o to generate array DC energy Ea. Its units are kW h/d_*kW p.

$$Y_A = E_A/P_O$$

where, Array energy output per day $E_A = I_{dc*}V_{dc*}t$ (kW h),

I_{dc} = DC current (A)
V_{dc} = DC voltage (V)
P_0 = Nominal Power at STC.

Reference yield

The reference yield is the total in-plane irradiance H divided by the PV's reference irradiance G. It represents the under ideal conditions obtainable energy. If G equals 1 kW/m^2, then Yr is the number of peak sun hours or the solar radiation in units of kW h/m^2. The Yr defines the solar radiation resource for the PV system. It is a function of the location, orientation of the PV array, and month-to month and year-to-year whether variability.

Its units are h/d.

$Y_R = [\text{kW h/m}^2]/1\ \text{kW/m}^2$.
$Y_R = H_t/G_o$

where,

H_t = Total Horizontal irradiance on array plane (Wh/m^2),
G_o = Global irradiance at STC (W/m^2).

Final yield
The final yield is defined as the annual, monthly or daily net AC energy output of the system divided by the peak power of the installed PV array at standard test conditions (STC) of 1000 W/m^2 solar irradiance and 25 °C cell temperature. Its units are kW h/d_*kW p.

$Y_F = E_{PV,AC}/P_{maxG,STC}$.

Performance ratio
The performance ratio is the final yield divided by the reference yield. Performance ratio can be defined as comparison of plant output compared to the output of the plant could have achieved by taking into account irradiation, panel temperature, availability of grid, size of the aperture area, nominal power output, temperature correction values.

$PR = Y_F/Y_R$.

Capacity utilization factor
It is defined as real output of the plant compared to theoretical maximum output of the plant.

$$\text{CUF} = \text{Energy measured (kW h)} / (365 * 24 * \text{installed capacity of the plant}).$$

Inverter efficiency
The inverter efficiency appropriately called as conversion efficiency is given by the ratio of AC power generated by the inverter to the DC power generated by the PV array system. The instantaneous inverter efficiency is given by,

$\eta_{inv}=P_{AC}/P_{DC}$.

System efficiency
The instantaneous daily system efficiency is given as PV module efficiency multiplied by inverter efficiency.

$\eta_{sys,T} = \eta_{PV,T} * \eta_{inv,T}$.

Energy output or energy fed to utility grid
The energy generated by the PV system is the measure of energy across the inverter output terminals for every minute. It is defined as the total daily monitored value of AC power output and the monthly AC energy generated.

3.2. Specific plant losses

Energy losses occur in various components in a grid connected SPV Power plant under real operating conditions. These losses are evaluated using the monitored data.

Array capture losses (L_C): These are of two types.

- Thermal capture loss (L_{CT}): Losses caused by cell temperature higher than 25 °C are called thermal losses. Thermal capture loss (L_{CT}) is the difference between reference field and corrected reference field.
- Miscellaneous capture loss (L_{CM}): Losses that are caused by wiring, string diodes, low irradiance, partial shadowing, mismatching, maximum power tracking errors, limitation through dust, losses generated by energy conduction in the photovoltaic modules

$L_{CT} = Y_R - Y_{CR}$
$L_{CM} = Y_{CR} - Y_A$
$L_C = Y_R - Y_A$.

System losses (L_S)
These losses are caused by inverter, conduction and losses of passive circuit elements.

$L_S = Y_A - Y_F$.

3.3. Data monitoring

A common weather monitoring station located next to the plant records the wind speed, ambient temperature and solar radiation data. A dedicated server with the principle of supervisory control and data acquisition (SCADA) for assessment of the monitored data is also present. The server records the data of voltage, current, power factor, power output of inverters for each and every minute. It also records the solar irradiance, wind speed and ambient temperature data received from automatic weather station. The server collects the data from measuring sensors and at the outgoing side of the inverters through bus. It transfers the data files periodically and the server retrieves the data. Server along with the SCADA software is located in a control room.

3.4. Simulation using PV SYST and Solar GIS

PV syst software (http://www.pvsyst.com, 2015) is one of the simulation software developed to estimate the performance of the solar power plant. It is able to import meteo data from many different sources as well as personnel data. This software is capable of evaluating the performance of grid-connected, stand-alone and pumping systems based on the specified module selection. The program accurately predicts the system yields computed using detailed hourly simulation data.

Solar GIS is a geographic information system designed to meet the needs of the solar energy industry (Tarigana and Djuwaria, 2014). This application combines solar resource data and meteorological data with a web-based application system to support planning, development, and operation of solar energy systems.

Four applications are implemented in the system: (i) iMaps – high-resolution global interactive maps, (ii) climate data – interactive and automated access to solar radiation and air temperature; (iii) PV Planner – PV performance simulator with a new concept of simulation algorithms and data formats and (iv) PV Spot – a tool for performance evaluation and monitoring of PV systems. All applications use an interactive map interface and geographical search utility (based on Google technology) and have extensive reporting capabilities (info delivered in standardized formats, such as csv, xls, and pdf).

In this study PV syst and PV GIS simulation software is used to predict the annual energy output of 10 MW peak grid connected solar PV plant.

4. Results and discussion

4.1. Solar irradiance vs. peak power output

Solar irradiance absorbed by solar modules is converted to useful power. The power output varies with the solar insolation

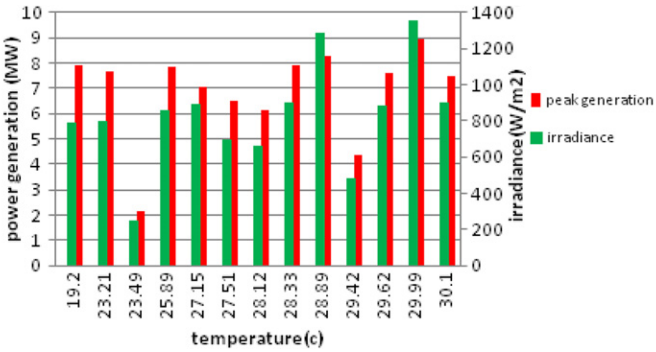

Fig. 3. Solar irradiance vs. peak power o/p.

and an ambient temperature. A typical day result is shown in Fig. 3 to understand the effect of irradiance and Temperature on power output of the system.

As, the temperature increases the power output decreases up to some extent even if there is good amount of radiation. Also, with increase in temperature, the power generation decreases slightly even when there is constant solar irradiance. The trend can be clearly observed from the Figure.

4.2. Variations in energy export vs. consumption on different days

Some amount of power generated from the plant is consumed for its internal power utilities. Every day the power output may vary accordingly as radiation varies but the consumption either day or night almost remains constant as there is no change in load of the solar plant. The difference in energy export and consumption should be high. The day's power consumed by the solar plant load is 150 kW h and correspondingly its night power consumption is 300 kW h. By using the net metering concept power consumed is calculated by the internal utilities and power export to the grid. The consumption also varies depending on the sun's radiation. If the solar plant cannot generate the power due to rains or less amount of radiation it may stop generating power. To analyze those all conditions the plant records every day's consumption and correspondingly night consumption also.

4.3. Performance Ratio (PR)

The annual average value of PR ratio is nearly 85.12%. The highest value of PR is found to be 97.5% in the month of December and the lowest PR was 73.88% in the month of April. System malfunction can be deducted based on the PR values. Lower PR is attributed to the incorrect operation of the system and inverter malfunction (see Fig. 4).

4.4. Capacity utilization factor

The annual average value of CUF factor is nearly 17.68%. It varies from 12.67% to 20.04%. The capacity utilization factor for the Indian PV plants varies from 12.29% to 18.8% based on one year operation. The variation in the capacity factor is due to the system losses as a result of local climatic conditions. However, the average capacity utilization factor of 17.68% of this plant is very close to the one recorded by other SPV plant in India (MNRE, 2011). Higher the capacity utilization factor lower will be the cost of electricity generation (see Fig. 5).

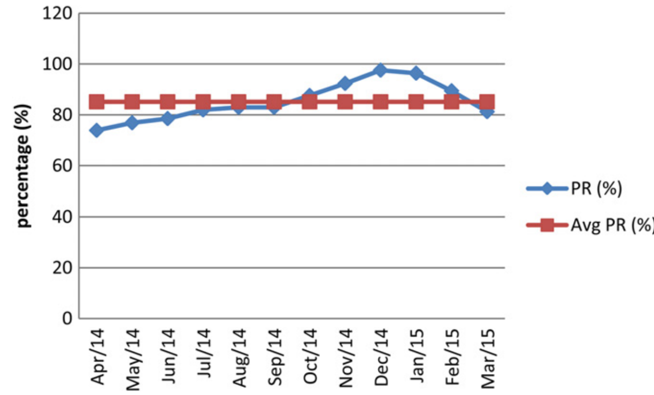

Fig. 4. Average performance ratio in various months.

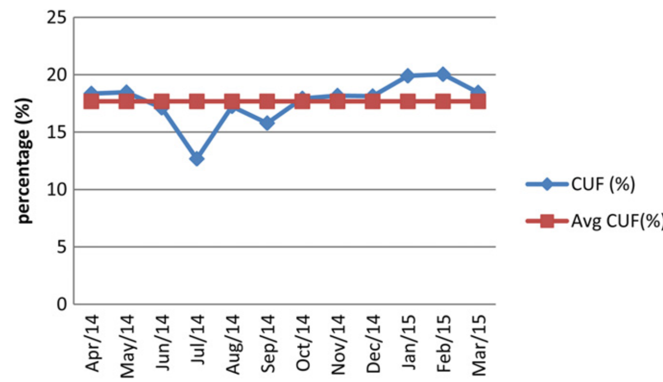

Fig. 5. Average capacity utilization factor in various month.

Table 1
Average monthly energy output.

Month	Average daily energy generation (MW h)	Monthly sum of energy o/p (MW h)	Total annual energy generated (MW h)
April-2014	44.870	1346.103	
May-2014	45.154	1399.789	
June-2014	41.918	1257.569	
July-2014	32.150	964.501	
August-2014	43.674	1310.255	
September-2014	38.691	1160.759	15 798.192
October-2014	45.418	1362.567	
November-2014	44.504	1335.140	
December-2014	45.864	1375.939	
January-2015	48.742	1511.003	
February-2015	49.070	1373.987	
March-2015	45.180	1400.580	

4.5. Energy generation

The data is collected manually by using SCADA software. The highest monthly sum of energy generation was 1511.003 MW h in the month of January and the lowest was 964.501 MW h in the month of July. This is all because of the seasonal tilt of the solar panels and the amount of solar radiation that is absorbed from the sun. The total annually generated output was 15 798.192 MW h (see Table 1).

5. Simulation using PV SYST

The maximum energy is generated in the month of December (1589 MW h) and minimum energy is in the month of July (926 MW h). The total amount of energy that is injected in to the grid for the entire year is 16 047 MW h.

Table 2
Balances and main results.

	GlobHor (kW h/m^2)	T Amb (°C)	GlobInc (kW h/m^2)	GlobEff (kW h/m^2)	EArray (MW h)	E_Grid (MW h)	EffArrR (%)	EffSysR (%)
January	147.5	22.11	189.8	185.7	1 552	1 508	10.77	10.47
February	159.3	24.46	187.1	183.1	1 506	1 462	10.60	10.29
March	195.2	28.37	205.5	200.0	1 611	1 565	10.33	10.03
April	203.0	31.63	199.3	193.6	1 536	1 493	10.15	9.87
May	202.4	33.93	187.8	181.4	1 425	1 384	10.00	9.71
June	156.8	30.95	144.6	139.2	1 116	1 082	10.16	9.86
July	130.8	28.55	122.8	118.0	957	926	10.27	9.93
August	131.4	27.55	126.7	122.0	998	966	10.38	10.05
September	151.9	27.69	154.9	150.1	1 225	1 189	10.42	10.11
October	164.0	27.06	180.2	175.0	1 435	1 394	10.49	10.19
November	149.0	23.93	189.5	185.2	1 533	1 489	10.66	10.35
December	147.6	21.91	200.2	196.2	1 637	1 589	10.77	10.45
Year	1939.9	27.36	2088.3	2029.5	16 532	16 047	10.43	10.12

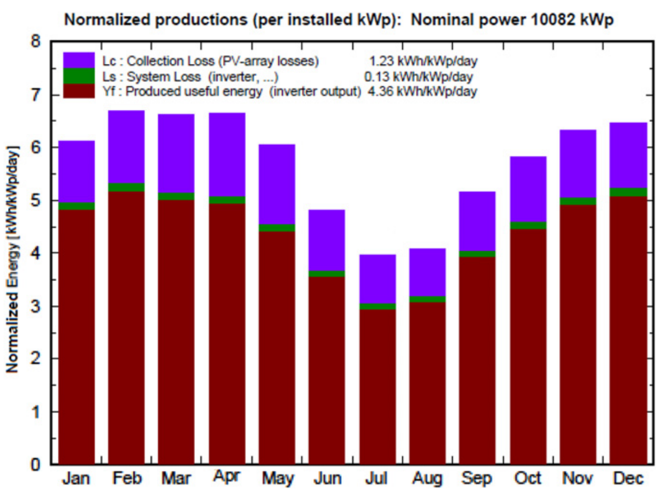

Fig. 6. Normalized energy per month.

5.1. Balances and main results

Annual global horizontal irradiation is 1939.9 kW h/m^2. Global incident energy that is incident on the collector plane annually is 2088.3 kW h/m^2. Total energy obtained from the output of the PV array is 16 532 kW h. Annual Efficient E_{out} array/rough area obtained is 10.43%. In the same way annual Efficient E_{out} system/rough area is 10.12% (see Table 2).

5.2. Performance ratio

The annual average performance ratio is 76.20%. From PV syst results the performance ratio obtained has no much difference with the actual performance ratio of the solar plant observed using SCADA system.

5.3. Normalized productions

The L_C value is recorded as 1.23 kW h/kW p/day and the L_S value is recorded as 0.13 kW h/kW p/day in the same way Y_F is given as 4.36 kW h/kW p/day (see Fig. 6).

5.4. Loss diagram

The global horizontal irradiance is 1940 kW h/m^2. The effective irradiation on the collector plane is 2030 kW h/m^2. Therefore, the loss in energy is 3.2%. The solar energy incident on the solar panels will convert into electrical energy. After the PV conversion, the nominal array energy is 20 489 MW h. The efficiency of the PV array is 13.30% at standard test condition (STC). Array virtual energy obtained is 16 532 MW h. After the inverter losses the available energy obtained at the inverter output is 16 047 MW h (see Fig. 7).

Table 3
Total energy generated during various months.

Month	E_{sm} (kW h/kW p)	E_{sd} (kW h/kW p)	E_{tm} (GWh)	E_{share} (%)	PR (%)
January	156.1	5.04	1.56	9.5	78.4
February	146.6	5.24	1.47	9.0	76.7
March	157.6	5.08	1.58	9.6	74.9
April	153	5.10	1.53	9.4	73.8
May	148.3	4.78	1.48	9.1	73.3
June	111.1	3.70	1.11	6.8	75.5
July	99.4	3.21	0.99	6.1	77.1
August	97.6	3.15	0.98	6.0	77.9
September	116.8	3.89	1.17	7.1	77.9
October	142.7	4.60	1.43	8.7	77.6
November	149.4	4.98	1.49	9.1	78.4
December	156.3	5.04	1.56	9.6	79.0
Year	1634.9	4.48	16.35	100.0	76.6

6. Simulation using solar GIS-PV planner

6.1. Global horizontal and in-plane irradiation

The plant has more global irradiation in the month of April (206.10 kW h/m^2) correspondingly more daily sum of global irradiation is recorded. The plant has more global in-plane irradiation in the month of April (207.2 kW h/m^2) correspondingly more daily sum of global in-plane irradiation was recorded (see Fig. 8).

6.2. PV electricity production

The plant generated more electricity in the month of March (1.58 GWh) correspondingly it has more daily sum of specific electricity produced. The share of monthly electricity of March is 9.6% which is almost equal to the month of December (see Tables 3 and 4).

7. Performance comparison

The results obtained from the monitored SCADA data system is compared with PVSYST and PV-GIS Software. The results are presented in Table 5. The actual performance closely matches with the simulated performance of PV syst and Solar GIS over the entire year.

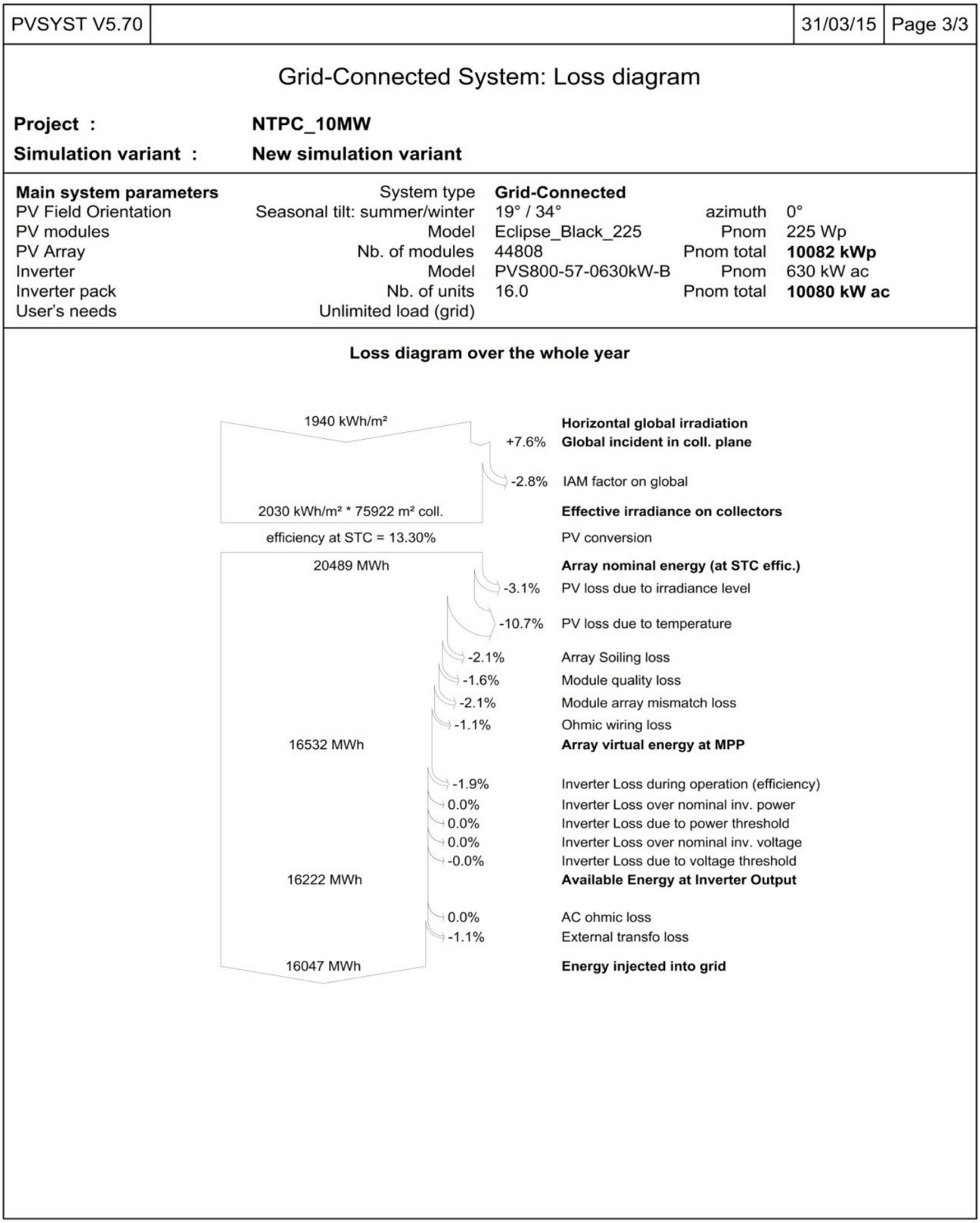

Fig. 7. Loss diagram over the entire year.

8. Conclusion

A performance study of 10 MW peak grid connected solar photovoltaic power plant installed at Ramagundam was evaluated on annual basis. The following conclusions are drawn from the study.

- A peak power output of 10.34 MW and 40.83 kW of minimum power output were observed during the year round operation.
- Maximum total energy generation of 1511.003 MW h was observed in the month of January and lowest total energy generation of 950.228 MW h was observed in the month of July.

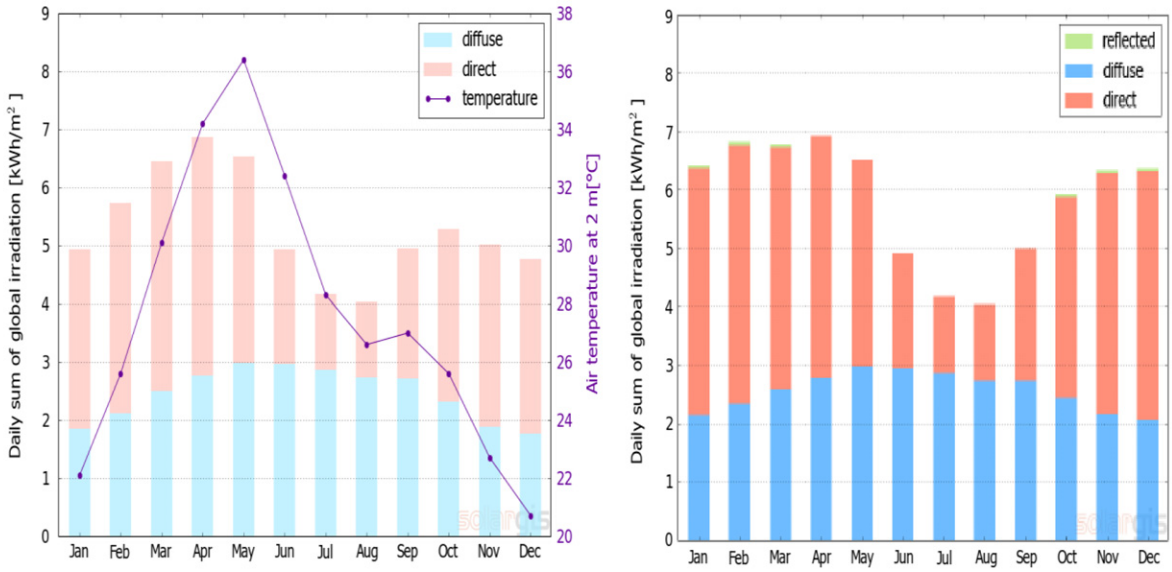

Fig. 8. Daily sum of global irradiation in horizontal and in-plane direction during various months.

Table 4
Overall plant system losses.

Energy conservation step	Energy output (kW h/kW p)	Energy loss (kW h/kW p)	Energy loss (%)	PR partial (%)	PR cumulative (%)
1. Global in-plane irradiation (input)	2134			100.0	100.0
2. Global irradiation reduced by terrain shading	2131	−2.0	−0.1	99.9	99.9
3. Global irradiation reduced by reflectivity	2075	−56.0	−2.6	97.4	97.3
4. Conversion to DC in the modules	1776	−299.0	−14.4	85.6	83.3
5. Other DC losses	1723	−53.0	−3.0	97.0	80.8
6. Inverters (DC/AC conversion)	1689	−34.0	−2.0	98.0	79.1
7. Transformer and AC cabling losses	1668	−20.0	−1.2	98.8	78.2
8. Reduced availability	1635	−33.0	−2.0	98.0	76.6
Total system performance	1635	−499.0	−23.4		76.6

Table 5
Energy generated results.

S.No.	Month	PV SYST result (MW h)	Monitored result (MW h)	Solar GIS: PV planner results (MW h)
1	April-2014	1 493	1332.626	1 532
2	May-2014	1 384	1384.810	1 485
3	June-2014	1 082	1241.880	1 114
4	July-2014	926	950.228	991
5	August-2014	966	1293.194	989
6	September-2014	1 189	1145.170	1 172
7	October-2014	1 394	1344.940	1 439
8	November-2014	1 489	1319.100	1 491
9	December-2014	1 589	1359.490	1 568
10	January-2015	1 508	1493.080	1 561
11	February-2015	1 462	1357.720	1 472
12	March-2015	1 565	1383.670	1 589
Total		16 047	15 605.908	16 403

- As far as the comparison of monitored data with PV syst and Solar GIS simulation results, plant is operating nearer to the predicted generation of energy modeling software.
- The annual daily average array yield is 4444 at reference yield of 33 333.
- 10 MW solar power plant has been operating with good amount of PR and CUF. The plant has been in operation and feeding energy to grid at an available percentage of almost 99%.

The study provides an insight to identify the location and suitable PV technology for large scale deployment of solar photovoltaic system in India. This information is useful in evaluating the operational benefits of the plant based on the net energy output. The monitored data and operating experience of PV system can be applied for future large scale projects.

Acknowledgments

We thank Mr. CH. Satyanarayana, Deputy General Manager, NTPC and Mr. K. Prakash and Mr. A. Panda, Managers, NTPC and Ashok Kumar Somasi Engineer-(Site Incharge), Lanco group (solar) for accessing the input data of the plant which was required for above analysis.

References

Ayompe, L.M., Duffy, A., McCormack, S.J., Conlon, M., 2011. Measured performance of a 1.72 kW rooftop grid connected photovoltaic system in Ireland. Energy Convers. Manage. 52, 816–825.
Besarati, S.M., Padilla, R.V., Goswami, D.Y., Stefanakos, E., 2013. The potential of harnessing solar radiation in Iran: generating solar maps and viability study of PV power plants. Renew. Energy 53, 193–199.
Elhodeiby, A.S., Metwally, H.M.B., Farahat, M.A., 2011. Performance analysis of 3.6 kW Rooftop grid connected photovoltaic system Egypt. In: International Conference on Energy Systems and Technologies, Cairo, Egypt, CEST 2011, 11–14 March.
Goura, R., 2015. Analyzing the on-field performance of a 1-641 megawatt-grid -tied PV system in South India. Int. J. Sustainable Energy 34, 1–9.
http://www.pvsyst.com, 2015.
IEA (International Energy agency) Country report on analytical monitoring of photovoltaic systems IEA PVPS Task13, 2014 [Available at: www.iea-pvps.org].
Labed, S., Lorenzo, E., 2004. The impact of solar radiation variability and data discrepancies on the design of PV systems. Renew. Energy 29, 1007–1022.
Makrides, G., Zinsser, B., Norton, M., Georghiou, G.E., Schubert, M., Werner, J.H., 2010. Potential of photovoltaic systems in Countries with high solar irradiation. Renewable Sustainable Energy Rev. 14, 754–762.

Marion, B., Adelsten, J., Boyel, K., Hayden, H., Hammon, B., Fletcher, T., Canada, B., Narang, D., Kimber, A., Michell, L., Rich, G., Towsend, T., Detride, A., Kimbler, A., 2005. Performance parameters for grid-connected PV system. In: Proceeding of the 31st IEEE Photovoltaic Specialist Conference, Lake Buena Vista FL, pp. 1601–1606.

Ministry of New and Renewable Energy, Solar energy in India. February 12, 2014. http://mnre.gov.in/schemes/decentralized-systems/solar-systems.

MNRE (Ministry of New and Renewable Energy). Performance of grid solar PV power Plants under demonstration programme. 2011, 32/54/2011-12/PVSE. [Available at: www.mnre.gov.in/filemanager/userfiles/Grid_Solar_Demo_Performance.Pdf [accessed 13.08.13]].

Pavlovic, T., Milosavljevic, D., Radonjic, I., Pantic, L., Radivojevic, A., Pavlovic, , 2013. Possibility of electricity generation using PV solar plants in Serbia. Renewable Sustainable Energy Rev. 20, 201–218.

Sharma, Vikrant, Chandel, S.S., 2013. Performance analysis of a 190 kW p grid interactive solar photovoltaic power plant in India. Energy 55, 476–485.

Sudhakar, K., Srivastava, T., Satpathy, G., Premalatha, M., 2013. Modelling and estimation of photosynthetically active incident radiation based on global irradiance in Indian latitudes. Int. J. Energy Environ. Eng. 4 (21), 2–8.

Tarigan, Elieser, Djuwari, Lasman Purba, 2014. Assessment of PV power generation for household in surabaya using solarGIS–pvPlanner simulation. Energy Procedia 47, 85–93.