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Operational performance of megawatt-scale grid integrated rooftop solar PV system in tropical wet and dry climates of India

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A R T I C L E I N F O

Keywords:
Solar PV plants
PV performance
PVGIS
PV watts
PV Syst
Simulation tools

A B S T R A C T

This case study presents the performance of a megawatt-scale grid-connected rooftop solar photovoltaic (PV) plant installed on the building rooftops of an educational institute (GITAM Deemed to be University) located in coastal regions (longitude 83° 23' 6.54'' E and latitude 17° 48' 8.208'' N) of Andhra Pradesh. A framework is proposed to validate the existing simulation models that are used for PV project modeling. The validation is done by comparing the simulated performance with the real-time monitored performance. The studied PV plant consists of 3078 solar panels and 23 inverters. For the analysis, we recorded the PV plant operational data for 12 months from 1st October 2018 to 30th September 2019. Based on the monitored data and by following the proposed framework, performance analysis is carried out. The results include the estimated parameters like energy outputs, yield factor, capacity factor, performance ratio, and the error matrices. The solar PV plant supplied energy of 1325.42 MWh to the grid during the monitored period. The expected outcomes of the solar PV plant are assessed using PVGIS, PV Watts, and PV Syst simulation tools. We observed an average mean bias error (MBE) of 5.33% (PVGIS), 12.33% (PV Watts) and 30.64% (PV Syst) and average normalized mean bias error (NMBE) of 2.954% (PVGIS), 7.88% (PV watts) and 22.75% (PV Syst). Overall, it is observed that there is a deviation between the simulated and monitored energy performance.

1. Background

Over the last few decades, the energy consumption levels are expanding due to increased use at various levels, and of course, the new developing technologies are one of the reasons. On the other side, the concerns related to the environment are also increasing. For

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mitigating the increased energy demands without affecting the environment seems to be only possible with renewables energy. The renewable energy sources like solar, biomass, wind are the widely used alternatives for meeting the increasing demand for electrical energy. The scenario has gained global attention, and many developing countries are also focusing on renewables penetration into their utility grids. Owing to the requirements, India electric grid has an installed capacity of 364.96 GW by 2019, with mixed electricity generation from coal (56.1%), large hydro (12.5%), small hydro (1.3%), wind (10.2%), solar (8.6%), biomass (2.6%), gas (6.9%), diesel (0.1%) and nuclear (1.9%) [1]. The above statistics and the preliminary understanding of renewable energy potential in India reveal that India has incredible scope for generating solar energy that benefited from its geographical location. It is a tropical country with 3000 h of sunshine, receiving solar radiation throughout the year. Relatively all regions in India receive 4.7 kWh/m^2 solar radiation. The highest potential for solar energy tapping is acquired in the states of Andhra Pradesh, Bihar, Gujarat, Haryana, Madhya Pradesh, Maharashtra, Orissa, Punjab, Rajasthan, and West Bengal due to their locations [2]. Consequently, the solar photovoltaic power generation had been initiated in various regions in the country for electrification. Solar power is sometimes used in parallel with diesel generating stations in remote areas. With the slowdown in solar energy devices and admiration for the need for advancements of solar technologies, projects have recently been executed. With the sliding in solar electric energy costs, grid-connected solar photo voltaic (PV) plants have grown in various levels ranging their capacities from small scale to large scale.

Earlier, rural electrification has introduced the usage of solar lamps, solar pumps, lighting for homes, lighting systems in the streets. Public awareness, government schemes, solar policies, easy installation, pollution-free environment gave a broad scope for the use of solar energy utilization. Extensive improvement in PV manufacturing encouraged the development of solar PV plants for industrial and commercial applications. As the technology develops over the years, it is becoming more viable for institutions and campuses to explore means of generating their electricity from renewable sources where solar energy is an attractive option to supplement the electrical sourcing from the public grid.

The progression of traditional forms of energy to meet society's growing energy needs at low prices is investigated. Some researchers discussed the capacity, constraints, and advantages of solar technologies in the India as well as globally [3,4]. The research in solar energy practices and future roadmap in the field of solar technology are discussed. Solar power is one of the trending areas in energy investments in the present scenario, but it needs an effective economic and environmental assessment to ensure the paybacks [5]. In addition, a risk assessment is essential, as there are many technical problems in solar PV systems that were explained, along with the risk assessment in Ref. [6].

Technical analysis proportionally plays a vital role in organizing relevant information and to have the decision for further improvements in the performance. Research in solar PV plants and their performance studies are ongoing, especially in the design, installation, and analysis of the commissioning of the solar plants [7]. The correct prediction of the energy produced by solar photovoltaic modules in any required location is essential for the expansions of solar generation. The energy production varies seasonally based on the solar radiation in that location. Many computer simulation models exist, and they are handy tools to predict the possible energy outputs and to have performance assessment [8,9].

This paper aims to evaluate the operating performance of the 1 MWp grid integrated solar PV power plant at Rushikonda, Visakhapatnam, Andhra Pradesh, India under tropical wet and dry climate conditions. The research highlighted in this case study is based on the following three objectives.

- Prediction and performance assessment of the proposed solar power plant energy outputs using the three popular simulation tools: PVGIS, PV Watts, PV Syst.
- Real-time monitoring of the power plant data and to evaluate its performance using the performance metrics like energy output, solar irradiation, yield factor, capacity factor, and performance ratio.
- To select the best simulation model by comparing the predicted and real-time monitored performance metrics.

2. Literature review

A brief literature study is carried out in understanding the role of simulation tools in the performance assessment of solar PV systems.

AP Dobos [10] summarized the calculation methods used in the PV Watts photovoltaic system performance model. The technical reference details of the individual sub-models, documentation assumptions, and hidden parameters were addressed. Detailed presentations of the sequence of calculations that yield the final performance estimate of the system are presented. Kumi et al. [11] aimed at progressing a standard approach in the design of large-scale academic grid-interactive solar PV systems utilizing the rooftops of buildings and car parking. Using RETScreen technology for grid-connected solar PV systems, a probability analysis of renewable energy projects was performed. The simulation results show an annual energy yield of approximately 1159 MWh, which is 12% of the annual electricity utilization. Manoj Kumar et al. [12] analyzed the viability of developing a 1 MW grid-connected solar plant on different campuses of (UMP) University Malaysia Pahang. The commercial and domain aspects of the PV plant were assessed with standard parameters using PVGIS and PV Watt software tools. Kumar et al. [13] evaluated the feasibility of installing a 100 kWp grid associated photovoltaic system with a PV Syst simulation tool. The feasibility analysis showed that 100 kWp plant generates 165.38MWh/year.

CS Psomopoulos et al. [14] presented the performance of existing PV parks in Greece (i.e., 9.6 kWp roof-integrated PV array, 105.6 kWp PV plant, and an installation featuring 2-axis tracking mechanism of 98.4 kWp). PVGIS, PV Watt, and RETScreen simulation tools are used to measure and quantify the output of electricity from existing PV parks. The software results were validated with real-time values highlighting the advantages of each software tool. Baitule and Sudhakar analyzed the viability of developing a 100% solar PV base on an academic campus at MANIT – Bhopal, India. A proposal is made to set up a 5 MWp PV plant in the open space and rooftop area on the campus. The technological and financial feasibility of the solar PV plant proposed is examined using Solar Advisory Model (SAM) and the PV Syst software tools [15]. Abbood et al. proposed a design of a 1 MW grid-connected PV system under the Iraq climate condition. It was observed that the city has considerably high solar radiation potential to build PV systems on large scales. The estimated 1757.8 MWh of energy was generated in the first year and achieved a total life cycle production of 40,445 MWh, with a performance ratio ranging from 86.4% to 73% and an average capacity factor of 19.83% [16]. Renu Sharma and Sonali Goel presented different parameters of 11.2 kWp rooftop grid-connected solar PV plant monitored in a time duration of one year. It was observed that 14.960 MWh of energy generated per annum, with a module efficiency of 13.42%, inverter efficiency of 13.42%, and a performance ratio of 0.78 [17].

Huld presented in detail about the PVMAPS software tool to calculate solar irradiation and photovoltaic power on inclined and tracking surfaces over large geological areas. A simulation tool has been implemented to provide data on altitude, horizon, average temperatures, solar irradiation, and also to measure the impact of wind variations on the output of solar plants [18]. Akash Kumar Shukla et al. focused their study on analyzing the performance of a 110 kWp rooftop solar PV plant using SolarGIS PV planner software. Simulation is carried for four different types of modules to determine the performance ratio and energy yield. The authors concluded that the performance ratio ranges from 70 to 80%, and the energy yields range from 2.67 kWh/kWp to 3.36 kWh/kWp are observed [19].

Malvoni investigated the performance of a 960 kWp photovoltaic (PV) system monitored over 43 months in southern Italy, to assess the energy yields, losses, and efficiency. A comparison is made with other photovoltaic plants built in different climates in terms of degradation rate. By implementing two commonly used PV simulation methods, SAM and PV Syst, the actual performance of the studied PV system are compared with the expected results. Results show that SAM underestimated the annual average energy injected into the grid by 3.0% and PV Syst by 3.3%, but overall, PV Syst outperforms the SAM method [20].

Kumar and Subathra proposed a machine-learning algorithm to forecast the solar irradiation for three years ahead. The article highlights that this algorithm can estimate future energy potentials and degradation rates for improving the power project capacities [21]. Kumar et al. adopted the PV Syst tool to predict the operation of a 200 kWp rooftop photovoltaic solar plant on a complex. Annual feasibility of 292,954 MWh of energy can be produced with an energy loss of 77.27% and a PR loss of −26.5% [22].

The performance analysis of 3 MWp solar plants located in Karnataka state, India, monitored for the years 2010 and 2011 is presented in Ref. [23]. Variations in the solar plant are tracked regularly and seasonally. Inverter failure and grid failure losses were evaluated. Due to inverter failure losses in 2010, the performance ratio was found to be less than 0.6 and an annual average of 0.7 reported in 2011 with decreased inverter failure losses [23].

In the literature review, researchers have shown the applicability of software tools in modeling a PV plant and in addition to assess the performance feasibility. From the review, it is understood that only a few software tools are widely used in literature say, for example, PV Syst. PV system is a premium software tool where one has to purchase the login for their use. In this study, we see scope for a few other open-access tools PVGIS and PV Watts. We tried to explore these two software tools performance with a premium software modeling tool. Hence, three different modeling are selected for this study along with real-time monitored data.

3. Description of the studied photovoltaic system

The studied PV plant is located in Rushikonda, Visakhapatnam, Andhra Pradesh, India. Geographically it is located at a longitude 83° 23’ 6.54’’ E and latitude 17° 48’ 8.208’’ N, in the midst of Eastern Ghats, in the coast region of Bay of Bengal. The elevation from sea level is about 40 m. The place has an average highest temperature of 34 °C during May with 75% humidity and an average wind speed of 3.5 m/s. A 1MWp grid-connected rooftop solar PV pant is installed utilizing the vacant space on various buildings of Gandhi Institute of Technology and Management Science (GITAM) educational institute. The institute has well-equipped laboratories with high power rating machinery in various facilities, massive constructions with air-conditioned rooms, lightning loads, etc. The total load of the campus is around 13.5 MW and the contracted maximum demand of 2500 kVA. Electrification to the campus is procured from a 3150 kVA, 33KV/11 KV substation. The campus is equipped with six distribution transformers of each 11 KV/433V and with

Table 1
Total energy consumption during the years 2017 and 2018.

Months	Energy Consumption (kVAh), 2017	Energy Consumption (kVAh), 2018
January	4,83,500	5,10,125
February	5,96,150	6,25,450
March	7,33,350	8,03,500
April	8,13,500	8,60,000
May	4,78,000	5,48,500
June	5,89,000	7,59,000
July	8,71,500	9,52,500
August	8,10,000	9,49,950
September	7,94,000	8,97,050
October	8,43,000	7,46,500
November	6,48,000	6,02,450
December	6,25,000	6,01,350
TOTAL	82,85,000 kVAh	88,56,375 kVAh

eight standby diesel generators of each 250kVA to serve the load demands. The total energy consumption of the University for 2017 and 2018 years are presented in Table 1.

The power plant was commissioned with an aim that the produced energy from it would contribute a certain percentage of the load. Installing the solar PV plants are quite convenient, with no disturbances during operation, requires less operational maintenance in general. Hence, ample rooftops are used for the installation of solar plants. The specifications of the 1 MWp grid-connected solar PV plant are presented in Table 2. The electrification of the campus integrated with the solar plant is shown in Fig. 1. The roof-top solar PV power plant utilized a free space of about 12,000 sq. m. on the terraces of 15 different buildings. The entire plant is equipped with 3078 panels, each with 325Wp capacity manufactured by Trina solar maker. The type of solar panel used is Poly-Crystalline silicon. The solar panel of rating 325W is chosen for the installation. Here 18 to19 modules are coupled in series to arrange like a string and 170–180 of such connected strings in parallel to produce the possible voltage and current. The physical and electrical parameters of the PV modules are displayed in Table 3. Inverters convert direct current electricity generated by the PV modules into alternating current electricity, ideally following the local grid requirements and also maximizes the plant output. Inverter plays a role in improving the voltage across the strings and accounting string performance to logging data, providing safe and desolation in case of asymmetry in the grid, or with the solar PV modules. A total of 23 inverters manufactured by KACO with string technology are used with a combination of 20 KW and 50 KW rating. The specifications of the inverters are presented in Table 4.

4. Methodology

The framework used in this study in understanding the performance of the megawatt-scale grid integrated rooftop solar PV system is presented in Fig. 2. The data related to the energy output of the PV plant is monitored using the data monitoring system. For simulating the PV plant performance in various tools specific data is required. Here the simulation study needs the targeted PV capacity value along with the installation configuration, and the type of PV technology. The simulation is carried out using three software tools PVGIS, PV Watts, and PV Syst. Almost all three software tools require similar data for simulation.

A step by step simulation procedure is commenced as follows [12,24]:

- The selected site is located in the topographical view in the map indicating the location or with an address.
- The electrical and mounting specifications of the PV module need to be selected, and these include PV technology, PV power capacity, tilt angle, and azimuth angle are given as an input along with the system losses in %.
- The monthly energy generation of the 1 MWp solar PV plant is measured and tabulated using the data monitoring system.
- The performance of the 1 MWp solar PV plant is estimated by defining the software tools (PVGIS, PV Watts, PV Syst). More details regarding the three software tools are given in section 4.1.
- From the measured and estimated values, mean bias error (MBE in %) and normalized mean bias error (NMBE in %) are calculated. More details are presented in section 4.2.
- Comparison of various parameters for the three selected software tools as well as real-time monitored data. These parameters include PV array energy output, yield factor, capacity factor, performance ratio, and the related mathematical expressions are given in section 4.3.

4.1. Simulation modeling tools

The simulation tools used in this article for the assessment of the grid integrated 1 MWp roof-top solar PV plant in University campus are PV Watts, Photovoltaic geographical information system (PVGIS), and PV Syst.

4.1.1. PV watts

PV Watts calculator is a useful map-based tool to analyze the photovoltaic sites. National Renewable Energy Laboratory designed it. It provides the global annual energy output of grid-connected PV systems. It can also provide PV energy output hourly values. PV Watts calculator can estimate monthly irradiation, annual solar irradiation, energy output in kilowatts, and energy value. The input parameters for the PV Watts tool are the DC rating of the PV plant, DC to AC derates factor, PV array type, PV array tilt angle, azimuth

Table 2
Highlights of SPV power plant.

Parameters	Details
Solar Plant Capacity	1 MW
No. of Modules	3078
The power rating of Module	325 Wp
Rating of Inverter	20 kW & 50 kW
Total Inverters	23
Average DC:AC Ratio	1.11
Tilt angle	10°
Surface Azimuth Angle	180°
Type of Mounting Structure	Fixed Tilt

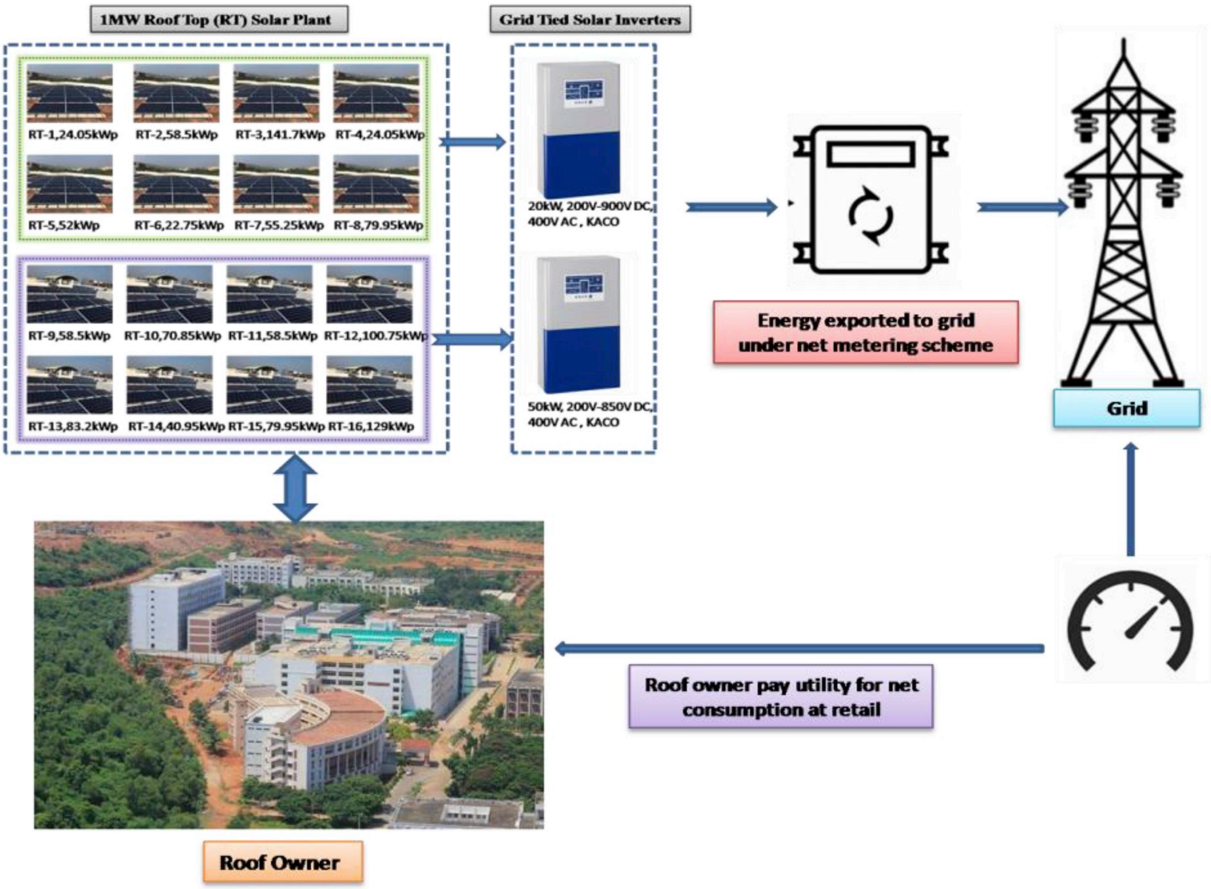

Fig. 1. Electrification of campus with Solar PV plant.

Table 3
Solar PV module specification.

Parameter	Details
PV technology type	Poly-crystalline (p-Si)
PV module manufacturer	Trina
Frame length	1960 mm
Module width	947 mm
Module thickness	40 mm
Maximum power	325 Wp
Maximum current	8.73 A
Maximum voltage	37.2 V
Short circuit current	9.19 A
Open circuit voltage	45.6 V

Table 4
Inverter specifications.

Parameter	Details
Inverter technology	String
Inverter manufacturer	KACO
Maximum DC operating current	108 A
Output voltage	400–480 V
Frequency	50 Hz
Efficiency	>98%

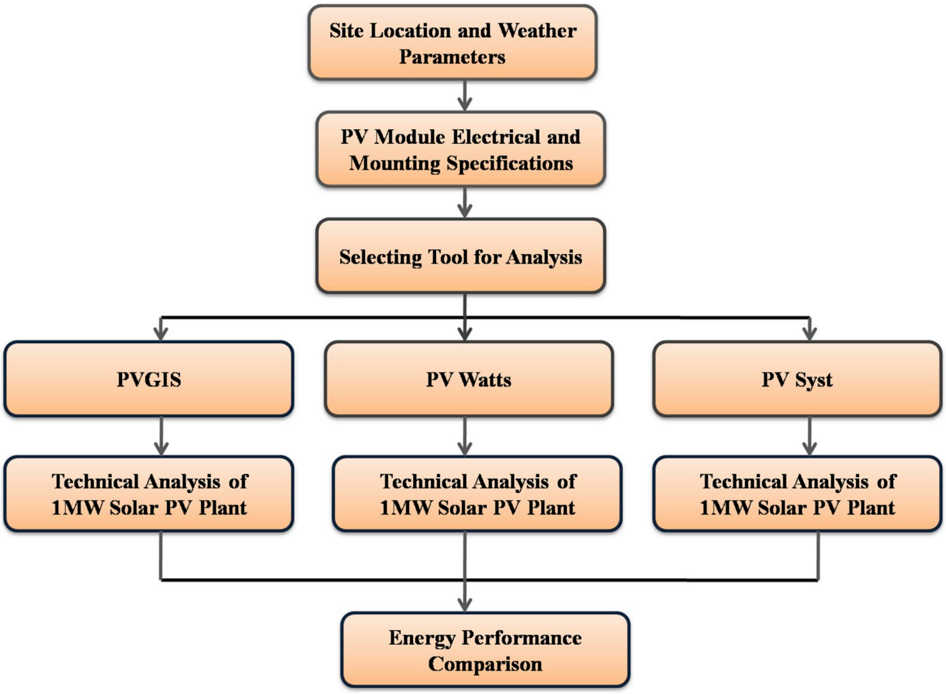

Fig. 2. Framework for validating the simulated and real-time monitored PV performance [12].

angle [8–10,12,24].

4.1.2. PVGIS

Photovoltaic geographical information system (PVGIS) is an explorative, graphic and policy-support tool for solar resources. It is one of the great tools for estimating the solar electricity production of a photovoltaic system. This tool is developed with combinations to provide solar irradiation, performance evaluation, and economic parameter analysis. PVGIS allows the user to calculate the monthly and annual potential in electricity generation [kWh] of a solar photovoltaic system with defined solar modules tilt angles and arrangements [8,9,12,24].

4.1.3. PV Syst

PV Syst is a computer simulation tool for the study, classification, and data analysis of complete solar photovoltaic systems. This software deals with grid-interfaced, stand-alone, DC-grid solar photovoltaic systems. PV Syst tool can perform the monthly PV system yield evaluations, load profile, estimated system cost using few system characteristics. Within the framework, the utilizer can perform different simulation iterations and compares them with existing values. PV Syst tool can define more detailed parameters of the system and it assesses light effects like thermal behavior, wiring, quality of modules, mismatch and incidence angle losses, partial shadings of near objects on the array. The results from the tool include dozens of simulation variables, which are displayed in monthly, daily/hourly values, and the data can be transferred to other software tools [8,9,12,24].

4.2. Mean bias error and normalized mean bias error

To assess the divergence between the estimated performance from the PVGIS, PV Watts, PV Syst, and measured energy from the solar PV plant, two parameters mean bias error (MBE) and normalized mean bias errors (NMBE) are being mentioned. The mean bias error gives the difference between the generated energy from installed PV plant and estimated energy from the software tools, whereas the normalized mean bias errors specify whether the framework is over or underestimated [20].

$$\text{Mean bias error} = \frac{\text{estimated value}(j) - \text{measured value}(j)}{\text{measured value}(j)} \times 100\% \tag{1}$$

$$\text{Normalized mean bias error} = \frac{\text{estimated value}(j) - \text{measured value}(j)}{\text{maximum measured value}_j^{12}} \times 100\% \tag{2}$$

where j index is used to consider the months (from 1 to 12) and the term *maximum measured value*$_j^{12}$ is the maximum recorded value during the monitored period.

4.3. Yield factor, capacity factor, performance ratio

Yield factor (Y_f): It is the ratio of net energy power output to the nameplate D.C power output of the existing solar PV array. It presents the total time that the PV array would need to function at its rated power to provide the same energy. The units of yield factor are hours or kWh/kWp [12,20].

$$\text{Yield Factor} = \frac{\text{PV array Energy Output(kWh)}}{\text{The capacity of the installed solar PV plant(kWp)}} \tag{3}$$

The Capacity factor (C_f) is the ratio of actual electrical energy output over a specific period to a maximum feasible electrical energy over that time. This capacity factor can be computed over a timescale of year and also for a month to attain the observations in seasonal fluctuations. The capacity factor is given by Refs. [17,20].

$$\text{Capacity factor} = \frac{\text{Yield factor}}{\text{Operating time}} \tag{4}$$

Performance ratio (PR) is a parameter that illustrates the long-range effect of losses on the solar energy output. PR is calculated monthly or yearly and depends on the PV module temperatures. PR value differs from season to season based on the sun irradiation incident on the PV cells. Performance ratio (PR) is defined as [17,20].

$$\text{Performance Ratio} = \frac{\text{Yield factor}}{\text{Solar irradiation*Area of the PV Plant}} \tag{5}$$

5. Results and discussions

It is well known that significant parameters affecting the quality of the photovoltaic module performance will be the climate parameters at the installation site. Solar irradiance is the primary one among them, and it is the power per unit area received from the sun in the form of electromagnetic radiation. The feasible study of the 1 MWp grid-connected solar PV plant positioned on the rooftops of the University campus is achieved using the PVGIS, PV Watts, PV Syst Simulation tools. Examination with the PVGIS Simulation, the maximum solar radiation potential at the campus is attained in May, which is 202 kWh/m^2 and next highest in April, i.e., 199 kWh/m^2. The minimum potential is detected in December, i.e.124 kWh/m^2. In the PV Watt simulation tool, maximum solar radiation potential is observed in March i.e., 205.38 kWh/m^2 and followed in April, i.e., 197.8 kWh/m^2. The minimum potential is studied in July, i.e., 142.6 kWh/m^2. Finally, in the PV Syst simulation tool, the maximum solar radiation potential of 190 kWh/m^2 is achieved in April. The minimum potential of 137 kWh/m^2 is observed in December. The monthly solar irradiation at the location is presented in Fig. 3. It is observed that the solar irradiation is high during March to May and minimum in December in all the tools.

The peak DC output power of 154,08 MWh produced in May for solar irradiation of 202 kWh/m^2 in PVGIS, 148,278 MWh generated in March for solar irradiation of 187 kWh/m^2 in PV watts and 172,76 MWh during March in PV Syst for 190,4 kWh/m^2 solar irradiation. The DC power output of the solar power plant is shown in Fig. 4(a). From the simulation study, the AC output of PV energy is estimated as 151 MWh in May using the PVGIS tool. In PVWatts, the annual energy production is maximum in March, i.e., 142.24 MWh and using the PV Syst tool the estimated AC energy is 169.306 MWh.

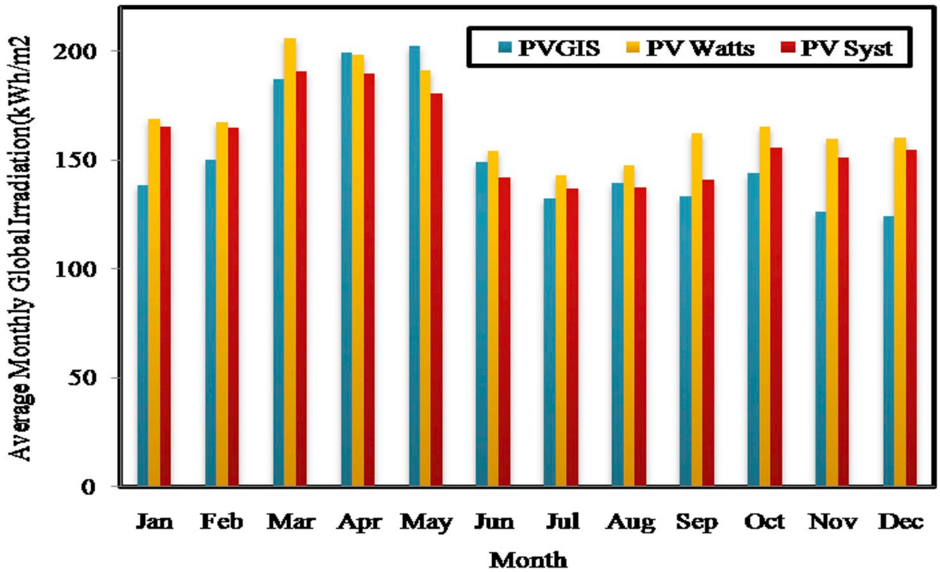

Fig. 3. Monthly solar radiation at the location.

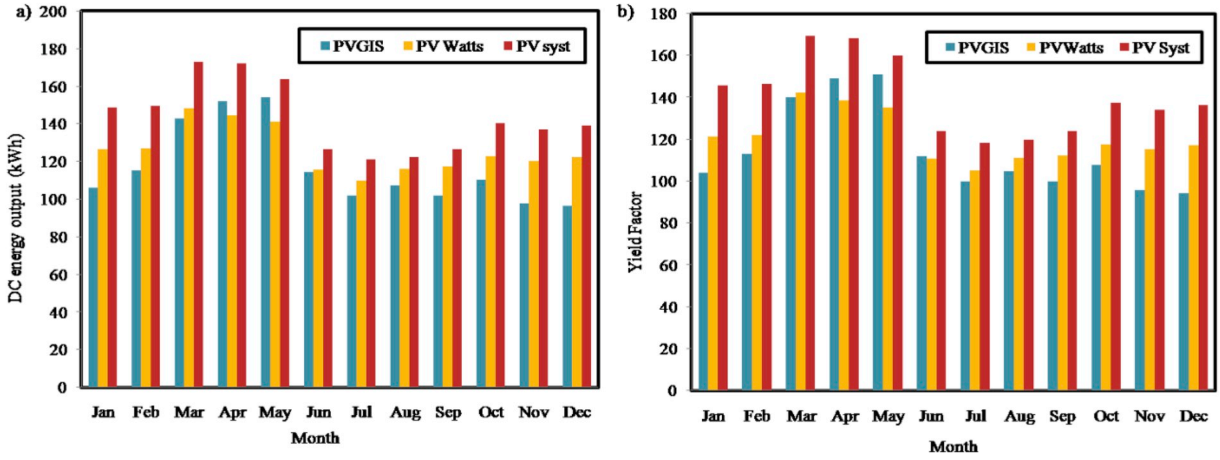

Fig. 4. (a). Monthly DC Energy Output (b) Yield Factor of installed solar PV plant

Table 5
Monthly PV energy output.

Month& Year	Measured power (MWh)	Simulated energy output		
		PVGIS (MWh)	PV Watts (MWh)	PV Syst (MWh)
Oct 2018	123.06	104	121.258	145.869
Nov 2018	117.46	113	122.005	146.384
Dec 2018	98.18	140	142.243	169.306
Jan 2019	116.36	149	138.782	168.52
Feb 2019	120.62	151	135.385	160.24
Mar 2019	131.62	112	110.875	123.915
Apr 2019	127.52	100	105.191	118.537
May 2019	128.38	105	111.27	119.807
Jun 2019	101.61	100	112.349	124.151
Jul 2019	91.13	108	117.768	137.67
Aug 2019	90.34	95.7	115.526	134.112
Sep 2019	79.14	94.4	117.264	136.37

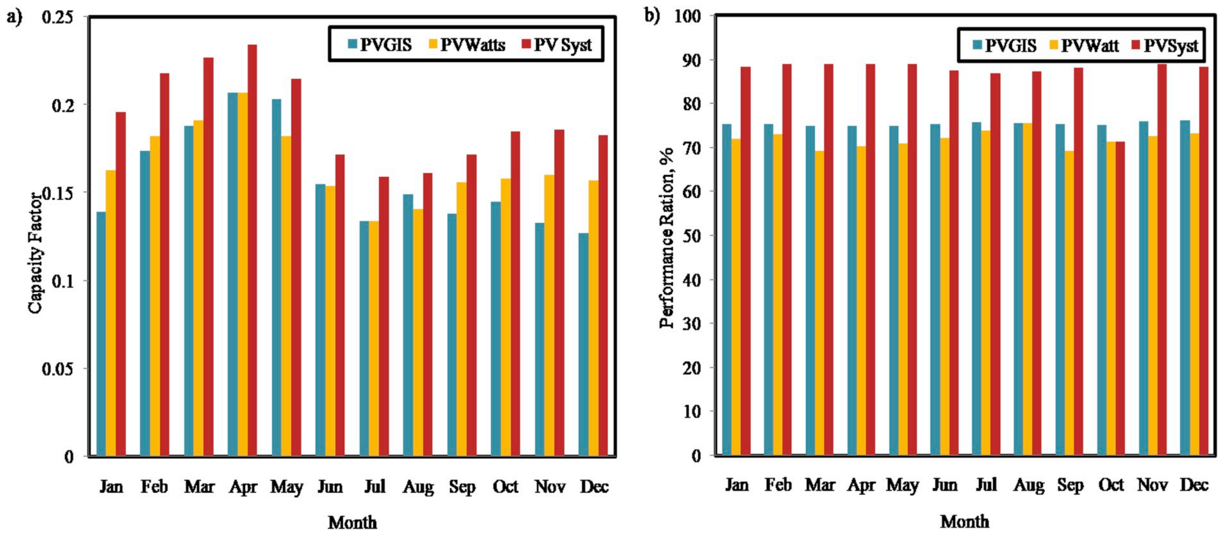

Fig. 5. (a). Capacity factor of 1 MW solar PV plant (b) Performance Ratio of the solar PV plant.

Table 6
Comparison of technical performance.

Technical Parameters	PVGIS	PV Watts	PV Syst
Yearly in plane solar irradiation (kWh/m^2)	1823	2020.565	1907.4
Annual average energy generation (kWh/year)	13,72,100	14,49,916	16,84,881
Yield factor (kWh/year/kWp)	1372.1	1449.916	1684.881
Capacity factor (%)	20.8	23.06	21.77

Table 7
Monthly MBE and NMBE for energy by PVGIS, PV watts, and PV Syst.

Month and Year	PVGIS		PV Watts		PV Syst	
	% MBE	% NMBE	% MBE	% NMBE	% MBE	% NMBE
Oct 2018	−15.48%	−14.48%	−1.46%	−1.37%	18.54%	17.33%
Nov 2018	−3.81%	−3.40%	3.86%	3.44%	24.6%	21.96%
Dec 2018	42.59%	31.77%	44.88%	33.48%	72.44%	54.04%
Jan 2019	28.05%	24.79%	19.26%	17.03%	44.82%	39.63%
Feb 2019	25.18%	23.08%	12.24%	11.22%	32.84%	30.10%
Mar 2019	−14.90%	−14.90%	−15.76%	−15.76%	−5.85%	−5.85%
Apr 2019	−21.58%	−20.91%	−17.51%	−16.96%	−7.04%	−6.82%
May 2019	−18.21%	−17.76%	−13.32%	−12.99%	−6.67%	−6.51%
Jun 2019	−1.59%	−1.22%	10.56%	8.16%	22.18%	17.12%
Jul 2019	18.51%	12.82%	29.23%	20.24%	51.06%	35.36%
Aug 2019	5.93%	4.07%	27.88%	19.14%	48.45%	33.26%
Sep 2019	19.28%	11.59%	48.17%	28.96%	72.31%	43.48%

Table 8
Performance Comparison with existing literature.

Location	PV technology	Plant Capacity	Annual energy (kWh)	Yield Factor (kWh/kWp)	Capacity factor	Reference
UMP Pekan and Gambang, Malaysia	Crystalline silicon	1MWp	13,90,000	1390	15.86%	[12]
Baghdad, Iraq	Poly Crystalline silicon	1MWp	17,57,000	1757	19.83%	[16]
Ghana	Poly Crystalline silicon	1MWp	11,59,000	1163	13.2%	[11]
Algeria	Mono Crystalline silicon	1MWp	13,90,000	1390	15.8%	[25]
Rushikonda, India	Poly Crystalline silicon	1MWp	16,84,881	1684	21.77%	This study

The measured monthly energy outputs of the solar PV plant, along with the estimated values using the software tools, are presented in Table 5. Peak energy generation of 131.62 MWh is observed from monitored data in March month. The energy output during the monitored period from October 2018 to September 2019 is observed to be 1325.42 MWh. But when the monitored data is compared with the simulated energy values, a deviation of 7–12% is observed between PVGIS/PV Watt, 8–15% between PVGIS/PV Syst, 8–15% deviation between PV Watt/PV Syst tool. The highest yield factor of 169.3016 kWh/kWp occurred in March in the PV Syst tool. PVGIS tool exhibited a high yield factor of 151 kWh/kWp in May, and PV Watts showed its highest value of 142.243 kWh/kWp in March as shown in Fig. 4(b).

The values of capacity factor and performance ratio of the PV plant are shown in Fig. 5(a–b). The PV Syst tool showed the highest capacity factor of 0.234 during April for the installed solar PV plant. PVGIS and PV Watt tools exhibited a similar capacity factor of 0.207 in April. The performance ratio of the installed 1 MW plant is around 86%–88% during a year in PV Syst, whereas the PVGIS tool generated a PR of almost 75%. However, the PV Watts resulted in a variable PR of 69%–75%. The brief comparison between the different performance parameters from the simulation study is highlighted in Table 6.

To explore the differences between the measured and estimated values of monthly energy generated, the mean bias errors and the normalized mean bias errors are evaluated and checked for all the three software tools. The 1 MW solar PV plant started energy generation from October 2018. Hence the values of energy are observed from October 2018 to September 2019 from the data monitoring system to estimate the error values. From Table.7, it is noted that the MBE and NMBE from March to May are negative. This indicates that all three software models under-estimated the energy injected into the grid. The yearly average MBE of 5.33% (PVGIS), 12.33% (PV Watts), and 30.64% (PV Syst) are observed. Similarly, the yearly average NMBE of 2.954% (PVGIS), 7.88% (PV watts) and 22.75% (PV Syst) are noted. It is observed that during December, January and February NMBE has the highest value. Further, the NMBE values are extreme for the PV Syst tool due to high estimation energy values.

Few current researches worked on similar installed peak capacity are considered from the literature for comparison. The comparison with existing literature is made by considering the parameters like annual energy, yield factor, and capacity factor, and shown in Table 8.

6. Conclusion

This article outlines the operational performance of a 1 MWp grid integrated roof-top solar PV plant installed in the University campus under tropical wet and dry climates of India. The energy generation from the installed solar PV plant is monitored for 12 months. In addition to real-time monitoring, the energy analysis of the plant is simulated using three different tools and then a comparison is made. These simulation tools will assist in the analysis of solar PV projects, feasibility of the solar plant estimation before installation, long term performance predictions, and energy estimations. After a detailed case study, the following conclusions are made:

- The predicted energy from the solar PV plant using the three simulation tools is ranging from 118 MWh to 170 MWh per month based on solar radiation.
- Annual energy generation at the present location of the solar PV plant is reported as 1325.42 MWh from the monitored database.
- The installed plant can produce average annual energy of 1684.881 MWh as per the PV Syst tool. Also, from the comparative simulation study, PV Syst showed better energy yields and PR.
- The performance ratio of the solar PV plant is around 88%, and it is observed that from the estimated values, the solar plant can cover approximately 20% of the annual energy consumption of the campus.
- From the comparative study, it is observed that the yearly average MBE varies as 5.33% (PVGIS), 12.33% (PV Watts), and 30.64% (PV Syst) and the average NMBE varies as 2.954% (PVGIS), 7.88% (PV watts) and 22.75% (PV Syst).

Declaration of competing interest

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

CRediT authorship contribution statement

Sandhya Thotakura: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Visualization, Writing - original draft, Writing - review & editing. **Sri Chandan Kondamudi:** Conceptualization, Visualization. **J. Francis Xavier:** Data curation, Writing - review & editing. **Ma Quanjin:** Data curation. **Guduru Ramakrishna Reddy:** Data curation, Writing - review & editing. **Pavan Gangwar:** Formal analysis, Methodology, Software, Writing - review & editing. **Sri Lakshmi Davuluri:** Formal analysis, Methodology, Software, Visualization.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.csite.2020.100602.

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