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Technical Note

Thermodynamic investigations on 227 kW_p industrial rooftop power plant

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ABSTRACT

With the growing demand of energy along with scarcity of natural resources and drastic fluctuations of the climate change implications, there has been a constant effort of mankind to switch towards renewable energy sources. Among various renewable energy systems, solar photovoltaics (SPV) has emerged out as an evident choice for the range of applications from commercial to residential end users. The performance of the SPV power system needs to be monitored, so that the plant can be operated efficiently and maximum electrical output can be generated out of it. For performance assessment, capacity utilisation factor (CUF) has been considered the parameter for monitoring of the SPV power plant. CUF is monitored for the industrial roof top SPV power plant and compared with the other CUF data available in the literature. In the present work, an effort has been made to monitor the CUF parameters, performance ratio (PR) and energy generation units for a 227kW_p SPV industrial rooftop power plant. It has been found that due to certain losses, the CUF is found to be lower than the ability of the system. The various technical causes of low CUF along with their remedial actions are proposed in view of improving CUF and overall efficiency of the system.

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INTRODUCTION

The continuous efforts by various stake holders from government to end users are making SPV technology viable and most popular. Considering the future energy demand, Government of India has taken very ambitious target of 100 GW solar photovoltaic capacity additions. Additionally, industrial users are also encouraged for the Solar PV applications via various policy interventions over the last decades. In industries, SPV roof top has emerged out as one of the economically viable option, thereby eliminating the need of land procurement. The net-metering policy has further accelerated the industrial SPV capacity installation. The solar photovoltaic power plant consists of solar panels/modules along with electronic equipment viz. charge controller, inverter, maximum power point controller (MPPT), charge controller, battery etc. as balance of system.

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The SPV panels are made up of solar cells which generate electricity when exposed to solar radiations. The solar power plant with longer life and low maintenance requirements has emerged as one of the feasible alternatives for energy generation. Moreover, the need to combat global warming and climate changes makes it more reasonable to be installed. The Government of India in the Intended Nationally Determined Contributions (INDC) document submitted to United Nations Framework Convention on Climate Change (UNFCCC) have committed that 100 GW of solar PV capacity generation will be installed by 2022. This is a very striving target and has accelerated development in the Industrial/commercial rooftop installation. Additionally, the net metering policy has further accelerated towards industrial rooftop Solar PV plants set-ups. The India has greatest advantage of having almost 300 sun-days with average 800–900W/m^2 solar intensity which could lead it to one of the biggest solar power generation entity globally. The different areas in India receive 4–6.5 kWh/m^2/day. Many researchers have carried out research/experimental studies related to SPV power plant monitoring by CUF parametric evaluation. There have been studies in the past related to the power plant performance monitoring by CUF monitoring. Mondal et al. [1] carried out the long throughput analysis of a solar power system installed at Ireland and found the respective value of CUF as 10.1%. Further, Makrides et al. [2] proposed that the accurate evaluation of a SPV system is feasible only when the operational characteristics of the plant are studied in detail. Doolla and Banerjee [3] enunciated the significance of capacity utilization factor on the cost of electricity output generated in SPV plant.

Besides, the performance evaluation of 1.72kW rooftop grid connected solar power plant has been proposed by Ayompe et al. [4] and found the various parameters affecting the system performance. Diez-Mediavilla et al. [5] assessed the performance of PV plants with respect to its characteristic parameters, ambient temperature, tilt, tracking mechanism and other cable losses present in the system. The output investigations of 3 MW grid interactive solar power system in Karnataka (India) is done by Padamavathi and Daniel [6]. They found that the CUF of the plant as 15.69%. A comprehensive short-term performance and characteristics evaluation of SPV power system, on the basis of CUF parameters, has been proposed by Khatib et al. [7]. Mediavilla et al. [8] enunciated the CUF analysis of 2 kW_p installed SPV plant in Serbia and came out with the figure of 12.88%. Futhermore, Micheli et al. [9] emphasised on the fact that as the SPV plant operated at the conditions away from STC the various losses occur in the system.

The performance investigation of 5MW grid interactive SPV plant of Karnataka, is presented by Bharath Kumar and Bryegowde [10] and the CUF is found to be 19% with annual performance ratio of 67.36%. A 10 MW grid interactive SPV power system in southern India was analysed and it was found that the power plant CUF is 17.68% [11]. Adaramola [12] accentuated that CUF performance assessment is the key step to classify the true potential of SPV power generation plant. Kumar and Sudhakar [13] carried out the investigations of 10MW grid interactive SPV system in India. The performance evaluation carried out by Vasisht et al. [14] for 20 KW power plant installed in Indian Institute of Science have recorded that the power plant was generating an average daily output of nearly 80 kWh with average CUF of 16.5%. In addition to this, the temporal variations of CUF parameter of PV based solar power plant has been done by Chaudhar et al. [15] and found the impact of various climatic conditions on the chosen configuration.

For a large-scale solar power plant, Mauritania (15 MWp) study carried out by Elhadi Sidi et al. [16] depicted the CUF variation from 11.7% to 20.5%. A 11.2 kW grid interactive SPV plant in the Siksha 'O'Anusandhan University, Bhubaneswar has been studied and annual/monthly mean CUF of the SPV is observed as 15.27% by Sharma et al. [17]. The throughput assessment of a 2.2 KWp SPV plant installed at the State University of Ceara, Fortaleza, Brazil by Lima et al. [18] has revealed that from Jun'13 to May'14 revealed that average daily reference yield and final yield was found to be 5.6 h/day and 4.6h/day respectively. Performance ratio and CUF were found to be 82.9% and 19.2% respectively. The CUF variation observed during the studies carried out by Lima et al. [18] are 15.5% in April to 23.1% in September. The present work can further be extended by applying various evolutionary algorithm techniques [19–48] in order to get optimum design of industrial roof top power plant system.

In this paper, an effort has been made to analyse the CUF and PR of 227kW_p industrial rooftop SPV power plant located at Mohammadpur, Jharsa (Gurgaon) having latitude and longitude of 28.4595°N, 77.0266°E. Afterwards, the comparative analyses of CUF and PR parameters have been carried out in context with that of available literature. The lower operating parameters of SPV plant accounts for the various losses caused to society and environment, as the low performance leads towards the consumption of power available through grid. This will further add to the harmful emissions along with severe/hazardous environmental degradation. The experimental data taken for the plant from January, 2017–December, 2017 ref of range 55.5%–84.07%.

SPV PLANT DESCRIPTION

The SPV system chosen for performance evaluation/investigation has been located in Mohammadpur, Jharsa (Gurgaon) namely Amtek Ring Gear Limited as shown in **Figure 1**. The solar roof top power plant has been installed in the manufacturing unit based in Gurgaon (28.4595°N, 77.0266°E). The panels are installed on the inclined roof of the plant having tilt angle of 33° which is in line with the slope of the inclined roof. The total number of 874 panels

Figure 1. View of 227 kW installed roof top power plant.

Table 1. Parametric coefficients of installed SPV plant

Nominal Power	**260 W**
Nominal power voltage	30.5 V
Nominal power current	8.5 A
NOCT	45.7^{0}C
Temperature coefficient of V_{OC}	–0.27%/^{0}C
Temperature coefficient of I_{SC}	0.024%/^{0}C
Cell type	60 multi-crystalline silicon 3 strings of 20 cells with bypass diodes

(REC260 PE) are installed leading to power plant capacity of 227 kWp. **Figure 1** shows the top view of SPV power plant, which is connected to 4 inverters Delta model RPI M50A120, in view of DC to AC conversion of output voltage. The outcome from the inverter is being fed to the LT distribution panel of the industry. **Table 1** shows the various parameters of SPV modules along with construction details of cell/module structure.

SYSTEM MODELLING

To analyse the electrical performance of the present grid connected PV system, some parameters like array yield, final yield, reference yield, capture loss, system loss, performance ratio etc. are measured for the complete year i.e., January 2017- December 2017.

Power plant energy generation performance is being monitored by 2 major indicators.

Performance ratio (PR)

Performance ratio (PR) evaluates the efficiency of the PV system design. It helps to identify the losses occurring in the PV system due to various losses with respect to rated output. The losses can be explained as PV module temperature, inverter inefficiency, wiring mismatch, soiling/dust or component failure. The performance ratio may be defined as the actual AC unit generations with respect the PV rated performance at STC. It can also be defined as the Final yield divided by reference yield. [13]

It indicates the overall effect of losses on the rated output due to t is a dimensionless quantity. For a well-designed power plant, the performance ratio will be in the range of 0.7 to 0.8.

Capacity utilisation factor (CUF)

Capacity utilisation factor (CUF) is the final yield of the power plant to the theoretical maximum output of the power plant. [13]

$$CUF = \frac{\text{Final yield}}{8760 \times \text{installed capacity of the plant}}$$

The power plant of 100 kWp installed capacity with CUF 20%, will generate equivalent energy of 20 kW continuous operation power plants. CUF is absolute performance measurement indicator. Hence in the research paper, the CUF is monitored for an industrial rooftop power plants located at the mentioned site.

The International Electro Technical Commission (IEC) published the International standard IEC 61724 in 1998 which describes few parameters for evaluating the performance of the photovoltaic systems. This standard has been accorded by Bureau of Indian Standards (BIS) in 1998.

The efficiency of SPV system has been given below:

$$\eta_{en} = \frac{V_{mp} \times I_{mp}}{A \times E} \quad (1)$$

Here, A is the area of the module in m^2 and E is solar insolation in Wm^{-2}.

The SPV energy efficiency is a amount of its ability to interpret solar insolation into useful electric output where the electric output consists of the voltage/current from the SPV. The converting energy efficiency varies through the concentration of solar insolation. In addition, at the peak power magnitude, one can get the determined value of energy efficiency with in the SPV using peak current I_{mp} and voltage V_{mp} as shown in **Figure 2(a)** and **Figure 2(b)**.

$$P_{\max} = V_{oc} \times I_{sc} \times FF = V_{mp} \times I_{mp} \quad (2)$$

The fill factor can also be written as:

$$FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \quad (3)$$

Array yield:

It can be given as the ratio of output energy from SPV array for a specific time span with the power rated at standard test conditions. [4]

$$Y_a = \frac{E_{dc}}{P_{stc}} \quad (4)$$

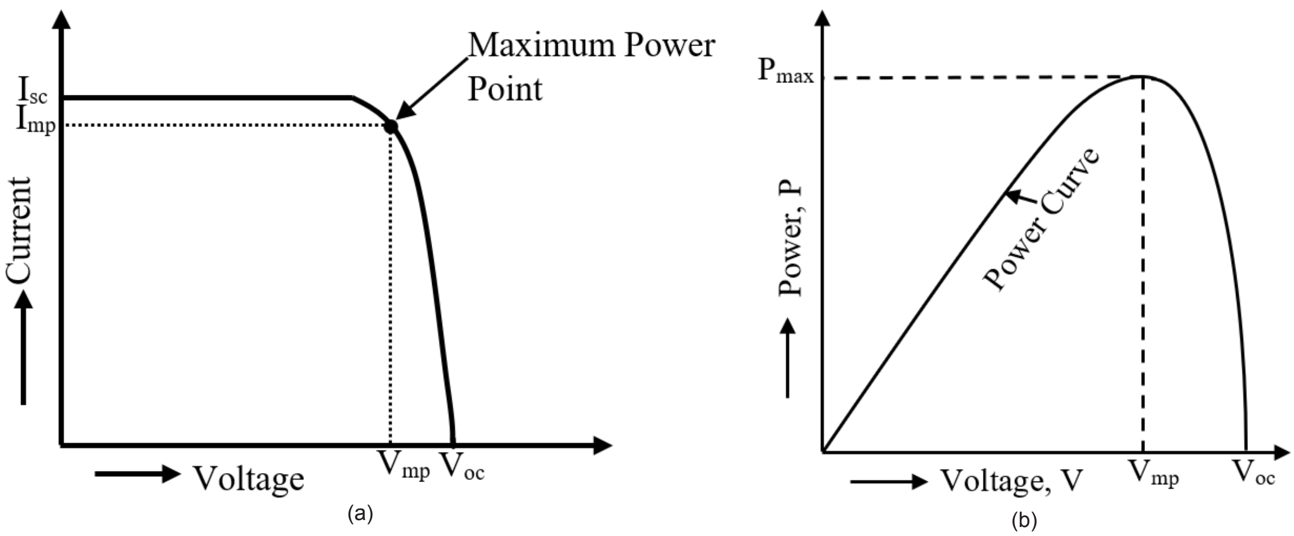

Figure 2. (a) I-V Characteristics. (b) P-V Characteristics.

STC condition refers to PV module operation at ambient temperature 25°C, solar Insolation 1000 W/m^2, 1 m/s wind speed and 1.15AM ratio.

Final yield (Y_f):

It is given as the ratio of net daily/monthly/annual AC output to the power rated of chosen PV system at standard test conditions. [4]

$$Y_f = \frac{E_{ac}}{P_{stc}} \tag{5}$$

Reference yield (Y_r):

This parameter can be given as the net daily solar irradiance to the reference insolation (Y_r). [4]

$$Y_r = \frac{H_t}{G} \tag{6}$$

It depicts the number of peak sun-hours per day (h/d) for SPV plant

Total Losses can be defined as the magnitude of difference amongst the parameters Y_r and Y_f.

$$L_t = Y_r - Y_f \tag{7}$$

Discussion of results

The modelling and analysis of chosen solar power system has been carried out using PVSYST software. The experimental data is collected for the duration of 12 months from January-December' 2017. Table 1 reflects the various parameters of the installed rooftop SPV system at the typical location of Gurgaon. It shows the magnitude of total number of energy units generated for hours rated for solar insolation with percentage CUF generation, Y_f, Y_r, L_t units. The CUF% is maximum for the month of April ie. 28621kWh, because of high input solar insolation. It is shown in **Figure 3** and **Figure 4** that, in this month CUF is maximum 17.5% but Performance ratio is on the lower side 61.53%, due to the difference in estimated and reference yield of the system. For the subsequent period of May-June the input solar insolation is quiet high but on the parallel side temperature also goes up. Due to this rise in temperature, the throughput of the system get degraded. The PR is on the lower side even below 60% for these two months. In May'18, Performance ratio is 55.51% and in Aug'17 is 57.96%. The lower performance ratio is due to various losses in SPV plant/system at elevated temperatures. The Y_f, Y_r shows the practical and reference yield of the system with the corresponding losses in the system. The annual average CUF has been recorded as 14.12% which is lower than the estimated one, as mentioned in available literature.

The CUF monthly variation has been found between 10.28 % in Jan'17 and 17.51% in Apr'17. Due to lower operating annual CUF, there is lesser generation of electrical energy. Hence there is loss to the environment and society as the lesser generation from PV system will in turn result in more generation from thermal power plants resulting in greater carbon dioxide emission. **Table 2** presents the amount of CO_2 generated due to difference in estimated and practical CUF and corresponding energy generated units. **Figure 5** represents the energy generation units for 227kW$_p$ SPV system for the complete year. Based on current experimental work, certain countermeasures are proposed for discounted throughput of SPV system. The major objective of the work is to improve CUF to 15.2% which will result in extra energy generation of 21459 KWh and avoiding 17.5 tons of carbon dioxide emission occurring from thermal power plants.

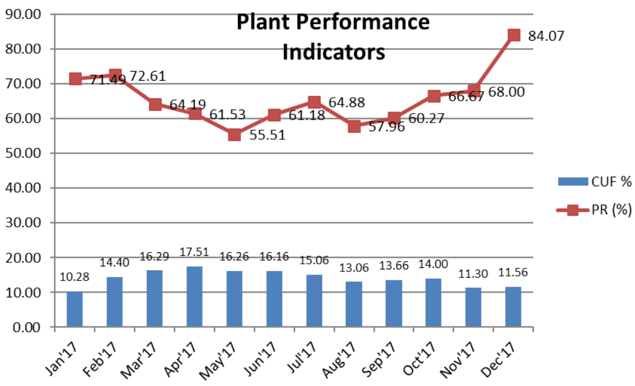

Figure 3. SPV system performance indicators across the year 2017.

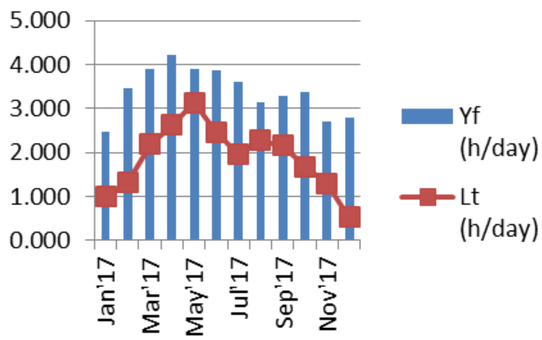

Figure 4. Observed values of final yield and solar insolation hours across the year 2017.

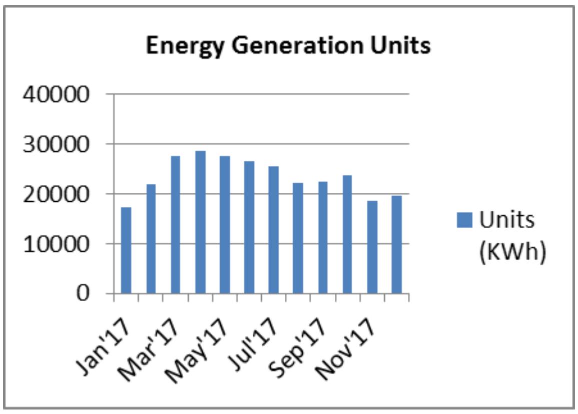

Figure 5. Observed energy generation units across the year 2017.

CONCLUSION

The major outcomes of the experimental study carried out can be summarized as below:

The system observes the maximum CUF of 17.5% for the month of April, 2017 while generating 28261kWh but due to the difference between estimated and practical yield of the system. Based on current analysis, following remedial solution have been proposed in order to increase the yield of the plant.

Table 2. 1 kWh electrical energy generation results in 0.82 kg of CO_2

Observed parameter (s)	Value (s)
Present CUF	14.12 %
Proposed CUF	15.20%
Present generation unit (kWh)	280796
Proposed generation (kWh)	302255
Extra energy generation (kWh)	21459
% increase in energy generation	7.6%
CO_2 emission avoided (kg)	17596

- The mounted panels should have air gap for ventilation and heat dissipation. This has resulted in lowest PR during summer season during month of May'17.
- This manufacturing unit is having heat treatment furnaces and the soot coming out from the ventilator gets deposited on the panel top which is very difficult to remove during regular cleaning. This deposition on one panel will affect the whole string. The unit was advised to divert the ventilator path.
- No maintenance checks are being performed on SPV power plant components other than cleaning of SPV panel top once in a week.
- The reference CUF is found to be 10 % (refer Fig. 3), hence, the percentage change of proposed CUF is observed to be 52%.

The system installation with the above stated remedies can lead it towards the better performance output.

NOMENCLATURE

E_{ac}	Output energy (AC), kWh
E_{dc}	Output energy (DC), kWh
P_{stc}	DC energy output under STC condition
G	Solar insolation, kW/m^2
H_t	Total mean daily in-plane solar insolation, kWh/m^2/day
PR	Performance ratio
Y_r	Reference yield
Y_a	Array yield
Y_f	Final yield
INDC	Intended Nationally Determined Contributions (INDC)
UNFCCC	United Nations Framework Convention on Climate Change (UNFCCC)

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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