

An Optimization Approach to Enhance Performance of a Solar PV System based on Performance Assessment of an Existing 5 MW On-grid PV System

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Abstract

This research article examines the performance assessment of a pre-existing 5 MW grid-connected utility-scale solar PV plant situated in EMC Naini, Prayagraj district of Uttar Pradesh. The various performance metrics viz, yearly energy generated, performance ratio, grid-injected energy, reference yield and system losses etc. are analyzed using PVsyst software for one year data collected between January 2022 and December 2022. The decision support tool PVsyst software generates the various technical performance characteristics, energy loss diagram and annual energy generated output. The total annually generated energy from PVsyst software was 7758.8 MWh with annual performance ratio of 67.9 % with existing components of solar PV system. The energy generated from real time SCADA monitoring system was 7064.805 MWh with performance ratio of 65.74% annually which was closely matched with PVsyst, but PVsyst can provide valuable insights and optimization options to optimize a solar PV plant. In this paper, Tabu Search (TS) optimization and Particle Swarm Optimization (PSO) design approach to enhance performance of solar PV system is also proposed for a fixed site and location. The design procedure includes three objectives: maximization of energy captured from solar PV plant, maximization of financial benefits and minimization of payback time period and concludes that the proposed design approach with PSO algorithm provides more efficient outcomes with respect to these three objectives.

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Keywords: SCADA; PVsyst; solar PV system; Tabu Search (TS) Optimization; Particle Swarm Optimization (PSO)

1. Introduction

Energy is undoubtedly one of the most crucial and fundamental factors for the growth of any country's economic system. Industry's over use of energy resources results in air pollution, which harms the environment. The management of energy resources and the protection of the environment are the most significant challenges of the 21st century. In order to combat climate change, it is crucial to adopt energy sources that are more environmentally friendly. Therefore, future of a sustainable energy is becoming a reality as technological advancements drive down costs and begin to deliver on the promise of a sustainable energy future. By 2035, sustainable and renewable energy sources are envisioned to contribute over 50% of global electricity production, as stated by the International Energy Agency. Furthermore, solar energy holds the position of being the world's third largest renewable energy source, with photovoltaic (PV) technology being the prevailing force, boasting an installed capacity exceeding 486 GW. Over last decade, utility-scale solar PV system has become more popular due to a notable reduction in the cost of components along with improvement in diverse

components' efficiency. A utility-scale solar plant produces solar power and feeds it into the grid, providing energy to a utility [1]. Almost every utility-scale solar installation has a power purchase agreement (PPA) in place with a utility, ensuring a market for its electricity for a certain period of time. The term "utility-scale solar" is becoming more extensively used to describe large-scale grid-connected PV generating; nevertheless, there are broad variances in how this is perceived. The Solar Energy Industries Association defines utility-scale solar as exceeding 1 MW while Developer Sun Power sets a minimum threshold of 1.5 MW for utility-scale solar projects. National Renewable Energy Laboratory (NREL) suggests a 5 MW barrier while Wiki-Solar chose a 10 MW threshold [2, 3]. As for utility-scale solar projects, different entities claim different minimum size limits, however any utility-scale solar project has a PPA. There are many different aspects and criteria that must be taken into account while constructing a utility-scale solar PV project. In order to develop such a solar PV plant, a feasibility study such as estimated solar resource and predicted yield is conducted first and the plant design is then modified to account for other local constraints. PV module type,

tilting angle, mounting and tracking systems, module layout, inverters, connectors, switches etc. are the key design elements [4]. To achieve the best utility-scale solar PV plant design, it's crucial to strike a balance between cost efficiency and high quality. This involves conducting optimization and performance assessments of the solar PV system to enhance both energy output and economic viability. Due to increasing solar PV plant and continuously decreasing the PV technology cost, the optimization of solar PV system may create an important performance difference. So, in order to achieve optimal performance for utility-scale PV systems, it is crucial to conduct a thorough optimization of the design parameters by exploring all available options. This ensures that the design is fine-tuned to maximize the system's overall efficiency and effectiveness. Global solar PV energy development can be observed from two perspectives: the proliferation of solar PV projects and investigations, and the progress of research and development (R&D). Over the past decade, the number of research publications focusing on the implementation of optimization approaches in solar systems has experienced significant growth [5]. In addition, a few studies have explored various approaches to enhance the performance and output of solar photovoltaic (PV) systems and contributed to the ongoing evolution of solar energy systems, paving the way for a more resilient and efficient future. Authors in [6] have reviewed on optimal design of solar PV system describing optimum tilt angles calculation, mathematical modeling and simulation and methods of testing. To enhance grid stability, the authors in [7] conducted an estimation of the PV potential and performed an analysis to determine the optimal orientation of a solar PV system. Additionally, they considered the system's operational efficacy across diverse climatic conditions, emphasizing the significance of effectively implementing the solar PV system. Authors in [8] investigated the viability of a 1 MW PV plant at an Algerian site for both fixed and seasonal tilt angle using PVsyst software and analyzed that annual production of 1893 MWh with seasonal tilt angle was more than annual production of 1805 MWh with fixed tilt angle having performance ratio 77.8 %. An extensive study of the technical, financial, and environmental viability of a 10 MW PV power plant connected to the grid in Saudi Arabia was carried out in [9] using RETScreen software encompassing various aspects including energy generation, environmental impact in terms of greenhouse gas

emissions, and financial considerations. The operational efficacy of utility-scale solar PV plants with a capacity of 10 MW in Ramagundam, India, was examined and compared using PVsyst and PV-GIS software in [10]. Authors in [11] optimized the annual performance of 100 MW photovoltaic (PV) solar power plant and a PTCS (Parabolic Trough Collector Solar thermal plant) using PVsyst and SAM software at Abu Dhabi region, UAE. A research study to monitor the operational efficiency of 5 MWp solar power system set up on the premises of Jordan University of Science and Technology (JUST) was carried out and performance parameter and economic analysis was evaluated using SAM software [12].

Furthermore, a wide range of PV module and inverter configurations, as well as power interconnection topologies, can have an enormous effect on the financial benefits, productivity, investment cost, and reliability of PV power plants. Authors in [13] described cost-effective methodologies for designing inverters in large-scale solar PV. An approach for designing PV plants to maximize economic gains during their lifetime was proposed in [14]. Authors in [15] developed a robust optimization model taking into account the selection of optimal size and location for PV systems and tackled the challenge of PV integration into electric grids by considering both spatial and temporal factors. The objective was to minimize energy costs while ensuring adequate satisfaction of electricity demand. Additionally, PV plant designs was discussed in [16] focusing on minimizing LCOE to achieve cost-effective and efficient PV installations. The various solar PV design parameters such as series and parallel PV module configuration, tilt angle, Inverter power ratings and characteristics, solar irradiation and ambient temperature etc. has been published in [6, 17-19] for the selection of optimal design process.

Therefore, this paper examines the performance assessment of a pre-existing 5 MW utility-scale solar PV plant that is connected to the grid considering various performance metrics viz, annual energy output, performance ratio, energy fed into grid, reference yield and system losses etc. To calculate these performance parameters one year data collected between January 2022 and December 2022, are analyzed using decision support tool PVsyst software. This PVsyst software generates the simulation results presenting various technical performance characteristics, energy loss diagram and annual energy generated output. The generated output energy from

PVsys software is compared with output energy generated from real time SCADA monitoring system in terms of performance ratio. This paper also suggests the optimization procedure to achieve higher energy yields, increased reliability, and improved economic viability of the solar PV system. The optimization procedure includes three design objectives: maximization of energy captured from solar PV plant, maximization of financial benefits and minimization of payback time period. For these three objectives, Tabu search (TS) optimization algorithm and particle swarm (PSO) optimization algorithm are used for a fixed site and location. These algorithms significantly influence the design process of solar PV plants and provide valuable insights into system design. The optimization process takes into account the specific characteristics and efficiency of different PV modules, enabling the selection of the most suitable module type that offers optimal energy production and considering the appropriate inverter size that balances performance and cost-effectiveness.

The paper is structured as follows: In section 2, an introductory overview is provided, highlighting the key aspects of the grid-connected solar PV system. Section 3 focuses on the geographical location and specific details of the installation site. Section 4, 5 and 6 describes the specification and tilt angle of solar panel, power conditioning units (PCU), power transformer respectively. The performance parameter is explained in section 7 while results and discussion are investigated in section 8. The performance

comparison is presented in section 9. Proposed objective design optimization approach is detailed in section 10 and the optimal plant design and corresponding results are discussed in section 11. Finally, section 12 concludes the paper by summarizing the findings and their implications.

2. Grid-Connected Solar PV System Overview

Under the JNNSM (Jawaharlal Nehru National Solar Mission) scheme of the Government of India, a grid-connected 5 MW solar PV project was developed within the existing factory premises of EMC in Naini, Allahabad district of Uttar Pradesh, India, in 2012. The primary goal of this project was to address the country's chronic power shortage by utilizing renewable energy sources to fulfill its energy demands. This initiative aimed to produce renewable energy in order to lower greenhouse gas emissions and promote sustainable development. The whole system consists of solar panels, inverters, safety equipment viz. fuses, circuit breaker, isolation switches etc. and equipment for grid-integration. Fig. 1 depicts the schematic layout of a 5 MW solar plant.

The harvested power from the solar PV panels is transmitted via a string combiner box to the PCU (inverter) for conversion into AC power in the plant configuration. The converted DC to AC power is fed to the transformer through compact secondary substation (CSS). The transformer's output is directly linked to the 33 KV utility grid.

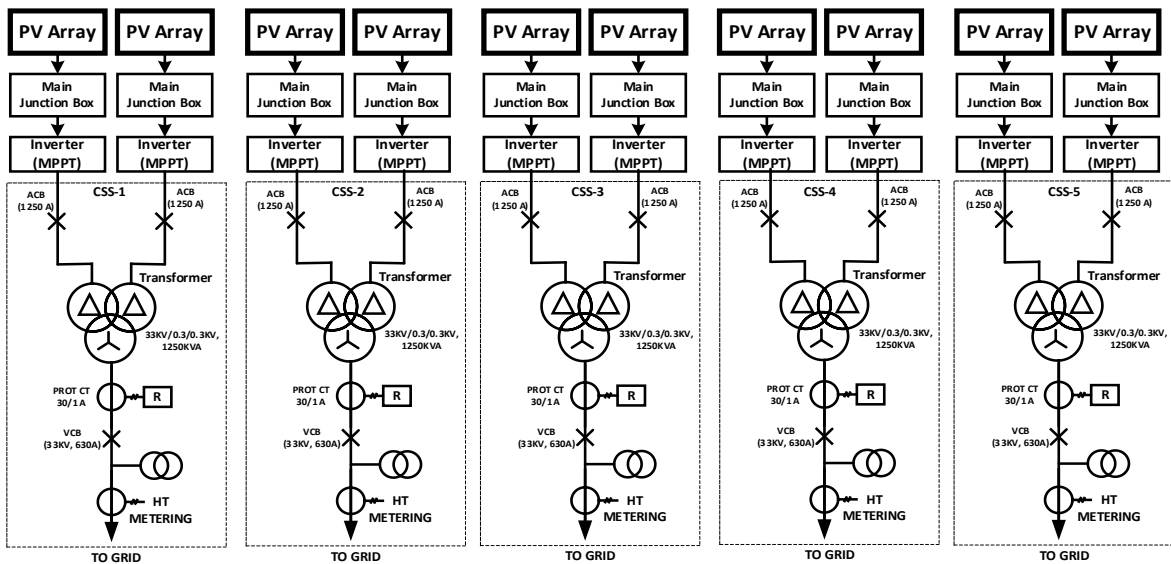


Fig. 1: Schematic diagram of Plant layout

3. Geographical Location and Plant Details of Site

The geographical co-ordinates of existing 5 MW solar PV plant is: Latitude: 25.37° N, Longitude: 81.87° E, Altitude: 89 m. The plant is located on 25 acres of land. The plant has a total the existing capacity of 5.75 MW_p (DC power). The solar PV module is mounted on structures with supporting 22 number of modules per structure. Each module consists of 60 cells assembled and is connected in series generating electricity from sunlight using photovoltaic effect. The

basic PV array is formed by connecting 22 modules in series. The PV array is divided into groups, each comprising 5 basic arrays connected in parallel. For each 1.15 MW_p of solar array, 2 inverters (2x500 KW_p) feeds power to LV switchboard, from which a 1250 kVA transformer unit feeds this power to a subsequent step up at 33 KV voltage level. The power plant has an output capacity of 5 MW (AC power), determined based on the installed inverter capacity. Table 1 displays the details of the plant configuration.

Table 1: Plant Details

Plant	Location	Developer	Coordinates	Land Area
5 MW _{AC} (~ 5.75 MW _p) Grid Connected Solar PV based power generation at Naini, Allahabad	Naini, Allahabad, Uttar Pradesh	EMC Ltd.	25° 22' 22" N, 81° 52' 18" E	25 Acres

4. Specification and Tilt Angle of Solar Panel

The solar PV panels made up of multi crystalline silicon are of fixed type. The ratings of PV panel are peak power of 235 W_p, open-circuit voltage (V_{oc}) of 37.2 V and short-circuit current (I_{sc}) of 8.48 A. The operating temperature of panel has 0-50 °C. The length, width and height of the module is 1.667 m, 1 m and 0.033m respectively. The installed solar panel has leg center to center distance 5 m and the distance between each panel is set to 25 mm. To enhance performance, the panels are cleaned on a monthly basis, typically three to four times per month. The tilt angle of the PV array is set to match the geographical

latitude. This alignment ensures that the PV array aligns with the path of sunlight, maximizing the reception of solar irradiation. However, to optimize radiation absorption, the tilt angle is manually adjusted periodically based on the changing seasons. This allows for increased exposure to sunlight and maximizes the efficiency of the solar panels. During the winter season (October to March), the panels are manually adjusted to a higher tilt angle of 40°. Conversely, in the summer season (April to September), the tilt angle is reduced to a lesser value of 10°. Table 2 shows the specification of Tata BP 235 W_p solar PV panel used in PV plant.

Table 2: Specifications of Tata BP 235 W_p Solar Panel

Particulars	Specifications
Peak Power (P _{max})	235 W
Production Tolerance of P _{max}	+5 - 3%
Voltage at P _{max} (V _{mpp})	29.8 V
Current at P _{max} (I _{mpp})	7.89 A
Open circuit Voltage (V _{oc})	37.2 V
Short Circuit Current (I _{sc})	8.42 A
Temperatur Coefficient of P _{max}	-0.43%/°C
Maximum System Voltage	1000 V
Dimension of Module (L x W x H) m	(1.667 x 1 x 0.033) m
Number of cells	60

5. Power Conditioning Units (PCU)

The PV solar plant have 10 inverters of 500 KW, which is responsible for the vital task of converting solar panels' DC power into usable AC power. The inverter receives an input of DC power from the PV

module, with a maximum voltage of 900 V and maximum current of 1145 A. This input is routed through the main string combiner box and converted into AC power, producing an AC voltage of 300 V and AC current of 965 A. The power produced by the inverters is fed to the compact secondary substation

(CSS), from where, further it is fed to power transformer. Table 3 presents the specifications of the

ABB Oy inverter utilized in the solar PV plant.

Table 3: Specifications of Inverter of ABB Oy

Particulars	Specifications
Maximum power point tracking voltage (DC)	450-750 V
Maximum voltage DC	900 V
Maximum current DC	1145 A
Output AC power	500 KW
Output AC voltage	300 V
Output AC current	965 A
Frequency	50/60 Hz

6. Power Transformer

The PV solar plant have five delta-delta-star three-phase transformers each having rating of 1250 KVA, 33 KV/0.3/0.3 KV. The transformer efficiency is almost 96%. The transformer' secondary is directly connected to the 33 KV switchyard through SF6 circuit breaker followed by the utility grid.

7. Performance Parameters

To estimate the overall performance assessment of PV grid-connected system, various performance metrics has been developed concerning energy efficiency, solar resources and system losses effect. Theses parameters was developed by IEA (International Energy Agency) [10, 20], which is described as follows.

Array yield

In order to generate array DC energy, array yield is the duration of time that the PV plant needs to operateat its nominal solar generator power. It is expressed in KWh/KWp/day.

$$\begin{aligned} \text{Array yield} &= \frac{\text{Per day energy output from Array}}{\text{Nominal Power at STC}} \\ &= \frac{\text{DC voltage} \times \text{DC current} \times \text{time}}{\text{Nominal Power at STC}} \end{aligned}$$

Reference yield

The reference yield is the ratio of the total in-plane irradiance of a PV system to the reference irradiance. It is expressed in (KWh/m²)/(KW/m²). It expresses the energy that can be obtained from a PV system when operating under ideal conditions. For the PV system, reference yield specifies the solar radiation resource.

$$\begin{aligned} \text{Reference yield} &= \frac{\text{Total in plane irradiance}}{\text{Reference irradiance of PV}} \end{aligned}$$

Final Yield

To calculate the final yield, the net AC energy output of the system (measured on a daily, monthly, or annual basis) is divided by the maximum power rating of the PV array installed at Standard Test Conditions (STC). It is expressed in KWh/KW_p/day.

$$\begin{aligned} \text{Final yield} &= \frac{\text{Net AC energy output of the system (daily, Monthly, annually)}}{\text{Maximum power of the installed PV array at STC}} \end{aligned}$$

Performance Ratio

The performance ratio is a metric used to assess how closely the actual operational performance of a PV plant aligns with its ideal performance. It takes into account various factors such as irradiation levels, panel temperature, grid availability, aperture area size, nominal output power, and temperature correction values. The performance ratio is calculated by dividing the final yield by the reference yield.

$$\text{Performance ratio} = \frac{\text{Final Yield}}{\text{Reference Yield}}$$

Capacity Utilization Factor

It is a metric that compares the actual output of a PV plant to its theoretical maximum output.

$$\begin{aligned} \text{Capacity Utilization Factor} &= \frac{\text{Energy measured in KWh}}{365 \times 24 \times \text{Installed capacity of PV plant}} \end{aligned}$$

Inverter Efficiency

The inverter efficiency, also referred to as

conversion efficiency, is calculated by dividing the AC output power of the inverter by the DC output power of the PV array system.

$$\text{Inverter efficiency} = \frac{\text{AC output power}}{\text{DC Power}}$$

System Efficiency

The system efficiency is determined by multiplying the PV module efficiency by the inverter efficiency..

$$\text{System efficiency} = \text{PV module efficiency} \times \text{Inverter efficiency}$$

Energy output

The energy output directed to the utility grid is determined by measuring the generated energy at the inverter's output terminals. It is quantified through the daily monitored AC output power and the monthly AC output power.

Energy losses

The efficiency and performance of a PV system are influenced by various losses that occur within the system. These losses can be categorized into two main types: array capture losses and system losses.

Array capture losses refer to the factors that impact the ability of the PV system to capture and convert solar energy effectively, such as shading, mismatch between modules, and soiling. It can be further classified into Thermal capture losses and Miscellaneous capture losses.

$$\begin{aligned} &\text{Thermal capture losses} \\ &= \text{Reference yield} \\ &\quad - \text{Corrected reference yield} \\ &\text{Miscellaneous capture losses} \\ &= \text{Corrected reference yield} \\ &\quad - \text{Array yield} \end{aligned}$$

System losses encompass losses that occur during the conversion and transmission process, including inverter inefficiencies, wiring losses, and transformer losses.

$$\text{System losses} = \text{Array Yield} - \text{Final Yield}$$

8. Results and Discussion

8.1 Data Monitoring using SCADA software

To effectively track and measure the ambient conditions such as temperature, solar irradiance, and wind speed, a weather monitoring system has been deployed near the plant. Furthermore, a dedicated

server, utilizing supervisory control and data acquisition (SCADA) technology, has been implemented within the control room to collect and store the data acquired from these sensors. The server gathers the monitored data and tracks voltage data, current data, power output data of the inverter, and power factor continuously over time. For the performance assessment of 5 MW solar plant, one year data from 1st January 2022 to 31st December 2022, are considered and monthly energy output obtained during this period is presented in Table 4. The total annually energy produced and exported to electric grid was 7064.805 MWh. The measured total global irradiation was 1868.9 KWh/m² and average temperature was 26.1 °C. Fig. 2 shows the monthly variation of global irradiation and temperature. The annually calculated performance ratio was 65.74 %.

Table 4 : Monthly Energy Output

Month	Average daily energy generation (MWh)	Monthly sum of energy output (MWh)	Total annual energy generated (MWh)
Jan-22	16.28606452	504.868	
Feb-22	20.89672414	606.005	
Mar-22	22.55477419	699.198	
Apr-22	24.62173333	738.652	
May-22	23.52729032	729.346	
Jun-22	18.24293333	547.288	
Jul-22	17.62256667	528.677	7064.805
Aug-22	18.42625806	571.214	
Sep-22	17.8877	536.631	
Oct-22	19.38470968	600.926	
Nov-22	17.3716	521.148	
Dec-22	15.51135484	480.852	

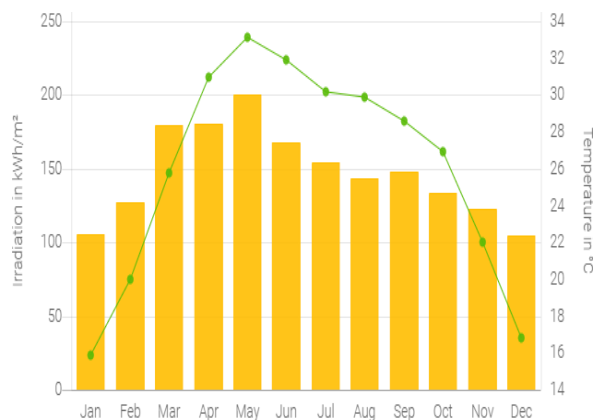


Fig. 2: Monthly Global irradiation and temperature variation

8.2 Performance Analysis using PYSyst software

The PVsyst software is the most commonly used software that are able to size, design, simulate, and analyze of solar plants. This software enables users to import meteorological data from various sources, facilitating accurate simulations and analyses. Therefore, the PVsyst software is employed to simulate and evaluate the operational efficiency of a 5 MW grid-tied PV plant. In the simulation, the Hay model is utilized to estimate incident solar irradiation on tilted surface planes. The following sections include the simulation results of different parameters of PV system from 1st January 2022 to 31st December 2022 using PVsyst software.

Orientation and inclination

Orientation and inclination are the two important characteristics in optimizing the system. The orientation of solar panel depends upon the solar trajectory. Fig. 3 illustrates the Sun’s path diagram.

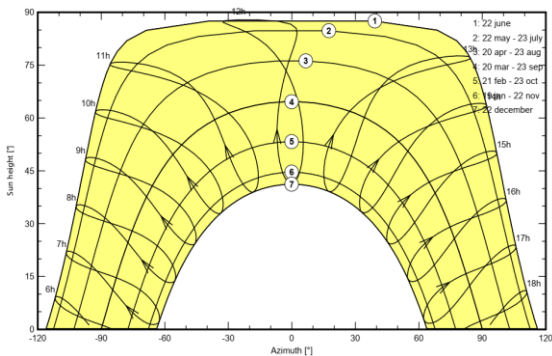


Fig. 3: Sun’s path diagram

Orientation of panel is optimized to achieve maximum solar radiation and this is achieved by adjusting the tilt angle based on the season. For summer inclination angle is tilted at 10° and for winter, it is at 41° (Fig. 4).

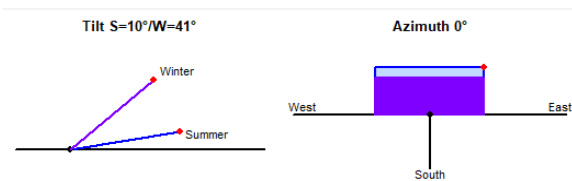


Fig. 4: Seasonal tilt adjustment

PV array efficiency

The voltage generated by PV module is affected by the incident irradiation and cell temperature. For the selected PV module of multi-crystalline silicon, 235 W_p with 60 cells, Fig. 5(a) shows the result of various P-V curve for different incident irradiation at fixed temperature of 45°C and Fig. 5(b) shows the result of various P-V curve for different cell temperature at fixed incident irradiation of 1000 W/m². The obtained peak power output is 250 W at 10°C and 1000 W/m². The PV array’s efficiency is determined by proportion of energy fed into grid in relation to the total incident global radiation. Fig. 5(c) shows PV array efficiency of 14.52% with respect to STC 1000 W/m².

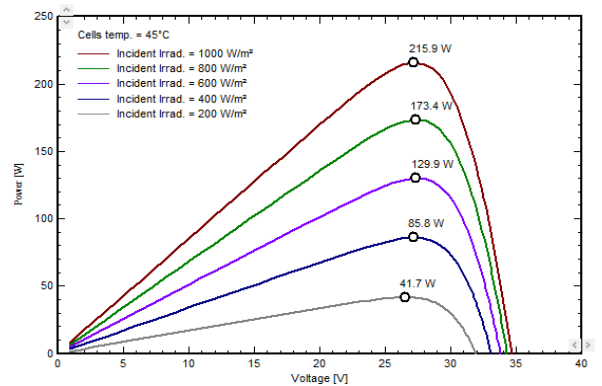


Fig. 5(a): P-V curve for different incident irradiation at fixed temperature of 45°C

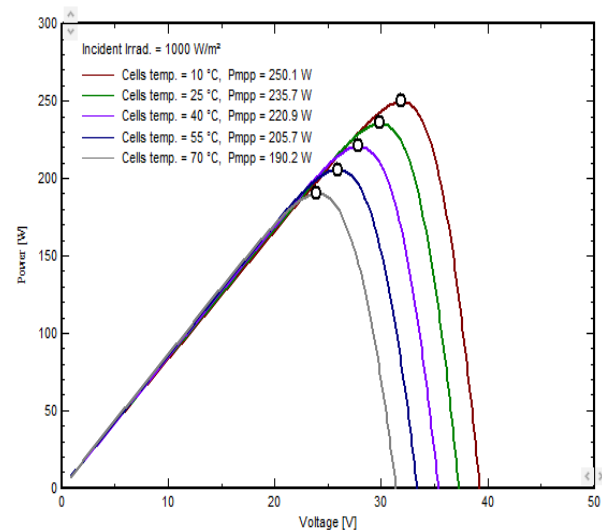


Fig. 5(b): P-V curve for different cell temperature at fixed incident irradiation of 1000 W/m²

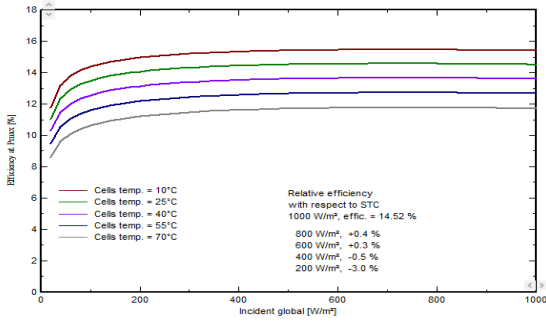


Fig. 5(c): efficiency-irradiation curve of PV module

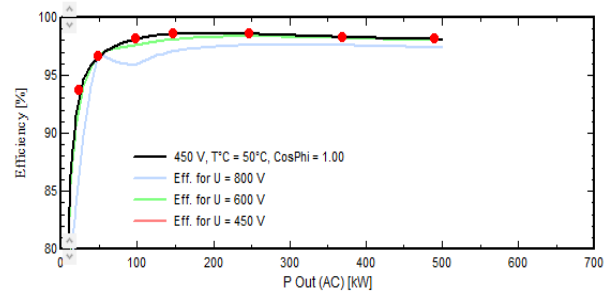


Fig. 6(b): Efficiency vs output power curve of inverter

Inverter's efficiency

It represents the effectiveness of the inverter in converting the DC power from the PV array into usable AC power. The selected inverter model (PVS800-57-0500kW-A) has nominal power of 500 KW. Fig. 6(a) and 6(b) present the efficiency curve of the inverter, showcasing the relationship between the input power and output power. The maximum efficiency is about 98 % for input voltage of 450-800 V.

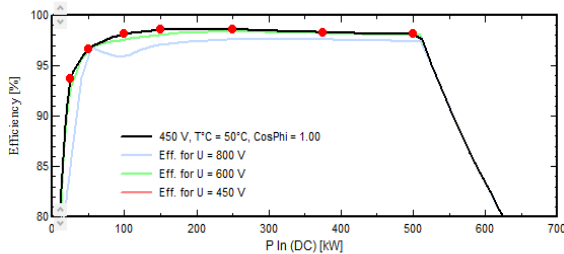


Fig. 6(a): Efficiency vs input power curve of inverter

Balances and Main results

The results generated from PVsyst software contains variables viz. global horizontal irradiation, global incident in collector plane, effective global irradiance for IAM (Incidence Angle Modifier) and shadings, ambient temperature, horizontal diffuse irradiation, effective energy at the output of the array, performance ratio and energy injected into grid (as shown in Table 5). Annually, the global horizontal irradiation is measured at 1804.7 KWh/m², while the global incident irradiation in the collector plane is recorded as 1983.9 KWh/m². The annual horizontal diffuse irradiation is calculated as 910.6 KWh/m², with an average ambient temperature of 26.12°C. The total energy output from the PV array is reported as 8136.5 MWh, and the annual energy injected into the grid is documented as 7758.9 MWh. The lowest energy injected into the grid is observed in August, with a value of 532.4 MWh, while the highest energy injection is recorded in May, with a value of 762.9 MWh. On average, the performance ratio is determined to be 67.9% annually.

Table 5: Balances and Main Results

	GlobHor kWh/m ²	DiffHor kWh/m ²	T_Amb °C	GlobInc kWh/m ²	GlobEff kWh/m ²	EArray MWh	E_Grid MWh	PR ratio
January	110.9	54.2	15.95	147.6	140.6	643.4	597.7	0.703
February	130.0	55.2	19.84	158.7	151.1	671.3	651.3	0.713
March	171.4	72.3	25.68	180.9	171.3	734.7	712.9	0.684
April	183.5	84.1	30.82	186.0	175.6	731.9	710.7	0.664
May	203.6	99.4	33.27	201.4	190.2	788.7	765.9	0.660
June	177.8	102.3	31.93	174.6	164.4	694.7	673.3	0.670
July	152.8	90.8	30.22	150.3	141.2	605.7	585.9	0.677
August	147.7	99.0	29.89	147.4	138.2	598.7	532.4	0.627
September	148.0	78.3	28.87	152.4	143.3	619.5	600.0	0.684
October	141.8	72.8	27.15	159.1	151.1	655.3	635.0	0.693
November	124.5	53.4	22.00	165.3	157.6	698.0	619.7	0.651
December	112.8	48.8	17.53	160.5	153.1	694.6	674.0	0.729
Year	1804.7	910.6	26.12	1983.9	1877.6	8136.5	7758.9	0.679

Legends

GlobHor Global horizontal irradiation
DiffHor Horizontal diffuse irradiation
T_Amb Ambient Temperature
GlobInc Global incident in coll. plane
GlobEff Effective Global, corr. for IAM and shadings

EArray Effective energy at the output of the array
E_Grid Energy injected into grid
PR Performance Ratio

Normalized performance coefficient and performance ratio

The International Electrotechnical Commission (IEC) has established standardized metrics known as the normalized performance coefficient and performance ratio which serve as benchmarks for assessing the performance of PV systems. Fig. 7 illustrates the monthly normalized production coefficient and it is tabulated in Table 6. Fig. 8 illustrates the monthly performance ratio, while the recorded normalized array losses (collection loss), denoted as L_c , amount to 1.56 KWh/KW_p/day. Additionally, the normalized system losses (including inverter losses, etc.), referred to as L_s , are recorded as 0.18 KWh/KW_p/day. The PV system has produced a useful energy output of 3.69 KWh/KW_p/day.

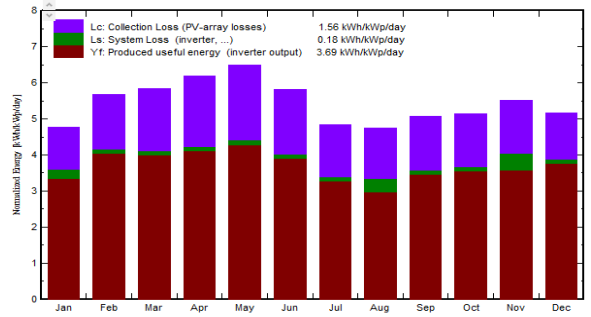


Fig. 7: Normalized productions (per KWp installed): Nominal power 5759 KWp

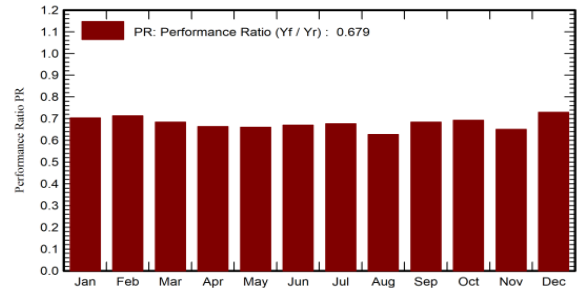


Fig. 8: Monthly Performance ratio

Table 6: Normalized Performance Coefficient and Performance Ratio

	Yr	Lc	Ya	Ls	Yf	Lcr	Lsr	PR
	kWh/m ² /day	ratio	kWh/kWp/day	ratio	kWh/kWp/day	ratio	ratio	ratio
January	4.76	1.158	3.60	0.256	3.35	0.243	0.054	0.703
February	5.67	1.504	4.16	0.124	4.04	0.265	0.022	0.713
March	5.84	1.721	4.12	0.122	3.99	0.295	0.021	0.684
April	6.20	1.962	4.24	0.123	4.11	0.317	0.020	0.664
May	6.50	2.078	4.42	0.128	4.29	0.320	0.020	0.660
June	5.82	1.798	4.02	0.124	3.90	0.309	0.021	0.670
July	4.85	1.456	3.39	0.111	3.28	0.300	0.023	0.677
August	4.75	1.400	3.35	0.371	2.98	0.295	0.078	0.627
September	5.08	1.493	3.59	0.113	3.47	0.294	0.022	0.684
October	5.13	1.461	3.67	0.114	3.56	0.285	0.022	0.693
November	5.51	1.470	4.04	0.453	3.59	0.267	0.082	0.651
December	5.18	1.286	3.89	0.115	3.77	0.248	0.022	0.729
Year	5.44	1.565	3.87	0.180	3.69	0.288	0.033	0.679

Legends

- Yr Reference Incident Energy in collector plane (Reference yield) = GlobInc [kWh/m²/day]
- Yf Normalized System Production (Final yield) = EAvail [kWh/kWp/day]
- Ya Normalized Array Production (Array yield) = EArray [kWh/kWp/day]
- Lc Normalized Array Losses (Collection loss)
- Ls Normalized System Losses (Inverter,...)
- Lcr Array Loss / Incident Energy Ratio (Lc/ Yr)
- Lsr System Loss / Incident Energy Ratio (Ls/Yr)
- PR Performance ratio

Diagram of Energy flow and Losses

Fig. 9 presents the energy flow and loss diagram for a 5 MW plant throughout the entire year. The collector plane receives a global horizontal irradiation of 1805 KWh/m², which is reduced by 5.43% due to losses from soiling and other factors, resulting in an effective irradiation on the collectors of 1878 KWh/m². After that incident solar energy on panels undergoes a conversion process to transform it into electrical energy. The efficiency of solar panels is 14.52% at STC and array nominal energy is 10847 MWh after

conversion. The virtual array energy obtained at the maximum power point (MPP) is 8137 MWh, considering module degradation loss, irradiation and temperature loss, mismatch loss, strings and modules loss, and ohmic losses. Due to inverter losses, the energy available at the inverter's output is decreased further, resulting in 7984 MWh. Subsequently, additional losses caused by transformer winding losses, AC ohmic losses, auxiliaries, and system unavailability contribute to a final available grid-injected energy of 7759 MWh.

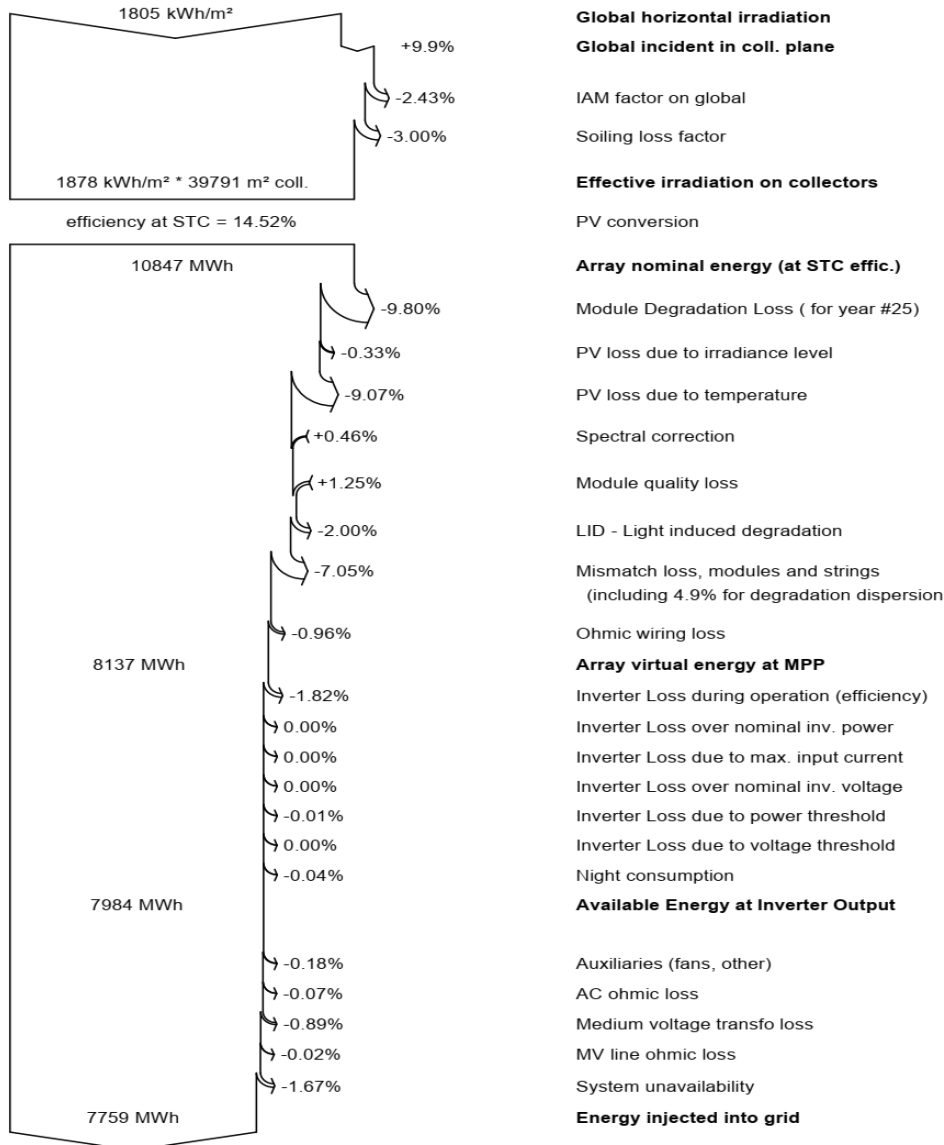


Fig. 9: Whole year energy flow and loss diagram

9. Performance Comparison

The comparative data output of obtained from SCADA monitoring system and PVsyst software is tabulated in Table 7. The annual real performance monitored from SCADA closely matches with data simulated from PVsyst software. However, SCADA systems are widely adopted in various industries nevertheless, PVsyst can provide valuable insights and optimization options in which it can help to optimize a solar PV plant.

➤ PVsyst allows to model and simulate different system configurations, including the arrangement of solar panels, inverters, and other components. By analyzing various design options, it helps to figure out the optimal sizing and layout of the system components to maximize energy production.

➤ PVsyst uses historical weather data and advanced solar radiation models to assess the solar resource at the project site accurately. This information is crucial for optimizing the plant's performance and ensuring that the system is designed to capture the maximum available solar energy.

➤ PVsyst includes financial analysis tools that can assist in optimizing the economic viability of the project by considering factors like system cost, energy production, and maintenance expenses.

➤ PVsyst analyses different parameters, such as tilt angle, azimuth, module type, and inverter sizing, to identify the optimal combination that can maximize energy production and cost-effectiveness.

Table 7: Monthly Energy Output

Month	Monitored energy output (MWh)	PVSYST energy generated output (MWh)
Jan-22	504.868	597.7
Feb-22	606.005	651.3
Mar-22	699.198	712.9
Apr-22	738.652	710.7
May-22	729.346	765.9
Jun-22	547.288	673.3
Jul-22	528.677	585.9
Aug-22	571.214	532.4
Sep-22	536.631	600
Oct-22	600.926	635
Nov-22	521.148	619.7
Dec-22	480.852	674
Total	7064.805	7758.8

10. Proposed Design Optimization Approach to Enhance Solar PV Plant

Based on a performance analysis conducted using PVsyst software the simulation results for the existing 5 MW on-grid solar PV system indicate that annual total generated power from 1st January 2022 to 31st December 2022 was 7758.8 MWh having annual performance ratio of 67.9 % which was closely matched to output of 7064.805 MWh having performance ratio of 65.74% from SCADA monitoring system. However, there are still concerns that system designers for solar power plants need to consider in order to make improvements to their systems. These problems involve several considerations such as site analysis, load analysis, inverter selection, PV module selection, financial analysis etc. to ensure the optimal performance and financial viability of solar power plants. Other than this, combination of nonlinear impacts in temperature and solar irradiance results in the PV system operating away from its maximum power point, and lead to significant variations in energy harvest over different times of the day and throughout the year, resulting in reduced energy production. This reduced energy harvest due to non-linear characteristics directly impact on the economic gains of the solar plant including determining the payback period and assessing the return on investment. Accurate consideration of these nonlinear characteristics enables plant designers to optimise system configuration and maximise energy production, resulting in a shortened payback period and improvement in financial outcomes. Therefore, this section suggests an optimization strategy by considering multiple variables, including PV modules interconnected in a series-parallel configuration, installation angle, assortment of PV module options and collection of inverter choices. The proposed optimization method employs two different optimization algorithms namely, Tabu Search (TS) algorithm [21] and particle swarm optimization (PSO) algorithm [22] with three different objective functions considering multiple variables as well as different solar irradiance and temperature conditions. The first objective function aims a measure of the total energy output expected from the solar plant over its operational lifespan. This can be computed by determining the expected energy yield of each solar module or panel based on its specifications, including

efficiency, estimating the count of solar modules incorporated in the plant, determining the lifespan of the solar modules, taking into account factors such as performance degradation over time and calculating the annual energy production of each module. The second objective function seeks to determine the overall cost or benefit of the solar plant throughout its operational lifespan and this can be accomplished by conducting a thorough analysis of the initial capital investment, including costs for solar modules, inverters, mounting structures, electrical components etc., considering the operational and maintenance costs over the plant's lifetime, including costs for cleaning, inspection, repair, and replacement of components and calculating the revenue generated by plant. The third objective function aims minimizing the payback time and can be calculated by determining the total initial investment required for the establishment of the PV plant and calculating the annual revenue generated by plant.

Objective Functions

The first objective function is set to calculate the maximum annual energy production based on the solar PV plant's output power during its lifetime and it is taken into account parameters such as module performance parameters, conversion efficiency of inverter, tilt angle, and environmental factors like irradiance and temperature to estimate the energy output at different time intervals. The following equation represents the energy output of the PV plant during a specific timeframe (year, day, and hour): -

$$\text{Energy}_{\text{Plant}} = \text{Power}_{\text{PV Plant}} \times \text{Efficiency}_{\text{Inverter}} \times \text{Time}$$

$\text{Power}_{\text{PV Plant}}$ represents the PV plant's output power at a specific time (year, day, and hour) and is determined by various factors such as derating factor due to dust accumulated on its surface, tilt angle, the annual reduction coefficient of the solar module, irradiance, temperature and rated power of the PV module. The following equation represents the power output for specific time of interval:-

$$\text{Power}_{\text{PV Plant}} = [1 - \text{year} \times \text{Reduction coefficient}] [1 - \text{Derating factor}] \times \text{Rated Power}_{\text{PV plant}} \times \text{Probabilty of Irradiance and Temperature}$$

$\text{Rated Power}_{\text{PV Plant}}$ refers to rated power of the PV module under standard test conditions (STC), which include a specific level of solar irradiance (typically 1000 W/m²), a temperature of 25°C, and an air mass

of 1.5 and represents as a reference value to estimate the power output of the PV module under non-standard conditions, taking into account factors such as the annual reduction coefficient, derating factor, tilt angle, irradiance, temperature, and other probabilistic factors. It also takes into account the number of series PV modules (N_s) and the number of parallel PV modules (N_p) in the electrical configuration which adjusts the rated power based on the chosen configuration.

$\text{Efficiency}_{\text{Inverter}}$ refers to efficiency of the inverter and can be defined as a function of the PV module's output power, the PV module's voltage, and the number of inverters selected.

Time refers to hourly intervals at which solar irradiance and temperature data are recorded or analyzed. The time interval can be adjusted based on specific requirements or availability of data.

The first objective function during a specific timeframe (year, day and time) can be expressed in following manner:

$$\frac{\text{Max}}{X_1} = \sum_{\text{year}}^{Y_n} \sum_{\text{day}}^{365} \sum_{\text{time}}^{24} \text{Power}_{\text{PV Plant}} \times \text{Efficiency}_{\text{Inverter}} \times \text{Time}$$

where, Y_n represents the lifetime of the modules.

The second objective function is set to minimize the net cost or maximize the total benefits by considering the energy production and costs associated with the plant. The calculation of the energy output of the PV plant during a specific timeframe (year, day and time) considers various factors including the quantity of PV modules and the tilt angle, annual reduction coefficient, irradiance, temperature, and probability values. The equation for second objective function is expressed as follows: -

$$\frac{\text{Max}}{X_2} = \sum_{\text{year}}^{Y_n} \sum_{\text{day}}^{365} \sum_{\text{time}}^{24} \text{Energy}_{\text{PV Plant}} \times \text{Cost}_{\text{Energy}} - \text{Cost}_{\text{Installation, operation \& Maintenance}}$$

where,

$$\text{Cost}_{\text{Installation, operation \& Maintenance}} = \text{Cost}_{\text{Installation}} + \text{Cost}_{\text{Operation \& Maintenance}}$$

$$\text{Cost}_{\text{Installation, operation \& Maintenance}} = [\text{Cost}_{\text{Inverter}} + N_s \times N_p \times P_{\text{rated}} \times \text{Cost}_{\text{PV}}] + Y_n \times [\text{Cost}_{\text{Inv_O\&M}} + N_s \times N_p \times P_{\text{rated}} \times \text{Cost}_{\text{PV_O\&M}}]$$

where,

$\text{Cost}_{\text{Inverter}}$ represents the installation cost of Inverter
 Cost_{PV} represents the installation cost of PV module
 $\text{Cost}_{\text{Inv_O\&M}}$ represents the operation & maintenance cost of Inverter

$Cost_{Inv_O\&M}$ represents the operation & maintenance cost of PV module
 P_{rated} represents the rated power of each PV module
 Y_N represents number of years

The third objective function is set to minimize the payback period. The objective is to find the time period when the cumulative cash flows equal or exceed the initial investment costs. The objective function can be formulated as follows:

$$\frac{Min}{X_3} = year \times 365 + day$$

Subject to $\bar{X}_2 = 0$

In this equation, payback period measured in days. It is determined by multiplying the year by 365 (complete set of days within a year) and adding the day. The constraint $X_2 = 0$ ensures that the cost attributed to the PV plant amounts to zero. This constraint represents the condition where the cumulative net cash flows from plant are sufficient to cover the initial investment costs, indicating that the payback period has been achieved.

Design Variables and optimization constraints

The design variables typically refer to a specific parameter or factor that can be adjusted or optimized to achieve certain design objectives or performance goals. Design variables play a crucial role in optimizing the PV plant's performance, energy output, and overall system design. To ensure that the solar PV plant meets both technical and economic design criteria, five design variables are taken into account.

1. Quantity of series connected PV module (N_s): This design variable determines the quantity of PV modules connected in a series configuration, which affects the voltage output of the PV system.
2. Quantity of parallel connected PV module (N_p): This design variable determines the quantity of PV modules connected in a parallel configuration, which affects the current output of the PV system.
3. Tilt angle (β): This design variable represents the inclination or tilt angle at which the PV modules are positioned in relation to the horizontal plane. The tilt angle, directly impacts the solar irradiance and can be

optimized to maximize energy production.

4. Number of PV modules selected (PV_n): This design variable determines the number of PV modules selected from a pool of options for installation in the PV plant. It directly influences the total power capacity of the PV system.
5. Number of inverters selected (Inv_n): This design variable determines the quantity of inverters selected from a pool of options for the PV system. It has a direct impact on the electrical configuration and power conversion.

The following vector Q allows for a concise and convenient representation of PV plant's design variables.

$$Q = [N_s \quad N_p \quad \beta \quad PV_n \quad Inv_n]$$

Each specific PV system design project may have unique constraints which may encompass the initial installation costs, limitations on available installation area, and other relevant factors. So, it is important to carefully analyze and incorporate the relevant constraints to meet the desired objectives. When formulating the design problem, multiple optimisation constraints can be taken into account. Constraints can be summarized as follows: -

$$Cost_{Installation} \leq Budget$$

$$N_s \times N_p \times A_{PV} \leq Available\ Area$$

$$PV_n \leq List\ of\ PV\ candidates$$

$$Inv_n \leq List\ of\ Inverter\ candidates$$

Where, A_{PV} is one PV module installation area.

Optimization Algorithm

Tabu search (TS) is the intelligent optimum solution algorithm for mixed integer non-linear problem. It is a heuristic search algorithm having number of iterations based on different memory structures. The optimization process in Tabu Search commences by initializing a viable solution and iteratively explores the vicinity until a specified condition is met. To begin the optimization process using Tabu search, first of all, each decision variables is represented as binary digits and then selected as a starting point. Each variable's size is determined by maximum value that can be assigned to each parameter. The detail information of Tabu search algorithm regarding its characteristics and implementation has been discussed in [21, 23]. Basic Tabu Search Optimization is detailed step wise below

in Fig 10:

Algorithm: Tabu Search Optimization	
Step 1	Start
Step 2	Initialize current solution and best solution
Step 3	Initialize tabu list
Step 4	Repeat until termination condition is met:
Step 5	Generate neighborhood solutions
Step 6	Evaluate fitness for each neighborhood solution
Step 7	Find best non-tabu solution
Step 8	Update current solution and tabu list
Step 9	End

Fig. 10: Steps of Tabu Search Optimization algorithm

PSO is algorithm that generates a beginning population via the use of a searching method in which each organism, or "particle," wanders about in different locations throughout the course of time [24]. The particles that make up the PSO system are endowed with the capacity to engage in conversation with the surrounding environment. Particles make their own decisions on their spatial arrangement, taking into account both their own past knowledge and the prior knowledge of their neighbours. The particle succeeded in locating itself in the optimal spot, which benefited both it and its neighbour. As a result, PSO may be considered as both a regional and an international search approach. The PSO algorithm explores the solution space in search of the optimal parameters at the present time. Due to their high accuracy, rapid convergence, and simple implementation, particle swarm optimization algorithms have garnered significant attention in recent years. PSO is detailed step wise below in Fig. 11:

Algorithm: Particle Swarm Optimization	
Step 1	Start
Step 2	Initialize swarm and particle positions
Step 3	Initialize velocities
Step 4	Initialize global best position and fitness
Step 5	Repeat until termination condition is met:
Step 6	Evaluate fitness for each particle
Step 7	Update global best position and fitness
Step 8	Update velocities and positions for each particle
Step 9	End

Fig. 111: Steps of Particle Swarm Optimization algorithm

11. Optimal Plant Design and Results

In the optimization formulation for achieving the optimum design considering the three objectives, the

selection of inverters and PV panels is expected to be made from a list of available choices. For that, four different commercially available inverters and solar PV panels are selected as a sample having different characteristics and specifications which is shown in Table 8 and 9. The installation costs, operation and maintenance costs per year, energy costs are estimated to be ₹ 90,000/KW, ₹ 1500/KW and ₹ 9/KW respectively. Depending upon different the objective functions, all case-studies have fixed available area of 100m² and fixed tilt angle of 41° south.

Table 8: Sample Specifications of Commercial PV Inverter

Parameters	Inv ₁	Inv ₂	Inv ₃	Inv ₄
Rated Voltage (V)	800	800	800	800
Max. Volatge (V)	1000	1000	1000	1000
Min. Volatge (V)	390	380	320	360
Rated Power (kW)	25	12.6	20	15.6
Cost (₹)	2,99,114	2,14,731	2,65,886	2,47,893

Table 9: Sample Specifications of Commercial Solar Panel

Parameters	PV ₁	PV ₂	PV ₃	PV ₄
Power (W)	305	245	250	260
Open circuit Voltage, V _{oc} (V)	44.8	37.3	37.59	38.9
Max. Power Point Volatge, V _{mpp} (V)	36.3	30.7	30.72	30.7
Short Circuit Current, I _{sc} (A)	8.97	7.98	8.65	9.18
Max. Power Point Current, I _{mpp} (A)	8.41	7.98	8.15	8.56
Surface Area, A _{pv} (m ²)	1.92	1.64	1.63	1.67
Temp.Coeff. at V _{oc} (%/°C)	-0.34	-0.35	-0.31	-0.3
Tem. Coeff. at I _{sc} (%/°C)	0.065	0.05	0.073	0.04
Temp.Coeff. at P _{max} (%/°C)	-0.43	-0.45	-0.431	-0.41
Type	Poly	Poly	Mono	Mono
Number of series cells	72	60	60	60
Cost (₹)	22,315	20,827	22,315	20,158

Particle Swarm Optimisation (PSO) and Tabu Search (TS) algorithms were independently implemented to address three objective functions, and the resulting optimal design outcomes are presented in Table 10. The outcomes indicate that for maximizing the energy captured from the solar PV plant, the recommended choice is Inv₁ and PV₁ with a configuration of 13/4 (number of series/number of parallel PV modules). The second objective of maximizing the financial benefits obtained from solar power plant is fulfilled when Inv₃ and PV₄ with a configuration of 19/3 are selected. Similarly, to minimize the payback time period, the optimal selection is Inv₄ and PV₄ with a configuration of 19/3.

Table 10: Comparison of Optimum Design Results by algorithm used

Algorithm Design Objectives	Tabu Search Optimization			Particle Swarm Optimization		
	Energy	Benefits	Payback	Energy	Benefits	Payback
Number of series PV module, N_s	13	19	19	13	19	19
Number of parallel PV module, N_p	4	3	3	4	3	3
Inverter, Inv_n	Inv_1	Inv_3	Inv_4	Inv_1	Inv_3	Inv_4
Solar Panel, PV_n	PV_1	PV_4	PV_4	PV_1	PV_4	PV_4
Available Area (m^2)	100	100	100	100	100	100
Installation costs, $Cost_{\text{installation}}$ (₹)	18,15,292	16,81,377	16,44,179	18,15,292	16,81,377	16,44,179
Energy Captured from solar power plant (MWh/y)	30.6	30.2	30	31.2	30.5	30.7
Total financial benefits from solar power plant (₹)	42,77,686	43,22,323	43,00,004	43,35,653	43,55,653	43,40,063
Payback Period (Days)	2684	2546	2475	2584	2446	2340

Considering the first objective, energy captured from solar PV plant is 30.6 MWh/y using TS algorithm and 31.2 MWh/y using PSO algorithm. The total financial benefits for the second objective with TS algorithm, are ₹ 43,22,323, but they are ₹ 43,55,653 with PSO algorithm. Using TS algorithm, third objective has a shorter payback period of 2475 days, but PSO algorithm has a payback period of 2340 days. In this hypothetical example, the specific results obtained from running these algorithms on dataset will depend on the specific fitness function, problem constraints, and parameter settings used in the implementation. The higher fitness values obtained from the PSO algorithm is considered to have produced better results for maximizing energy transferred to the grid.

It can be observed that the proposed design approach, which considers the specific characteristics of solar PV module and inverter, demonstrates its capability to deliver more efficient outcomes. Furthermore, different locations and climates experience varying levels of temperature and solar irradiation, which can impact the system's effectiveness and efficiency. Consequently, a solar PV plant that is designed for one specific site may not be optimal for another location with different temperature and solar irradiation variations. It should be noted that the optimal design of a solar plant is not only afflicted by the detailed properties of the PV module and inverter but also by variations in average temperature and solar irradiation levels. To maximize the financial benefits and harvested energy from a solar power plant, it becomes necessary to redesign the system considering the specific climatic conditions and variations in temperature and solar irradiation levels. By accounting for these variations and adjusting the design accordingly, the solar PV plant can achieve the

greatest possible financial benefits and harvested energy output.

12. Conclusion

This paper examines the various performance parameter of existing 5 MW on-grid utility-scale solar PV system installed at Naini, Prayagraj district of Uttar Pradesh, India, using PVsyst software in order to establish a fundamental comprehension of existing systems and performance evaluation presenting various technical performance characteristics, energy loss diagram and annual energy generated output. The solar PV plant was configured with varying tilt angles based on the seasons, in which 10° inclination was for summer and 41° inclination for winter season and azimuth was considered at 0° . The average ambient temperature was recorded as 26.12°C . The annual global horizontal irradiation was obtained $1804.7\text{ KWh}/m^2$, while the global incident irradiation on the collector plane was measured at $1983.9\text{ KWh}/m^2$. The produced average useful energy was found $3.69\text{ KWh}/\text{KWp}/\text{day}$. The effective irradiation on collectors was found to be $1878\text{ KWh}/m^2$ without considering the shading losses. After PV conversion, the array's nominal energy was determined to be 10847 MWh and the measured energy at the inverter's output was found to be 7984 MWh. The simulation result shows that the annual total generated energy from 1st January 2022 to 31st December 2022 was 7758.8 MWh having annual performance ratio of 67.9%. The performance comparison showed that generated energy from real time SCADA monitoring system was 7064.805 MWh having performance ratio of 65.74% which was closely matched with PV SYST software, nevertheless, PVsyst can provide valuable insights and optimization options to optimize a solar PV plant. This paper also proposes an optimization procedure including three design objectives: maximization of energy captured from solar PV plant, maximization of financial benefits and minimization of payback time period. The optimization procedure was formulated with sample of four different commercially available inverters and solar PV panels using Tabu search (TS) optimization and particle swarm optimization (PSO) algorithm for a fixed site and location. The design approach provided more efficient outcomes for three considered objectives and concluded that to enhance the operational effectiveness of a solar PV system in accordance with these considered objectives, solar PV system should

be re-designed. With hypothetical example, the specific results obtained from running PSO algorithm on dataset performs better in terms of maximizing energy transferred to the grid. To increase the effectiveness of a solar plant by using a hybrid algorithm, the strengths and capabilities of multiple optimization algorithms can be combined to achieve better performance and optimization results. Hybrid algorithms leverage the complementary nature of different algorithms to overcome limitations and improve overall efficiency.

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