



Analysis on Large-Scale Solar PV Plant Energy Performance–Loss–Degradation in Coastal Climates of India

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This article presents a detailed analysis of the performance, rate of degradation, and power and energy loss of a 1 MWp scale solar photovoltaic (PV) plant in the academic institution GITAM (Deemed to be University), located in the coastal region of Andhra Pradesh, India. The PV plant consists of 3,078 polycrystalline PV modules of 325 Wp rating, installed on the rooftop of the institute buildings. The annual energy generated is 1684.881 MWh. In this study, performance analysis involves the calculation of efficiency, capacity factor, and performance ratio with data simulated using the PVsyst tool. Degradation analysis involves energy light-induced degradation (LID) and degradation rate (DR). The predicted result provides an estimate for optimal functioning of PV plant with an annual capacity factor, performance ratio, and energy loss of 11.3%, 87.9%, and –26%, respectively. Energy loss by light-induced degradation is predicted as –2.7%/year, and the degradation rate of module per year is –0.6% to –5%.

Keywords: photovoltaic, performance parameters, energy loss, degradation rate, PV SYST

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INTRODUCTION

The focus on increasing renewable resources has become one of the crucial methods to overcome the scarcity of electricity after the depletion of traditional energy sources and reduce atmospheric issues by utilizing fossil fuels. Decommissioning and dismantling conventional energy plants such as nuclear and thermal are implemented worldwide. Solar power, biomass, and hydropower are all excellent sources of renewable energy. The total installed capacity is 378.43 GW as of 31.10.2020 in India. Among this electricity mix, renewable energy sources contribute 36.2% (according to a report on load generation 2019–2020 by the Ministry of Power, Government of India, listed on its website: <https://powermin.gov.in/en/content/power-sector-glance-all-india>). The power generating capacity has to be increased to reach peak energy demand. Owing to the several advantages of solar energy resources over the other non-conventional sources, solar energy can increase the electricity generation capacity. The benefits of employing solar energy resources are abundant: eco-friendliness, decreased tariff, less maintenance, and reliability (Thapar et al., 2018). Research presented the initiative policies made by the government of India on encouraging grid-connected roof-top photovoltaic (PV) systems and off-grid systems.

The research by Subramaniyan et al. (2018) discussed the contribution of non-conventional resources such as solar and wind power and the estimation of these resources with a peak period technique in Rajasthan. In the study presented by Rodrigues et al. (2019), feasibility analysis to install

a grid-connected PV plant to the state university of Campinas is estimated using two simulation tools, one of which is PVsystV6 and the other is Helioscope. The performance rate of the proposed plant is about 81.2 and 80.83% in PVsyst and Helioscope, respectively. In a performance study of a 100 kWp grid-connected solar PV system, the performance ratio (PR) is observed to be 80% using PVsyst V6.52 software (Kumar et al., 2017a). In the research conducted by Kumar and Sudhakar (2015) on a 10 MWp solar photovoltaic plant, the largest PV plant located at Ramagundem, the PR is observed to be 86.12% and capacity utilization factor (CUF). A performance study of PV systems situated in Eastern India exhibited a PR of 0.78, PV efficiency of 13.42%, and system efficiency of 12.05% (Sharma and Goel, 2017). In a performance analysis carried out by Yadav et al. (2015) on a 1 kWp PV system located in Hamirpur, the PR and average solar radiation are recorded as 0.724 and 4.4 kWh/m², respectively, on a specific day. In a degradation study conducted in the semi-arid climate on a c-si photovoltaic system for four years, the highest PR of 76.46% is spotted in the presentation (Kumar and Malvoni, 2019). In a performance analysis carried out by Kumar et al. (2016) on a 10 KW roof-top photovoltaic system, the capacity factor is noticed as 17.8%, 18.5%, and 19.3% with two crystalline silicon-type and one thin-film-type technology, respectively. In an article by Thotakura et al. (2020), research was carried out on the performance of 1 MW scale grid-tied roof-top solar PV plants in a coastal region in India having tropical wet and dry conditions. Real-time data are monitored and compared with PVGIS, PV Watts, and PVsyst software simulation tools. The megawatt plant's capacity factor is 21.77%, with an annual energy generation of 168.488 MWh.

The operational performance was analyzed by Sudhakar et al. (2021) on a 2 MWp solar plant in Kerala, India, and an average performance ratio and capacity utilization factor of 73.39 and 15.41% were stated. Because of the monsoon season, there is a reduction of 35% in energy generation, mainly due to cloudy and rainy weather conditions. Dahmoun et al. (2021), in their research, published the literature on the operational performance analysis of a grid-tied 23.92 MWp solar PV plant located in Algeria for a period of 36 months. They reported a 5.46 kWh/kWp/day of an annual average daily array, 4.95 kWh/kWp/day of final yield, 82.02% of PR, and 20.64% of CUF. The real-time data are compared with the PVsyst and solar GIS tools and found a strong coincidence. The article by Bansal et al. (2021) presented a study on a 5 MW grid-integrated solar PV plant installed with crystalline silicon modules investigated for seven years. The authors checked the degradation analysis and performance assessment in Gujarat, India, which has hot and dry climate. It is mentioned that, from 2013 to 2016, the yearly average PR, CUF, inverter efficiency, and PV system efficiency of 73%, 17–18%, 96%, and 10.29–10.415% are attained and during 2017–2019, the values are in the range of 70% of PR, CUF of 14–16%, respectively.

The study by Ameer et al. (2022) covered six-year working data of a 5.94 kWp PV system comprising 2.04 kWp polycrystalline, 2.04 kWp monocrystalline (m-Si), and 1.86 kWp amorphous (a-Si) technologies to estimate the

long-term performance and degradation rate for different climatic conditions of Ifrane, Morocco. Correlating with the present study technology, the polycrystalline system has a degradation rate of $0.36 \pm 0.01\%/year$ and $0.28 \pm 0.004\%/year$ with linear regression and classical seasonal decomposition statistical techniques and a performance ratio of 84.32%. In the literature (Makrides et al., 2010; Sharma et al., 2014; Sinha and Chandel, 2014; Gökmen et al., 2016; Kichou et al., 2016; Khandelwal and Shrivastava, 2017; Kumar et al., 2016; Kumar et al., 2017a; Kumar et al., 2017b; Jiang et al., 2016; Dubey et al., 2017; Sharma and Goel, 2017; Vasita et al., 2017; Atluri et al., 2018; Bhullar and Lalwani, 2018; Kichou et al., 2018; Prakhya and Reddy, 2018; Sudhakar and Samykan, 2018; Kumar N. et al., 2019; Kumar and Subathra, 2019; Navothna et al., 2020; Aoun, 2020; Thapar and Sharma, 2020), the researchers addressed about the performance factors, losses, and efficiency of solar PV plants located in various climatic regions. Few authors adopted simulation tools PVGIS, PV Watts, and PVsyst to compare with the monitored data. However, this kind of exploration is site specific, as various factors influence the technical activity of the solar PV plant of the region in which it is located. This analysis has not been carried out in the present study location (coastal region, Visakhapatnam, India) to the best of the authors' knowledge.

In the present study, the analysis of grid-connected PV systems near coastal areas is evaluated using the PVsyst simulation tool. Analyzing performance parameters is also essential to improve the solar photovoltaic system installations. Hence, the following are the present study's goals:

- To model and comprehend the operation of a roof-top grid-connected PV system installed on the rooftops of an educational institution Gandhi Institute of Technology and Management, Visakhapatnam, Andhra Pradesh, India
- To comprehend the energy conversion process and explore the various energy losses of roof-top polycrystalline solar PV systems built in the coastal region
- Degradation estimation of the photovoltaic plant

In the present study, performance specifications are identified, which are helpful for the feasibility analysis of the solar PV system in coastal areas. The results obtained from this study will create awareness of the potential of such a system being used to control the problem of energy scarcity and increase the use of non-conventional energy sources in various parts of the world. The developing countries can be global leaders in utilizing these sources.

SYSTEM DESCRIPTION

In the present study, a 1 MWp roof-top solar photovoltaic power plant connected to the grid was assembled on an educational Institute, Gandhi Institute of Technology and Management, Vishakhapatnam, located in the coastal region of Andhra Pradesh, India, is discussed. The plant consists of 23 PV arrays

installed at 15 building terraces and 23 inverters with a capacity of 20 kWp/50 kWp. The plant is located in latitude $17^{\circ} 48' 8.208''$ N and longitude $83^{\circ} 23' 6.54''$ E. The detailed electrical specifications of the PV plant and the geometrical site map are provided in **Supplementary Data**.

FRAMEWORK AND METHODOLOGY

The performance study of the grid-connected PV system installed on the rooftops of academic buildings includes the normalized parameters that characterize the operating performance of the PV system. The parameters considered for the assessment in the present study location are array energy, net array energy output, array efficiency, grid energy, net energy output of PV system, system efficiency, capacity factor, performance ratio, loss, and degradation rate. The performance of this system can be compared to that of other PV systems under various working situations once these parameters have been determined. To predict and analyze the working of the PV system, the data related to the plant and selective simulation tools are required. The current study indicates the performance parameters of the solar plant located in a coastal area. The critical parameters and their equations for analysis are also furnished (Malvoni et al., 2017a). The methodology for the analysis is illustrated as follows:

- The critical data for the analysis of PV plants such as the geographical specification of the study location (coordinates, weather conditions, temperature, solar irradiation, and wind speed), PV module, and inverter specifications are accumulated.
- One of the most widely used PV system simulation tools is identified. In this study, PVsyst is preferred for the performance and irradiation analysis of the PV system.
- Performance parameters of the solar PV plant are studied in detail and presented with their equations. The energy and efficiency parameters are estimated.
- Degradation analysis of the solar PV plant is analyzed by mainly focusing on the light-induced degradation (LID) and degradation rate (DR).

PVsyst Software Tool

PVsyst software is one of the most widely used simulation tools in the design and calculation of basic considerations of photovoltaic systems PVsyst (2021). Modeling in PVsyst starts with system sizing, which comprises desired power rating or available area, PV module, and inverter sizing. Based on the given input specifications, the PVsyst will propose module configurations for further simulation study. This software updates weather details of the selected location, which helps in evaluating output parameters. PVsyst tool gives monthly global irradiance, diffuse irradiance, temperature, and wind speed of the selected location. Based on these data, the trajectory of the Sun, which provides information on losses that occur during period of a year, is also given. The results of the simulation tool include total energy produced, performance ratio, and specific

energy. By utilizing these results, energy yield, capacity factor, and efficiency of PV array and PV system can be calculated. The existing PV system behavior and further expansion of the system can be carried out Photovoltaic Software (2021).

Array Energy [E_{AE}]

It is the energy generated by a photovoltaic array. Array energy mainly depends on the area of the total array of the PV system [A_A], solar radiation [I_s] incident on PV modules, and the efficiency of the PV module [η_{PV}], how successfully it transforms solar energy into electrical energy. The area of the total array [A_A] of the PV system is calculated by considering the total number of PV modules multiplied by the area of individual modules. The extra space to accommodate the panels in specified orientation and between the strings is also added. The area used by the total arrays of the installed PV system is 12,000 m². Therefore, the array energy is expressed as a product of all the mentioned three parameters, as shown in the following equation:

$$E_{AE} = A_A \times I_s \times \eta_{PV}, kWh. \quad (1)$$

Net Array Energy Output [D_{EA}]

A solar array is a group of solar modules joined in series and parallel. Hence the net array energy output mainly depends on the area of the total arrays of the PV system, the efficiency of the PV module for the incident solar irradiation, and the full capacity of the solar PV plant. It is also expressed as the ratio of energy array to the entire plant capacity (PC), as shown in the following equation:

$$D_{EA} = \frac{E_{AE}}{PC}, kWh. \quad (2)$$

Array Efficiency [η_A]

Any system's efficiency is determined by the input it receives and the output it produces. The efficiency of an array is determined by the input, which is the solar irradiation dispersed across the entire array, and the generated output energy as expressed in the following equation:

$$\eta_A = \frac{E_{AE}}{A_A \times I_S} \times 100. \quad (3)$$

Grid Energy [E_{GE}]

The existing plant is an integrated grid system, the energy generated by the PV arrays is converted to AC and pumped into the grid *via* inverters. Solar energy generation depends on solar irradiation, and energy conversion depends on the inverter's performance and losses. Hence the grid energy is expressed in Eq. 4 as a product of array energy [E_{AE}], the efficiency of the inverter [η_{inv}], and loss efficiency [η_{LOSS}].

$$E_{GE} = E_{AE} \times \eta_{inv} \times \eta_{LOSS}, kWh. \quad (4)$$

Net Energy Output of the PV System [D_{EG}]

It is the solar PV system's net energy output, expressed as a ratio of energy injected into the grid to the capacity of the solar PV plant, as shown in the following equation:

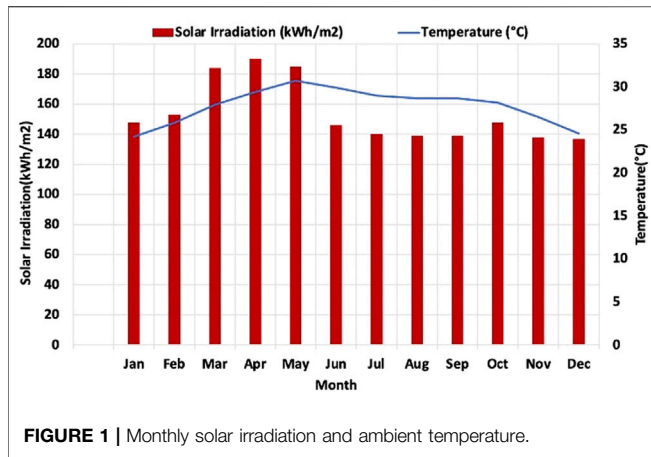


FIGURE 1 | Monthly solar irradiation and ambient temperature.

$$D_{EG} = \frac{E_{GE}}{PC}, kWh / kWp. \tag{5}$$

System Efficiency [η_{sys}]

A solar System’s efficiency is commonly defined as the ratio of solar energy input to electrical energy output. The system efficiency depends on many parameters, whereas here, it is declared as the ratio of grid energy [E_{GE}] to the solar irradiation [I_s] and the area of total PV arrays [A_A].

$$\eta_{sys} = \frac{E_{GE}}{A_A \times I_s} \times 100. \tag{6}$$

Capacity Factor [F_c]

The capacity factor can be defined as the actual electricity production divided by a power plant’s maximum feasible electrical output over some time, as shown in the following equation:

$$F_c = \frac{D_{EG}}{OH} \times 100. \tag{7}$$

Performance Ratio [PR]

The performance ratio (PR) is a frequently used term for assessing the relative performance of solar panels with different designs, technologies, capacities, and locations. PR is calculated using Eq. 8, where it is expressed as a percentage ratio of net grid energy output [D_{EG}] to the reference energy yield [Y_R].

$$PR = \frac{D_{EG}}{Y_R} \times 100. \tag{8}$$

Loss and Degradation Rate [DR]

Loss and degradation rate are the two essential parameters for analyzing the performance of PV systems. In a survey conducted by the National Centre for PV Research and Education at the Indian Institute of Technology,

Bombay, and National Institute of Solar Energy, Haryana, it is assumed that the deterioration in crystalline silicon modules would vary from -0.6 to -5% /year (Dubey et al., 2016; Dubey et al., 2017). The mathematical equation for degradation rate can be expressed as (Kumar et al., 2019)

$$\%DR = \frac{12 \cdot m}{c} \times 100, \tag{9}$$

where m: slope and c: intercept. These values are considered for the present study directly from the literature (Kumar N. M. et al., 2019).

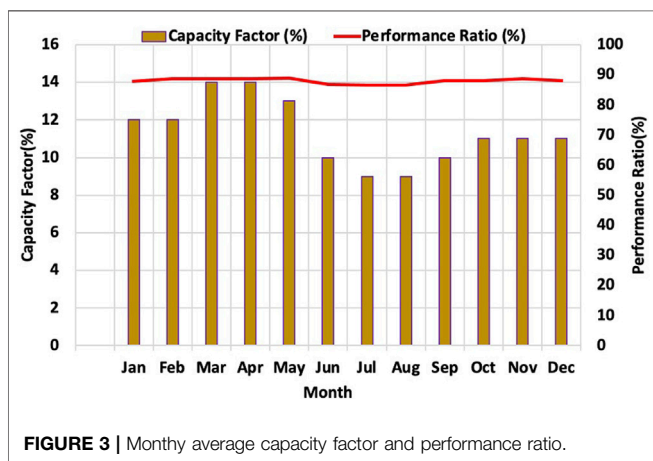
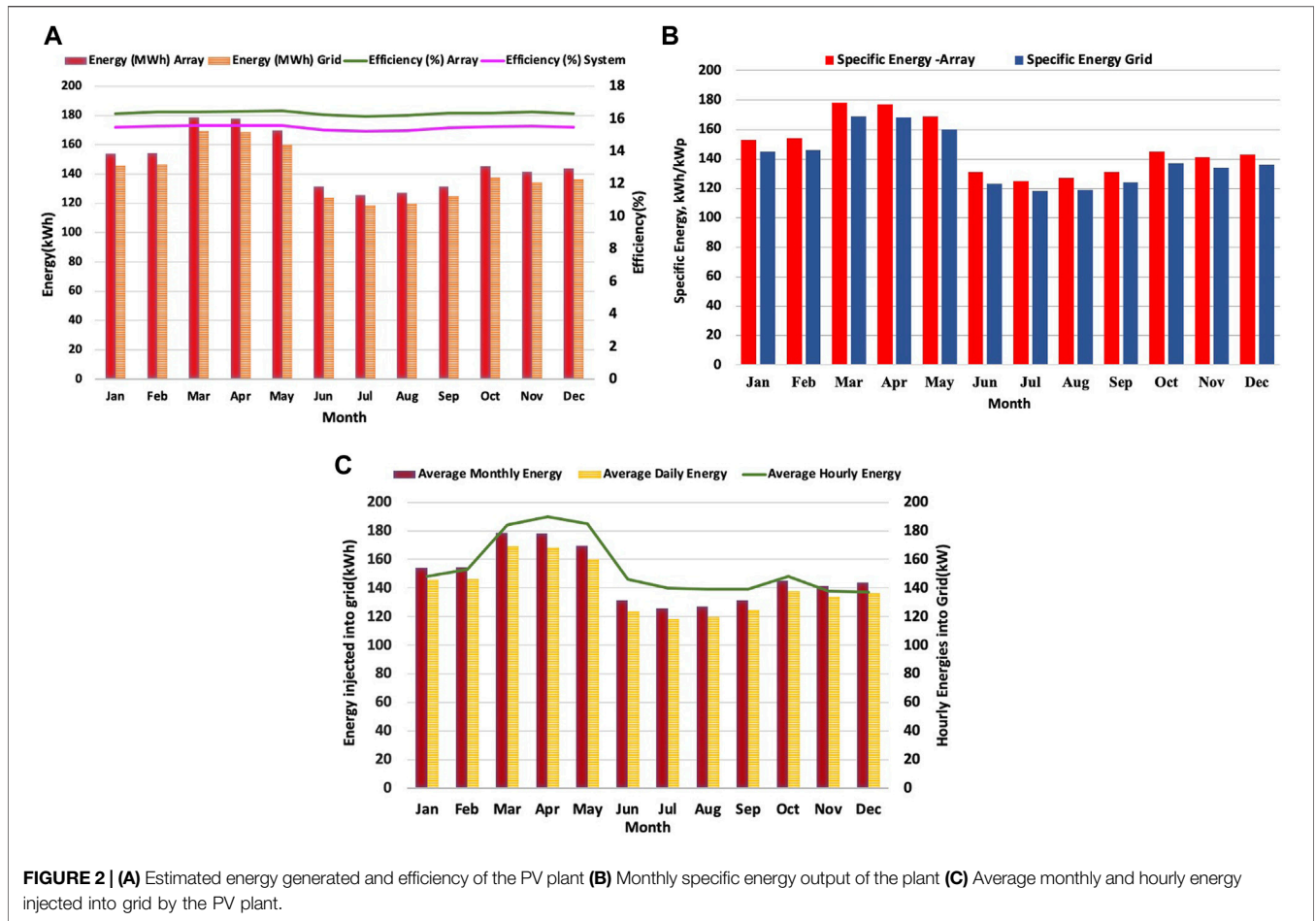
RESULTS AND DISCUSSION

Analysis of Solar Radiation and Ambient Temperature

The solar irradiation and ambient air temperature of the study location from January 2020 to December 2020 are shown in Figure 1. Monthly solar irradiation and ambient temperature are obtained for analysis from the PVsyst simulation software tool. The annual average horizontal global solar irradiation is observed as 153.91 kWh/m^2 . The maximum Sun irradiation of 190 kWh/m^2 is recorded in April, and the lowest in December, with 137 kWh/m^2 . The maximum ambient temperature is in May at 30.7°C and the minimum in December at 24.6°C .

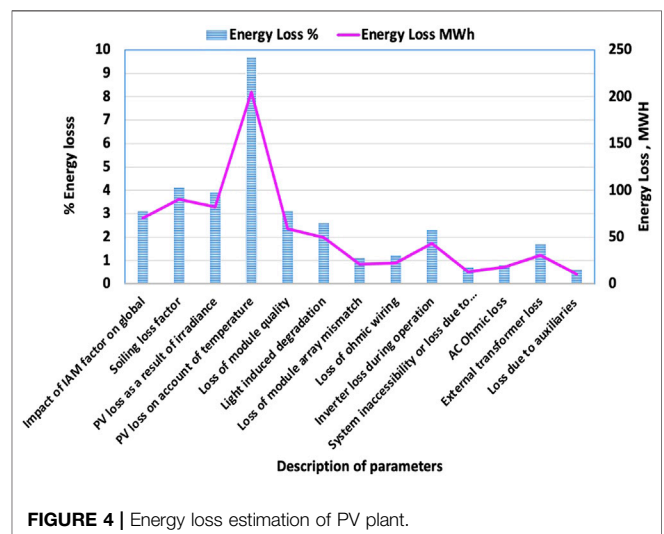
Energy Analysis

Figure 2A presents the estimated energy yields and energy given to the grid of the PV system. The total amount of energy generated from the PV system is 1780.878 MWh . The PV system yield ranges between 118.537 MWh in July and 178.499 MWh in March. Each year, the total quantity of AC energy put into the grid is about 1684.881 MWh . In July, the AC energy output was 118.537 MWh , while in March, it was 169.306 MWh . It is observed that the difference between DC and AC energy yields is caused by energy loss. This energy loss is due to module temperatures and various system constituents (Sharma and Goel, 2017). The PV system’s average efficiency in each month is estimated and shown in Figure 2A for extensive examination of PV system performance. The average annual efficiency of the total system is 16.3% , whereas the array efficiency varies between 16.24% (July) to 16.48% (May). In Figure 2B, the variation of specific energy over 1 year is presented. The total yearly electricity yielded from the PV system was 1774 kWh/kWp . The least and maximum possible monthly definite energy predicted are 125 kWh/kWp in July and 178 kWh/kWp in March, respectively. The total yearly energy at grid end is 1679 kWh/kWp , with a minimum monthly specific energy of 118 kWh/kWp predicted in July and a maximum of 169 kWh/kWp in March. The total annual energy delivered into the grid is estimated to be around 1684.881 MWh , with a minimum of $3,823 \text{ kWh}$ anticipated in July and a maximum of $5,617 \text{ kWh}$ during April. The average amount of energy injected every hour into the grid is forecasted to be 159 kWh in July and 234 kWh in April, which are presented in Figure 2C.



Capacity Factor (F_c) and Performance Ratio (PR)

The two key performance indicators of the PV system are capacity factor and performance ratio. The yearly average capacity factor was 11.3%, with the least forecasted value of 9% in August and a peak



forecasted value of 14% in March. The average annual performance ratio was 87.96%, with the least indicated with a value of 86.51% in July and peak forecasted with 88.79% in May. **Figure 3** displays the F_c and

TABLE 1 | Performance correlation with existing roof-top PV plants.

Location	Solar plant capacity	Energy (MWh)	F _c (%)	PR (%)	Energy loss (%)	References
Kerman	11 kWp	-	23.81	82.92	-	Edalati et al. (2015)
Hoon City	14 MWp	24,964	-	76.9	-	Kagilik and Tawel (2015)
Hamirpur	100 kWp	01.36	15.40	72.4	32.0	Ramoliya (2015)
Hyderabad	100 kWp	161.60	18.44	80	20.0	Dubey et al. (2016)
Southern Italy	960 kWp	1262.10	15.60	84.4	26.1	Malvoni et al. (2017b)
Chandigarh	200 kWp	292.9	16.70	77.3	26.5	Kumar et al. (2017b)
Ahmedabad	~150 kWp	150.79	-	75.1–82.5	-	Vasita et al. (2017)
Bhubaneswar	~100 kWp	14.96	-	78	-	Sharma and Goel (2017)
South America	27 kWp	37	15.5	74.5	-	Raghoebarsing and Kalpoe (2017)
Haryana	50 kWp	-	-	87	-	Berwal et al. (2017)
Gujarat	25 MWp	50,091	22.80	80.1	-	Bhullar and Lalwani (2018)
Brazil	7.82 MWp	82.7	-	81.2	-	Rodrigues et al. (2019)
Tamil Nadu	83 kWp	5.499	-	52	-	Aravindan et al. (2019)
Palestine	7.68 kWp	-	-	76	-	Ibrik and Hashaika (2019)
Odisha	100 kWp	-	16.17	80	-	Mohanty (2020)
Manisa, Turkey	30 kWp	45.59	17.35	83.61	-	Ates and Singh (2021)
Tamil Nadu	5.00 kWp	7.144	16.31	76.83	-	Duraivelu and Elumalai (2021)
Saudi Arabia	467 kWp	-	15–18	80–86	-	Minai et al. (2022)
Vishakhapatnam	1.00 MWp	1684.81	11.33	87.9	26.0	Present study, 2022

PR of the PV plant. Even though the capacity utilization factor and performance ratio both depends on the energy yield of the solar PV system, there are other individual parameters that each of them depends on. Capacity factor also depends on the operating time of the PV plant, whereas performance ratio is proportional to reference energy yield, which makes the difference in their final values.

Loss Analysis

In this section, the energy losses are evaluated in a 1 MW roof-top connected PV system over 12 months using a PV system modeling technique and are presented in **Figure 4**. The energy loss varies from -0.7% (-12900.311 kWh) to -9.7% (-204877.98 kWh). The minimum foreseen worth is because of auxiliaries (-0.6%), system inaccessibility (-0.7%), and from the side of the electrical converter, there are losses in the AC resistance unit (0.7%). The temperature was the source of the greatest anticipated energy loss (9.7%). Nonetheless, the loss in energy due to solar irradiance levels on the PV module (3.9%), module quality loss (-3.1%), and light-induced deterioration are all significant (2.6%), and also the electrical converter operational loss (-2.3%) is additionally limiting the effectiveness of the PV system. The total energy losses are estimated as 715.76 MWh, with a total energy loss of 34.9%.

Degradation Analysis

The loss in the performance of the solar modules due to exposure to sunlight is named light-induced degradation (LID). Accurate measurement of power loss over time is marked as degradation rate (DR), where these two parameters play as vital performance indicators of a PV system. The observations show a LID of -2.7%, which accounts for the energy loss value of -49,588.921 kWh/year for the PV system. Estimated energy loss because of the degradation rate within 1 MW crystalline PV plant ranges from -10,689.3 to -89,099.5 kWh/year, respectively.

Correlation With the Present-Day Literature

The forecasted parameter in this study is equated with different PV systems based on the given performance information in their literature. The findings of this investigation appear to be consistent with those of previous studies, as shown in **Table 1**. This study helps the investors and researchers function of PV plants in the coastal areas.

CONCLUSION

The present case study involves a detailed analysis of the performance of a 1 MW power solar PV plant for coastal weather conditions in Visakhapatnam, India, mainly using the energy outputs, losses, and degradation rate. As per the weather conditions of the location, the following observations are made:

- The annual average horizontal global solar irradiation at the present study location is recorded as 153.91 kWh/m², with maximum sun irradiation of 190 kWh/m² in April and the lowest value of 137 kWh/m² during December
- The total energy generation from the 1 MW power plant is estimated as 1780.878 MWh
- Each year, the AC energy injected into the grid is 1684.881 MWh
- The average annual efficiency of the entire plant is approximated as 16.3%, whereas the PV array efficiency may vary between 16.24 and 16.48%
- The yearly average capacity factor of the solar PV plant is around 11.3%
- With the polycrystalline panels, the 1 MW power PV plant operates with the PR% of 87.9%, with the highest PR value of 88.79% in May due to the highest solar irradiation during the summer season
- The energy losses are -26%
- Under these climatic circumstances, the degradation rate of a photovoltaic array is between -0.6 and -5% every year

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

Conceptualization, writing—review and editing, and supervision: ST; data curation, formal analysis, investigation, and writing: BN.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenrg.2022.857948/full#supplementary-material>

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NOMENCLATURE

PV Photovoltaic

LID Light-induced degradation

DR Degradation rate

E_{AE} Array energy (kWh)

A_A Array area of PV system (m²)

I_S Incident solar radiation on the surface (kWh/m²)

η_{pv} Efficiency of the PV module (%)

D_{EA} Net array energy output (kWh)

PC Plant capacity (kWh)

η_A Array efficiency (%)

E_{GE} Grid energy (kWh)

η_{inv} Inverter efficiency (%)

η_{LOSS} Loss efficiency (%)

D_{EG} Net energy output of PV system (kWh)

F_c Capacity factor (%)

OH Operating hours (h)

PR Performance ratio (%)

Y_R Reference energy yield (h/d)