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Research Article

Analysis of a 5.0 kWp solar rooftop system: Techno-economic, design, and simulation using pvsyst

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ABSTRACT

The paper focuses on performance of a 5.0 kWp PV solar system, a second-generation PV technology. The experimental PV solar system was installed on the rooftop of G.P. Convent School, located in Sankat Mochan Nagar Morar, Gwalior, M.P, India (78.21°E, 26.22°N). The observed data indicates that daily average energy yields for experimental solar system were 5 kWh/kWp (array yield), 6.25 kWh/kWp (reference yield), and 4.91 kWh/kWp (final yield). While PVsyst simulation estimates the slightly higher values of 5.46, 6.39, and 5.32 kWh/kWp, respectively. The total yearly power generated was 6910.2 kWh for the experimental PV solar system and 7485 kWh according to PVsyst software. The payback period for the PV solar rooftop system ranges from between 4.57 years and 11.41 years, depending on the initial cost. The ROI ranges from 119% to 447.5%, with the system providing substantial long-term savings. Based on these outcomes, PV solar system will perform well under the meteorological conditions.

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INTRODUCTION

The global demand for energy to generate power continues to grow, with different resources contributing to the energy mix. According to the U.S. Energy Information Administration's 2020 report, fossil fuels accounted for 75% of energy consumption. The ratio has not changed much over the last ten years, but experts say the world's energy needs could grow by around 50% by 2050. Over the past 30 years, renewable energy sources have played a vital role in power generation, offering reduced emissions compared to fossil fuels. Moving forward, renewable energy is expected to contribute a larger share of the global energy consumption. This research aims to explore optimal solutions for

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utilizing these alternative, more environmentally friendly energy sources to mitigate emissions associated with fossil fuels and other conventional power generation methods. Renewable energy, often referred to as alternative, sustainable, or non-conventional energy, is derived from natural, replenishable sources such as wind, solar, hydroelectric, geothermal, bioenergy, and ocean energy [1]. The growing global demand for energy and the depletion of fossil fuel reserves have driven increased adoption of renewable energy. Renewable energy presents a viable, eco-friendly solution in remote as well as rural areas, where electricity availability is limited and the installation of traditional transmission lines is often cost-prohibitive [2-,5]. Furthermore, the renewable energy sources are inherently clean and environmentally beneficial. However, several challenges persist, limiting the widespread use of renewable energy [6]. The prime challenge is the variability of energy generation, which is greatly dependent on climate conditions that vary by region. Energy availability is not constant, with intermittent periods of zero generation, such as at night for solar energy or during cloudy days. Traditionally employed for residential and commercial electricity generation, there has been increasing interest in using PV panels to power air conditioning systems [7]. This innovation addresses the growing need for cooling in many societies and provides an environmentally friendly alternative to conventional fossil fuel-powered air conditioning. By harnessing solar energy, PV panels can operate air conditioners without reliance on the public electrical grid. The installation of solar panels on rooftops or other open, sunlit areas allows the conversion of sunlight into electricity, which is then used to power air conditioning units [8]. Furthermore, the integration of sun-tracking systems can optimize energy absorption by ensuring the panels are always oriented towards the sun. The use of PV panels to power air conditioners offers numerous advantages, including a reduced dependence on the electrical grid, lower energy consumption, and significant savings on electricity bills [9,10].

The integration of renewable energy into existing electrical grids has made great progress, especially with solar energy conversion both electrical and thermal becoming more common. Solar energy is abundant and accessible to nearly everyone, making it a valuable resource. Over the years, significant efforts have focused on maximizing its use. To achieve the best results, it's important to analyze solar energy from thermodynamic, environmental, economic, and policy angles. This helps develop optimized systems that balance energy output, cost-effectiveness, and environmental sustainability using current technologies.

Solar photovoltaic (PV) systems have become a popular choice for clean energy in both homes and industries, thanks to their many benefits they're easy to install on rooftops, require little maintenance, have no fuel costs, and don't pollute. But unlike traditional energy sources, PV systems face challenges like lower efficiency and power output that can change with weather conditions, temperature, sunlight levels, and panel angle. There is plenty of room to improve how much energy from solar panels using available solar panels infrastructure and techniques including Maximum Power Point Tracking (MPPT), reconfiguring panel arrays, controlling cell temperature, cleaning dust off panels, optimizing their orientation and tilt, using advanced multilevel converters, and enhancing performance with mirrors (MAPV) systems [11]. While these methods can significantly boost energy output, making them practical means keeping costs down and efficiency and longevity up. For instance, a study by Li [12] in Hong Kong found that the energy payback period for an on-grid PV system was 8.9 years.

Sharma et al. [13] conducted an analysis of a PV solar system under various load scenarios in a building to optimize factors such as performance ratio (PR), maximum power, efficiency, as well as specific production, leading to improved efficiency of the system. The system was tested with laboratory loads, using a fixed tilt angle and adjustable azimuth angle. The outcomes showed that when the azimuth angle was set to zero, the system achieved maximum specific production, with a 1.7% increase in efficiency. Yadav et al. [14] examine the performance of a 1 kWp PV system in Hamirpur, Himachal Pradesh, India, using measured solar radiation data. Simulated through PVsyst software, the system's energy generation and associated losses were analysed. The performance ratio for the year is estimated at 0.724, signifying that PV systems are a viable option to support the region's increasing energy needs. Kasim et al. [6] studied the performance of a 5 kWp CIGS grid-connected PV system was assessed in Baghdad, Iraq. The system was compared with PVsyst simulations to evaluate its efficiency under the local climate. The real system's annual energy yield was 1781.8 kWh/kWp, while PVsyst predicted 1924 kWh/kWp. System losses, efficiencies, and performance ratios were analyzed, showing that the real system's average performance was close to the simulated results. With minimal differences in energy yield and efficiencies, the study concluded that the CIGS PV system performs well in Baghdad's climate, offering reliable energy generation. Hammed et al. [15] proposed PV system at the National University of Sciences and Technology (NUST) in Islamabad, Pakistan, a region with abundant solar resources to combat climate change. The system is expected to save 75,478.60 tons of CO2 over 18 years, equivalent to planting 348,754 teak trees. With a low energy generation cost of $0.0141/kWh, the system will generate 11,270,771 kWh/year, with a performance ratio of 76.2% and a capacity utilization factor of 16%. The plant will break even in 12 years, offering valuable insights for future renewable energy projects. Srivastava et al. [16] evaluated the performance of a grid-connected silicon-polycrystalline photovoltaic (PV) system, and designed with a peak power capacity of 20.0 kW and a voltage of 17 V. To carry out the performance analysis, the software PVsyst (version 7.1.7) was used, a widely recognized tool used for simulating energy generation and optimizing the design of PV systems. In this study, PVsyst was used to design a grid-connected PV system tailored for the Karunya Institute of Technology, providing valuable insights into the system's efficiency and potential performance. Nababan et al. [17] carried out a comprehensive techno-economic analysis of a solar rooftop system, focusing on the city of Medan, Indonesia. The analysis is based on solar intensity data specific to Medan, with measurements taken over several days. By employing this measured data, along with available solar PV panels from the Indonesian market, a technical evaluation of the system's performance was conducted. The economic analysis results indicate that the annual electricity production from the PV system in Medan is valued at IDR 3,672,895. With an investment cost of IDR 33,271,986 for the installation of 2.0 kW PV solar rooftop system and considering the total yearly electricity value of IDR 3,672,895, it was determined that the initial capital investment for the 2.0 kW system would be recovered in approximately 10 years. Kumar et al. [18] studied the load requirements of the Mechanical Engineering Department (MED) office at an engineering college in Bikaner, and consequently focuses on design and installation of a standalone solar PV system to full fill these requirements. This work also includes an analysis of performance ratio (PR) and losses, which was concluded by using PVsyst simulation software. The average annual energy requirement for the MED office is 1,086.24 kWh; however, the energy generated by the solar panels is 1,143.6 kWh. Though the energy supplied to the office is 1,068.12 kWh, which is slightly less than the required load. The performance ratio analysis indicates that the highest PR was recorded in December, at 86%, while the lowest PR, 64%, was observed in April. The average performance ratio for the entire year is 72.8%.Salmi et al. [19] evaluated the feasibility of a PV solar rooftop system with battery storage in a residential area of M'sila, Algeria. Using PVsyst6 software, it was observed that the average daily electricity consumption was noted as 12.6 kWh, with an annual grid contribution of 4,615 kWh. The system's performance ratio was recoded as 62.9%, with the highest energy production occurring from June to August, peaking at 354.4 kWh in July. Energy losses, mainly due to the temperature of the PV field, were 12.14%. Sonam and Agyekum [20] studied the assessment of rooftop solar PV potential in Thimphu, Bhutan, amid rising energy demand and hydropower shortfalls. A 12 kWp system simulated via PVsyst showed strong performance. Scenario analysis revealed significant energy and cost savings, highlighting rooftop solar as a viable, sustainable solution for Bhutan's energy diversification and environmental goals. Zue et al. [21] discovered the technical potential and economic benefits of rooftop photovoltaic (PV) systems across three different university campuses in China, considering available rooftop areas and local solar intensity. Seven scenarios were analyzed for Tibet University, Qinghai University, and Qilu University of Technology, located in different solar zones. The potential PV installation capacities for the campuses are 11,291, 9,102, and 3,821 kW, respectively. These correspond to maximum annual power production of 28.19, 18.03, and 5.36 GWh for each university, respectively. Aktas and Ozenc [22] focused on the design, evaluation, and analysis of a grid-connected solar photovoltaic (SPV) system to meet the energy requirements of the College of Science and Technology in Siirt Province, Turkey. It offerings detailed financial and technical data, along with thorough economic and environmental assessments. The system's design and evaluation were supported by using PVsyst, PV*SOL, as well as HOMER Pro software. The analysis outcomes indicate that the photovoltaic system will produce approximately 762 MWh of energy annually. The economic evaluation reveals an internal rate of return (IRR) of 19.55%, a net present value (NPV) of 346,085 USD, and a Levelized Cost of Energy (LCOE) of 0.1892 USD/kWh. The payback period for the present system is projected to be 17.4 years. Furthermore, the implementation of the photovoltaic plant will contribute to a reduction of around 6,852 tonnes of CO_2 emissions. Mohammad and Zabihi [23] designed a solar power plant using PVsyst requires careful planning, especially when working with bifacial panels. A recent study based on a real 100-kW rooftop project in Arak, Iran, highlights the importance of correctly setting the bifacial factor to avoid errors in energy yield predictions. It explores key design challenges like optimizing panel angles, spacing, and height to capture rear-side radiation while minimizing shading. Tools like PVsyst, AutoCAD, ETAP, and RET Screen were used to simulate and analyse both technical and economic aspects. The study shows how local conditions and environmental factors must be considered for more accurate and efficient PV system design. Tajjour et al.[24] evaluate a 100 kWp rooftop solar micro grid in the Western Indian Himalayas, aiming to enhance energy generation by optimizing the panel tilt angle. Using isotropic, NASA, PVsyst, and PVGIS models, the study finds a 6.5% improvement in output, emphasizing the importance of site-specific tilt angle optimization.

This work discovers how well a 5.0 kWp rooftop solar system performs in real-world conditions in Gwalior, Madhya Pradesh. Installed at G.P. Convent School, the system's actual energy output in 2024 was compared with PVsyst simulation results to see how closely reality matches predictions. It not only looks at technical aspects like energy yields but also evaluates cost-effectiveness through payback period and ROI. The novelty lies in combining real performance data with simulation for a second-generation PV system, helping us better understand how these systems work in local Indian climates and how viable they are for everyday energy use.

The objective of this study is to evaluate the performance of a 5.0 kWp second-generation PV solar rooftop system installed at G.P. Convent School in Gwalior, India. Specifically, the study aims to:

- Analyse the real-time operational data of the solar system under actual climatic conditions of Madhya Pradesh.
- Compare the system's real-world energy yields and performance ratios with those predicted by PVsyst simulation software.
- Assess solar irradiance and quantify the technical performance indicators such as array yield, reference yield, and final yield.
- Examine the economic viability of the PV system through indicators such as payback period and return on investment (ROI).

This study contributes by evaluating a 5.0 kWp rooftop PV system's real-world performance in Gwalior, India, and comparing it with PVsyst simulations. It offers technical and economic insights, confirms solar viability in semi-arid climates, and supports informed decision-making for sustainable energy planning and rooftop solar adoption in similar regions.

MATERIALS AND METHODS

Numerical Modeling of PV Solar Rooftop

PVsyst 8.0.6 is an advanced simulation tool designed for the simulation and modeling of PV solar systems [25]. It offers a comprehensive solution for designing grid-connected, pumping, standalone, and DC grid PV systems. The software is user-friendly, requiring only a few known variables, and provides detailed insights into the sizing of systems, no. of inverters, number of PV arrays, and the overall system performance analysis. 3PP is an all-in-one tool designed to analyse various aspects of photovoltaic (PV) systems, whether they are connected to the grid, autonomous, or used for water pumping. The software is capable of importing weather data from multiple sources, as demonstrated in Figure 1. PVsyst6 provides a range of valuable information, such as energy output, solar radiation, installation investment costs, required surface area, and annual energy generation. It allows for rapid estimations of energy generation for initial feasibility studies, as well as detailed project design, analysis, and dimensioning. The software also supports time simulations and generates comprehensive reports. Additionally, it includes features like importing meteorological data, synthetic generation, and a component database for PV modules, inverters, batteries, pumps, and more. PVsyst6 also offers educational tools and optimization features, such as solar geometry, orientation adjustments, and analysis of the electrical performance of PV fields with shading effects. Figure 2 represents an overview of project setup. The project title is entered at the top, and in "site file" box, you can select the relevant site file, with an existing map for reference. The city and country info can be entered in the respective fields. The meteorological data file can be selected using NREL's resources. On the main parameters page, you can configure key system settings, such as the orientation and specifications of the system.

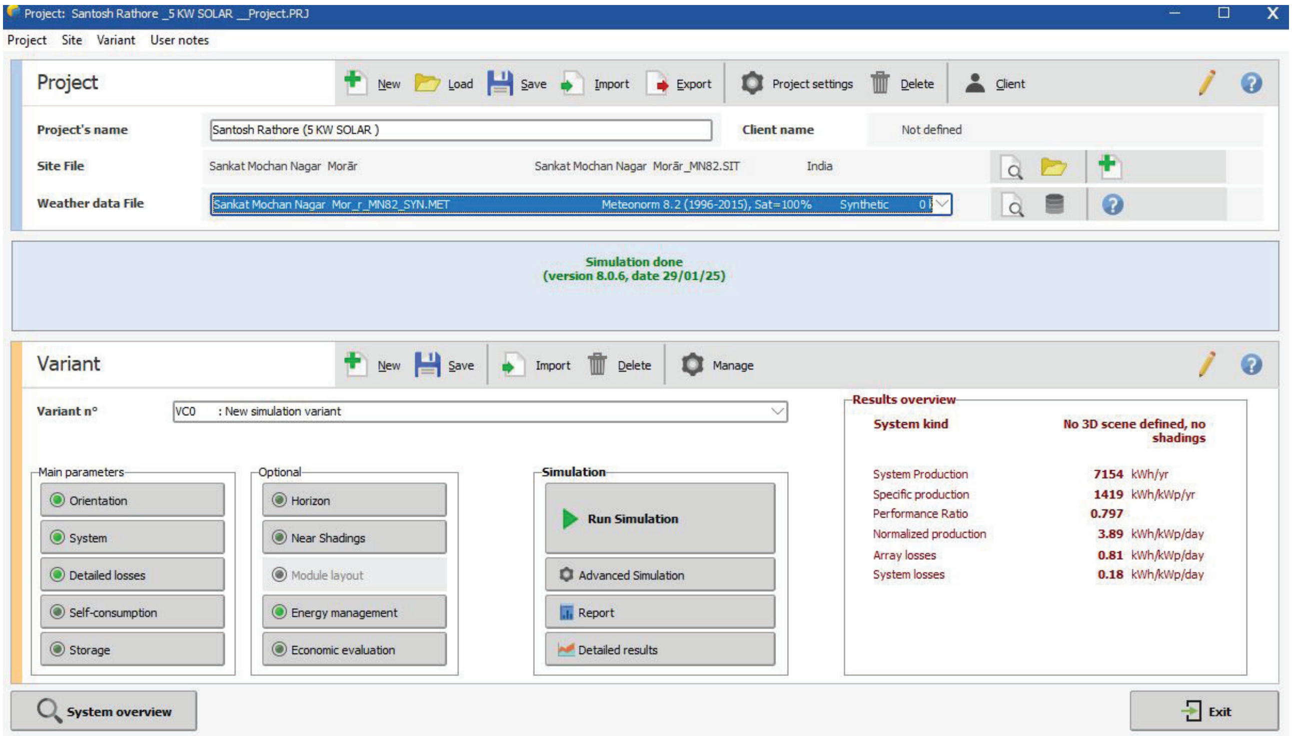


Figure 1. Dissemination of interface of PVsyst software in Gwalior region.

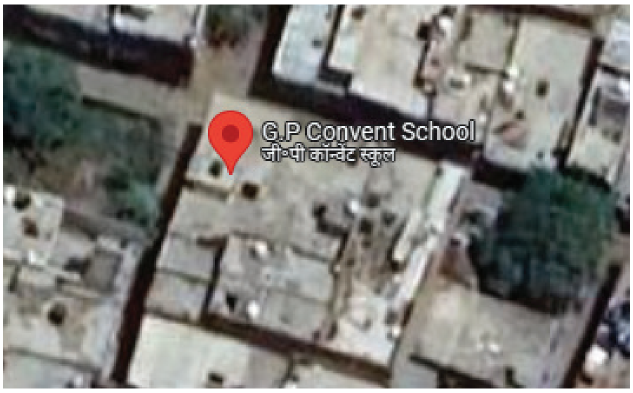


Figure 2. GP Convent School Geographical Location.

Selection of Location (Geographical Coordinates)

For this simulation, G.P. Convent School, located in Sankat Mochan Nagar Morar, Gwalior, M.P, India (78.21°E, 26.22°N), was selected as the site for analysis (Fig. 2).

The system was designed to meet a 5.00 kWp load. Input data needed for simulation include the geographical coordinates of the site. After inputting the values for longitude and latitude, solar irradiance is calculated, which is crucial for the design of the solar PV system. The performance analysis of the grid-connected PV system was conducted for various panel tilt angles. The specific tilt angles were considered as a 22° inclination (Fig. 3) for the annual irradiation yield of the 5.00 kWp unit, and also to assess the system's performance based on the plant's latitude.

The system design incorporated the SUN2000-4.95TL-JPL1 inverter and the Vision 60M construct, 315 Wp PV array, select to meet 5.00 kWp load. The complete description of PV modules is presented in Table 1. The subsequent design factors were considered for simulation and modeling of the solar photovoltaic system. The PV array characteristic is demonstrated in Figure 4.

- **PV Array Specifications:** The system design for G.P. Convent School utilizes Vision 60M construct, 315Wp, with each polycrystalline solar module having a rated peak power output of 300 W.
- **Inverter Specifications:** The system's 5.00 kWp design uses the SUN2000-4.95TL-JPL1 inverter, with a capacity of 4.95 kWp per unit, manufactured by Sun Power Solutions.

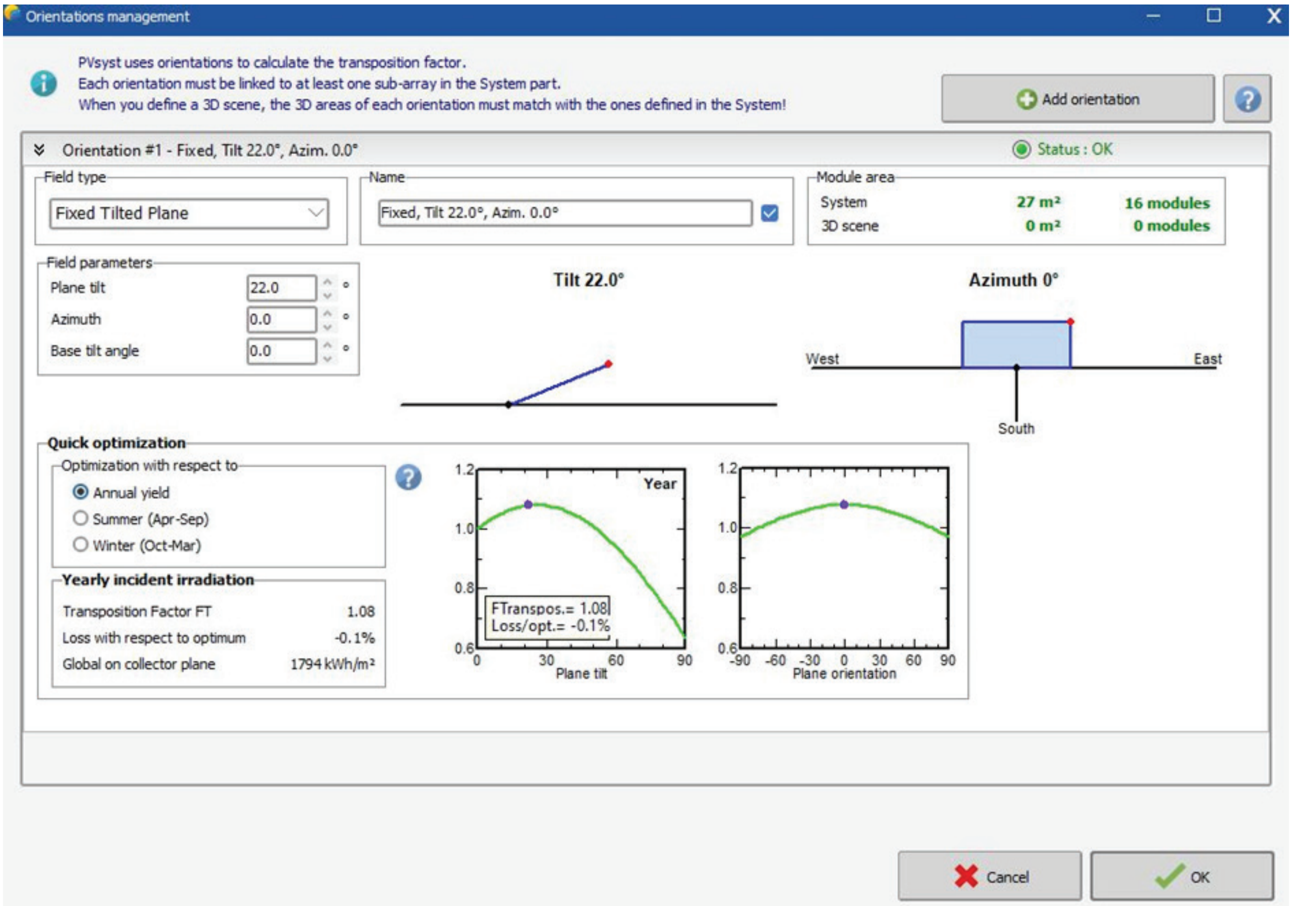


Figure 3. Representation of orientation of PV modules.

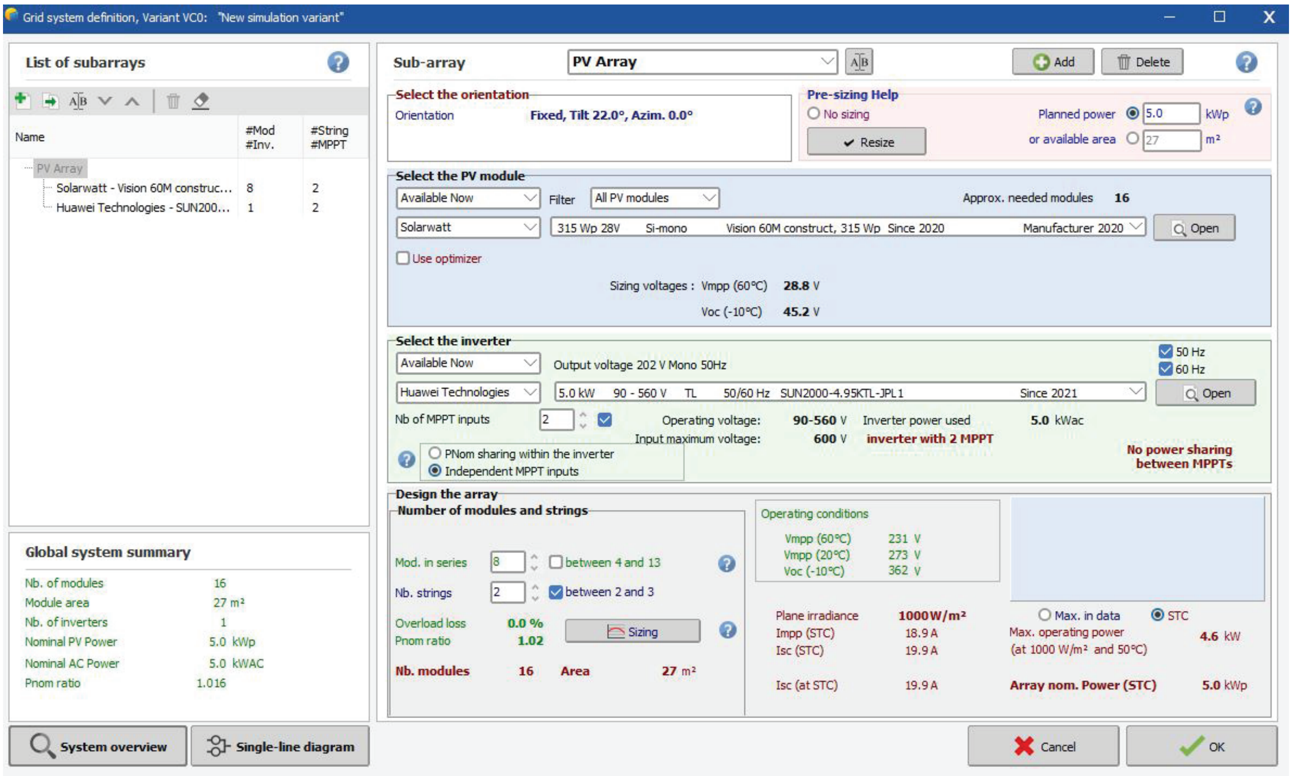


Figure 4. Representation of PV array characteristic.

Solar Radiation: The average solar radiation at geographic coordinates 26.21°N and 76.23°E is approximately 5.477 kWh/m²/day, which is deemed adequate for efficient electricity generation. The solar radiation represents amount of solar energy incident/unit area, typically expressed in W/m². This value exhibits seasonal variation, reaching its peak during the summer months and its minimum during the winter. The simulation process for determining solar irradiance in PVsyst and single line diagram of a 5.00kWp grid-connected is illustrated in Figures 5 and 6, respectively.

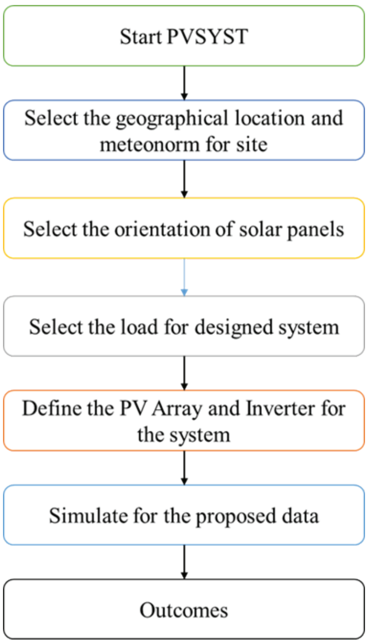


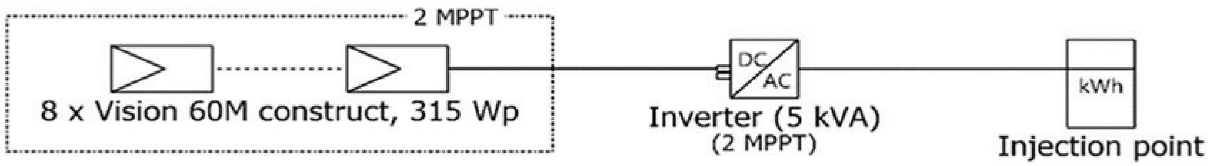
Figure 5. Flowchart of simulation in PVsyst.

Assessment of Solar Potential in Terms of Solar Path

The evaluation of solar potential takes into account the system-dependent occurrence angle modifier, which fluctuates based on the tilt angle of installation. The incidence angle modifier changes with the tilt angle at a specific site location, and this variation is called as the sun path or location diagram. In PVsyst, defining shading requires a horizon line, as this helps define how the sun's path interacts with environment. The solar path ascends from December to June and descends from July to Dec. The 21st of June marks the longest day of the year, whereas the 21st of Dec has the shortest day. The months of Mar and Sept feature equal day and night lengths. Figure 7 shows the sun path for the selected location.

Data Analysis

Performance analysis factors for evaluating the grid-connected solar PV system included the assessment of: Losses in the System and Array, yields (Final, Reference and Array), System Efficiencies (Inverter, Array and



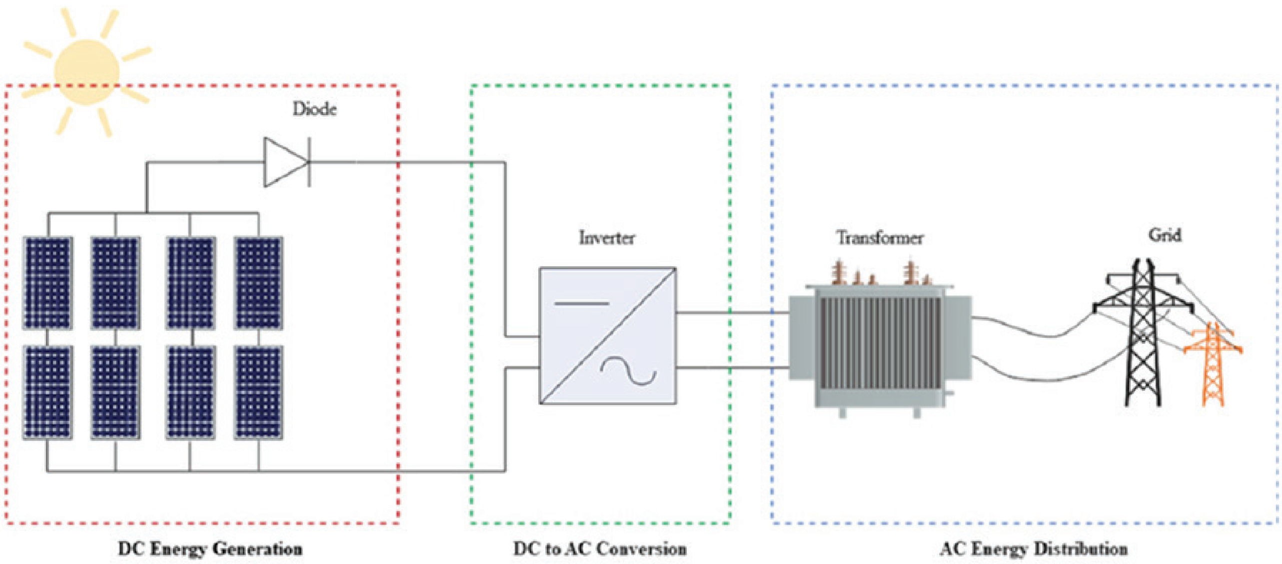


Figure 6. Schematic layout of 5kWp PV rooftop system at G.P. Convent School, India.

Table 1. G.P. Convent Solar PV system specifications

Description of the System	Experimental System	Simulation system
PV Panel Model	Vision 60M construct, 315Wp	Vision 60M construct, 315Wp
No. of PV panels	16 units	16 units
Model of Inverter	SUN2000-4.95TL-JPL1	SUN2000-4.95TL-JPL1
Size of Inverter (kWp)	4.95	4.95
Efficiency of Inverter	97%	97%
Capacity of System	5.00kWp	5.00kWp
Tilt angel	22°	22°
Modules	2 string x 8 units kWp In series	2 string x 8 units kWp In series
At operating condition	50°C	50°C
Module Area	26.6m^2	26.6m^2

System), Capacity Factor (CF), Performance Ratio (PR), Total Energy produced and Economic Analysis.

Analysis of system yields

The system's energy yields are classified into 03 types: Final Yield, Reference Yield, and Array Yield. The Array Yield (Y_a) is defined as, direct current (DC) energy generated by the photovoltaic solar array, divided by the nominal (rated) power of photovoltaic solar system. It characterizes the duration for which system operates at its rated power, expressed in kWh/kWp, as discussed below:

Array yield (Y_a)

It may also be determined by considering the ratio of produced direct energy to the nominal (rated) power of

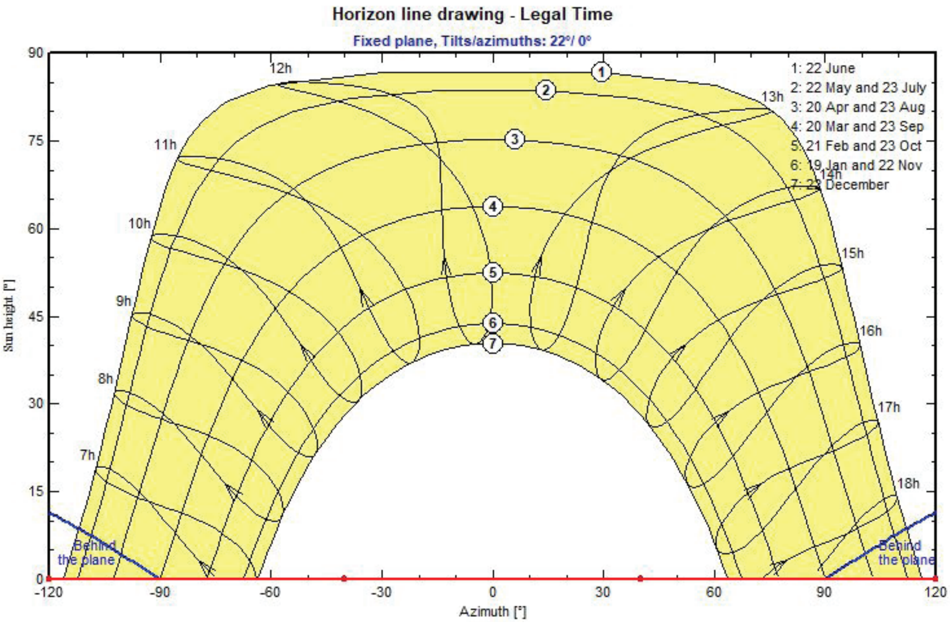


Figure 7: Representation of solar path at coordinates 78.21°E, 26.22°N**.**

the photovoltaic solar system. The daily array yield ($Y_{a,d}$) is determined using the following Eq.[26]

$$Y_{a,d} = E_{DC,d}/P_{pv,rated} \tag{1}$$

The mean value of the monthly array yield ($Y_{a,m}$) is calculated using the following Eq.

$$Y_{a,m} = (1/N) * \sum_{d=1}^{N} Y_{a,d} \tag{2}$$

The Array yield (Y_a) indicates the period the PV system obtains to operate at nominal power generation in units of h/day.

Final yield (Y_f)

Final Yield (Y_f) refers to the alternating current (AC) energy produced by the PV solar system over a specific time, divided by the nominal (rated) power of system. It denotes the duration for which the system operates at its rated power, expressed in the term of kWh/kWp. It may be also defined as the ratio of the final generated power to the rated photovoltaic power specified by the manufacturer under standard test conditions. This metric shows the time required for the photovoltaic system to generate its final energy output relative to its nominal power capacity [26].

The daily final yield ($Y_{a,f}$) is determined using the following Eq.

$$Y_{f,d} = E_{AC,d}/P_{pv,rated} \tag{3}$$

The average value of monthly array yield ($Y_{f,m}$) is calculated using following Eq.

$$Y_{f,m} = (1/N) * \sum_{d=1}^{N} Y_{f,d} \tag{4}$$

Reference yield (Y_r)

It may be defined as, the total in-plane solar irradiance ratio to the reference insolation under standard operating temperature conditions of 1 kW/m^2. It can be computed as follows Eq.

$$Y_{r,d} = T_r * \sum G_{i_{day}}/G_{STC} \tag{5}$$

Moreover, the improved reference yield (Y_r) is computed by considering the module's modification impact and atmospheric temperature, as written in Eq.

$$Y_{impr} = Y_r * [1 - C_t(T_m - T_{STC})] \tag{6}$$

Energy Output

The energy fed to the utility grid (E_{AC})

The whole-day analysis of alternative current (AC) energy production is calculated using the following Eq.

$$E_{AC,d} = \sum_{t=1}^{t=T_{rp}} V_{AC} * I_{AC} * T_r \tag{7}$$

Alternative current (AC) output produced in a month is determined as using Eq.

$$E_{AC,m} = \sum_{d=1}^{N} E_{AC,d} \tag{8}$$

Energy generated through Photovoltaic systems (E_{DC})

The entire energy output is defined as the quantity of alternative current (AC) power produced by the Photovoltaic solar system over a given period.

The overall monitored everyday direct current power is evaluated using Eq.

$$E_{DC,d} = \sum_{t=1}^{t=T_{rp}} V_{DC} * I_{DC} * T_r \quad (9)$$

The monthly produced direct current energy is determined using the following Eq.

$$E_{DC,m} = \sum_{d=1}^{N} E_{DC,d} \quad (10)$$

where, N, m, and d indicate the no. of working days of a plant and monthly, and daily value respectively.

Efficiencies of The System

Efficiency of a photovoltaic system is categorized into 03 different types: array efficiency, system efficiency, as well as inverter efficiency. All these three efficiencies can be determined on a yearly, monthly, daily, as well as hourly basis, respectively. System efficiency (η_{sys}) is computed using alternating current (AC) power output, therefore array efficiency (η_{PV}) is evaluated by direct current (DC) power output. The array efficiency is defined as ratio of daily, monthly, or annual average direct current (AC) energy output of array to total solar insolation received on the inclined plane, multiplied by area of a photovoltaic solar array. photovoltaic solar array efficiency is determined as:

Photovoltaic module efficiency (η_{PV})

Efficiency of a Photovoltaic module reports, how much amount of energy a PV module produces compared to available irradiance. It can be determined using the following Eq.

$$\eta_{PV} = \left[{P_{DC}}/{G_i * A_m}\right] *100\% \quad (11)$$

The PV module efficiency on a monthly basis is calculated using the following Eq.

$$\eta_{PV} = \left[{E_{DC,m}}/{G_i * A_m}\right] *100\% \quad (12)$$

Inverter efficiency (η_{inv})

It is defined as the ratio of alternative current energy generated by an inverter to the direct current energy produced by a PV solar system array. During the determination of inverter efficiency, it should be noted that, both the η_{PV} and η_{sys} are the higher, therefore it is the conversion efficiency of Direct current to Alternative current. The instantaneous inverter efficiency (η_{inv}) can be evaluated as:

$$\eta_{inv,m} = \left[\frac{E_{AC,m}}{E_{DC,m}}\right] * 100\% \quad (13)$$

System efficiency (η_{sys})

It can be determined as the multiplication of photovoltaic module efficiency (η_{PV}) and inverter efficiency (η_{inv}). The System efficiency (η_{sys}) can be computed using the following Eq.

$$\eta_{sys} = \eta_{PV} * \eta_{inv} \quad (14)$$

Capacity Factor

The capacity factor (CF) is a measure of how efficiently a photovoltaic (PV) solar system produces energy over time. It is determined by taking total alternating current (AC) power generated by the system and dividing it by the product of system›s rated (nominal) energy and the specified time period, usually a month or a year. Capacity Factor (CF) can be defined as the ratio of actual yearly generation of energy to the power produced by a photovoltaic (PV) solar system of rated capacity for 24 hours/day throughout the 01 year. The annual CF of the photovoltaic solar system is evaluated using the following Eq. 15:

$$CF = {Y_{f,annual}}/{24 * 365} = {E_{AC,annual}}/{P_{pv,rated} * 8760} \quad (15)$$

Eq.15 can be also written as:

$$CF = \frac{\frac{h}{day} * peak\ sun}{24\ hrs/day} \quad (16)$$

The CF varies in a similar pattern to the final yield. It indicates that how much energy a power system actually delivers compared to its maximum possible output. If the system operated at its full rated power all times, the CF would be 01.

Performance Ratio

The Performance Ratio (PR) reveals all the losses in a photovoltaic solar system. It denotes how efficiently the system operates in real operating conditions in comparison to its ideal performance. A higher PR value means the system is performing closer to its maximum potential. PR allows for a fair comparison between different photovoltaic systems, regardless of factors like angle, tilt, orientation, location, or rated power capacity [27].

It is evaluated as the ratio of the final yield (Y_f) to the array, yield (Y_a) of the PV system, written as [26]

$$PR = \frac{Y_f}{Y_a} \quad (17)$$

As discussed in Eq. 18, it can be considered as function of temperature efficiency ($\eta_{temperatue}$), degradation efficiency ($\eta_{degradation}$), inverter efficiency ($\eta_{inverter}$), and soil efficiency (η_{soil}):

$$PR = \eta_{degradation} * \eta_{tempearture} * \eta_{soil} * \eta_{inverter} \quad (18)$$

System and Array Energy Losses

The array losses (L_a) indicate the energy losses that occur throughout the operation of photovoltaic array, highlighting its inability to fully convert available solar radiation into the electricity. These losses are calculated by difference b/w the reference yield (Y_r) and array yield (Y_a). The array losses (L_a) are determined using Eq.19.

$$L_a = Y_r - Y_a \tag{19}$$

System energy losses (L_s) occur during the conversion of direct current power to alternating current by the inverter. These losses result from the inefficiencies in the inverter›s conversion process [25].

$$L_s = Y_y - Y_f \tag{20}$$

Economic Analysis

The cost of energy generated by grid-connected PV solar rooftop system is influenced by a variety of factors. Having precise information about these variables is crucial for accurately estimating the energy generation costs. Some of these key factors include:

- ❖ Weather conditions specific to the location (i.e., daily solar radiation, sunshine hours, and ambient air temperature).
- ❖ System components (i.e., PV panels, which are influenced by the module technology and efficiency, as well as cost of inverters, cables, and other electrical components).
- ❖ Economic factors specific to the region/location (i.e., interest and inflation rates, along with installation, operation, and maintenance costs).
- ❖ The local electricity costs.
- ❖ The economic lifespan of system.

Several economic indicators are commonly used to evaluate the economic performance of PV solar rooftop systems, such as life cycle cost (LCC), lifetime net income (NI), net present value (NPV), levelized cost of energy (LCOE), and return on investment (ROI) are discussed in Table 2.

Environmental analysis

The power grid supplies the electrical energy required for government buildings as well as academic campuses, with electricity produced from conventional, nuclear, hydroelectric, and renewable energy resources. Therefore, a substantial amount of CO_2 is released during the generation of power. By substituting grid electricity with solar PV-based electricity, the CO_2 emissions reductions from avoiding the use of grid power are evaluated using emission factors from the Central Electricity Authority of India (CEA, 2019) using following equation:

$$\text{CO}_2 \text{ emisson factor } = 0.9247\text{tCO}_2/\text{MWh} \tag{21}$$

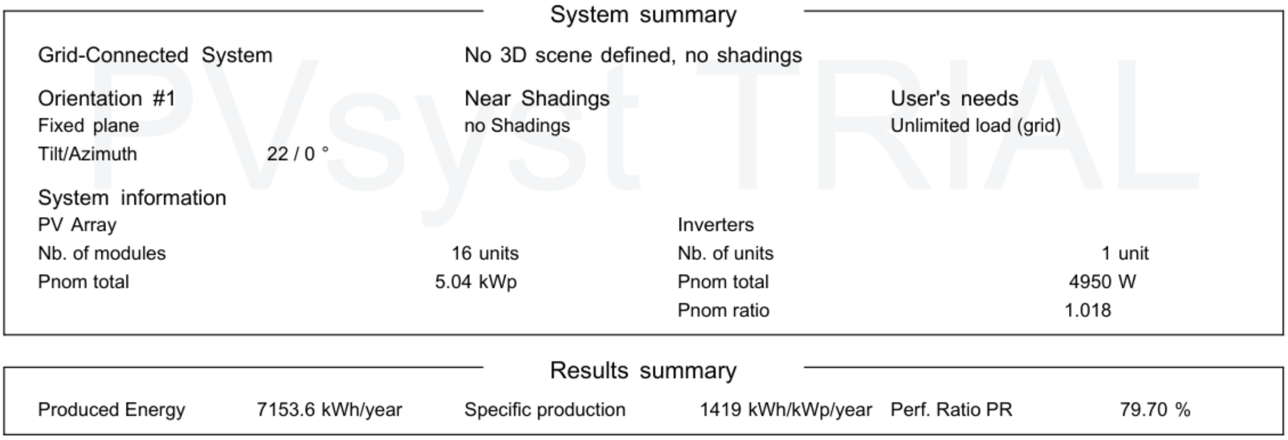
RESULTS AND DISCUSSION

This section deals with the comparison of performance analysis results of the experimental system with PVsyst software.

A grid-connected Photovoltaic solar system with a fixed tilt angle (22°) was selected for site. Based on location’s solar radiation and site specifications, the optimal tilt angle was calculated to be 22°, with an azimuth angle of 0° as shown in Figure 6. A PV panel and inverter from a suitable manufacturer were chosen, with the number of panels optimized to meet the required load demand. The total power demand is as follows: Entire building: 5.00 kWp. PVsyst provided a comprehensive simulation report detailing the system’s performance. According to the simulation findings (Fig. 8), the system generates 7153.6 kWh/year with a specific energy yield of 1419 kWh/kWp/year and a performance ratio of 79.70% when the PV modules are fixed for the building’s energy needs.

Table 2. Parameters, Equations and Values used in Economic Analysis [28]

Parameters	Equations	Description for the value
Life cycle cost (LCC)	$LCC = \sum_{i=1}^{25} \frac{\{(C_{componet,i} + C_{O\,\&\,M,i}) \times Capacity\}}{1.05^i}$	$C_{omponent,i}$ = Component investment $C_{O\,\&\,M,i}$ = operation and maintenance cost
Revenue during its lifetime	$Rev_k = \sum_{i=1}^{25} \frac{E_{pi} \times P_k}{1.05^i}$	Rev_k= Lifetime income P_k = Cost of electricity
Net present value (NPV)	$NPV_i = \sum_{t=1}^{i} \frac{R_i}{1.05^i}$	
Lifetime net income (LNI)	$LNI = Rev_k - LCC$	
Return on investment (ROI)	$ROI = {}^{LNI}/_{LCC} \times 100$	
Levelized cost of energy (LCOE)	$\frac{LCC}{E_{p25}} = \frac{\sum_{i=1}^{25} \frac{\{(C_{componet,i} + C_{O\,\&\,M,i}) \times Capacity\}}{1.05^i}}{\sum_{i=1}^{25} E_{pi}\, K^{i-1}}$	


System summary

Grid-Connected System — No 3D scene defined, no shadings

Orientation #1		Near Shadings	User's needs
Fixed plane		no Shadings	Unlimited load (grid)
Tilt/Azimuth	22 / 0 °		

System information

PV Array		Inverters	
Nb. of modules	16 units	Nb. of units	1 unit
Pnom total	5.04 kWp	Pnom total	4950 W
		Pnom ratio	1.018

Results summary

Produced Energy	7153.6 kWh/year	Specific production	1419 kWh/kWp/year	Perf. Ratio PR	79.70 %

Figure 8. Comprehensive simulation report of PVsyst software.

Analysis of Electrical Energy Generation

Table 3 presents the monthly generation of electrical power as well as solar irradiance in the collimated plane.

Figure 9 represents the monthly generation of electrical power as well as solar irradiance in the collimated plane.

The lower value of generated electrical power was noted as 588 kWh, due to low solar insolation, clouds, and rain in December. Therefore, the higher value of electrical power generation (885 kWh) was achieved in month of June due to higher solar intensity, clear sky, as well as long day. The solar irradiances fluctuate from 4590.2 kWh to 7612 kWh in Dec and Jun, due to rainy as well as partially cloudy days and arid summer days, respectively. In twelve months, the generation of electrical power was 6910.20 kWh, therefore, a monthly average of 575.5 kWh. It was noted that the electrical energy produced during the 12 months over the nominal power of photovoltaic solar system was 1795.5 kWh/kWp. The temperature also fluctuated in the range of 17.2 to 45.2°C in the months of Jan and July respectively, therefore, the annual average of the highest temperature was noted as 31°C. It was observed that, despite the high temperatures in June, which reduced the efficiency of the photovoltaic solar system, the maximum electrical energy production was still noted in this month. This is mainly because June has the longest daylight hours (15 hrs) and the highest solar irradiance intensity. In another aspect, December sees lower energy production because of its shorter daylight hours (9 hrs) and lower solar radiation intensity. When comparing actual energy generation with simulated results,

Table 3. Monthly solar energy and performance ratio by PVsyst

Month	GlobHor kWh/m²	Diff Hor kWh/m²	T_Amb °C	Glob Inc kWh/m²	Glob Eff kWh/m²	E_Array kWh	E Grid kWh	PR Ratio
January	98.5	47.4	14.01	124.0	121.8	550.9	526.3	0.842
February	124.1	54.6	18.37	149.3	146.5	645.1	617.6	0.821
March	166.4	70.5	24.95	185.1	181.5	771.4	738.5	0.792
April	179.1	83.8	30.34	182.8	179.1	743.9	711.6	0.772
May	192.4	98.0	34.50	184.9	180.7	742.6	710.1	0.762
June	167.1	102.9	33.52	156.7	152.9	641.7	613.2	0.777
July	146.8	101.9	30.76	138.9	135.3	583.2	556.8	0.795
August	133.3	88.9	29.47	130.6	127.4	548.9	523.4	0.795
September	137.4	74.0	28.67	144.3	141.2	599.7	572.6	0.787
October	127.3	67.9	26.30	144.9	142.3	607.7	580.4	0.795
November	100.3	58.0	20.31	121.7	119.2	528.4	504.8	0.823
December	91.7	47.5	15.36	117.7	115.5	521.7	498.3	0.840
Year	1664.6	895.4	25.58	1780.8	1743.3	7485.0	7153.6	0.797

Key: Glob Inc =…, …

the experimental photovoltaic solar system generated an annual average of 6910.20 kWh at an average ambient temperature of 31°C. This was compared to results from PVsyst, a widely used software for PV system analysis and simulation, which estimated an annual average of 7485 kWh at a lower average air temperature of 25.5°C. The difference between experimental data and simulation results is relatively small, even though the experimental system operates under higher temperatures and is affected by external parameters such as rain, clouds, and dust. In contrast, PVsyst simulations are based on ideal conditions with lower temperatures and no environmental disturbances. This close match between experimental and simulated data indicates that the practical performance of the

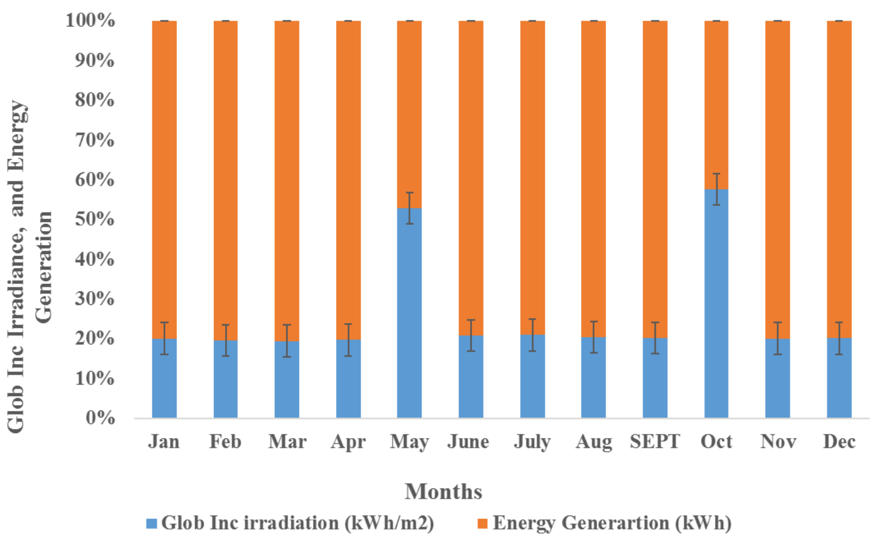


Figure 9. Representation of monthly energy generation and Glob Inc. irradiation.

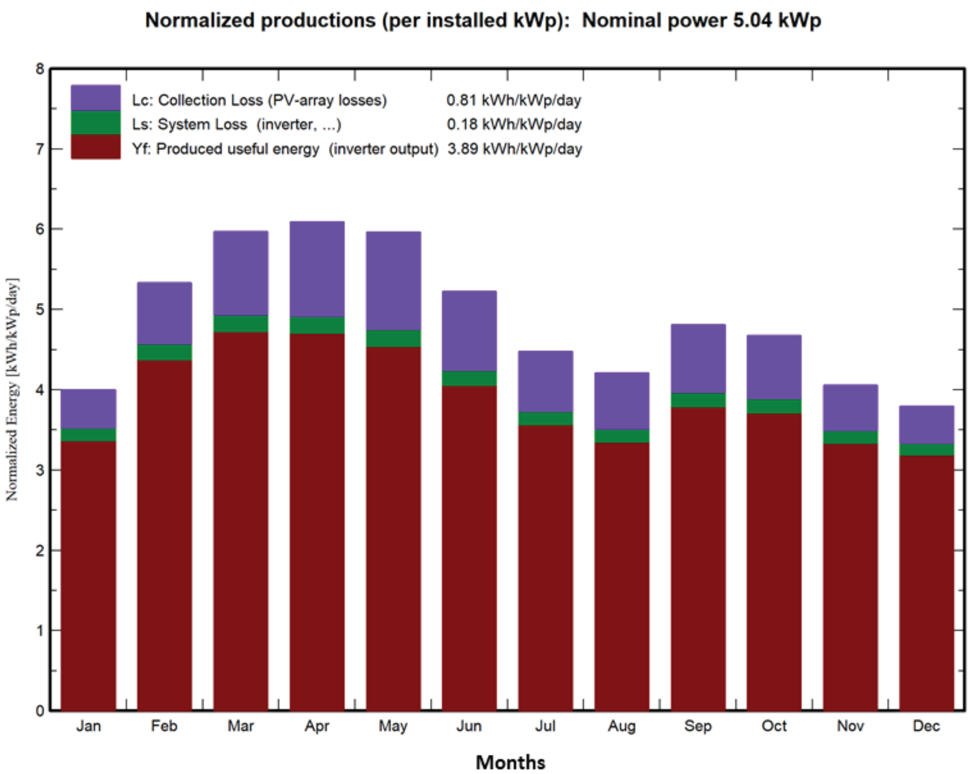


Figure 10. Representation of monthly normalized energy generation.

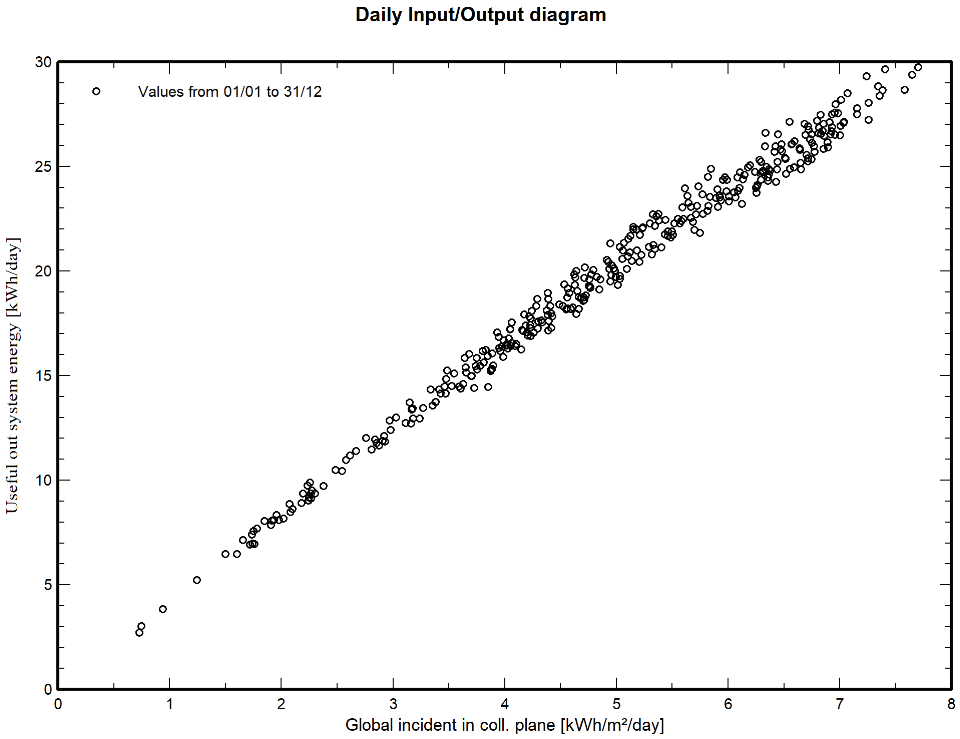


Figure 11. Representation of Glob Inc. irradiation in coll. plane.

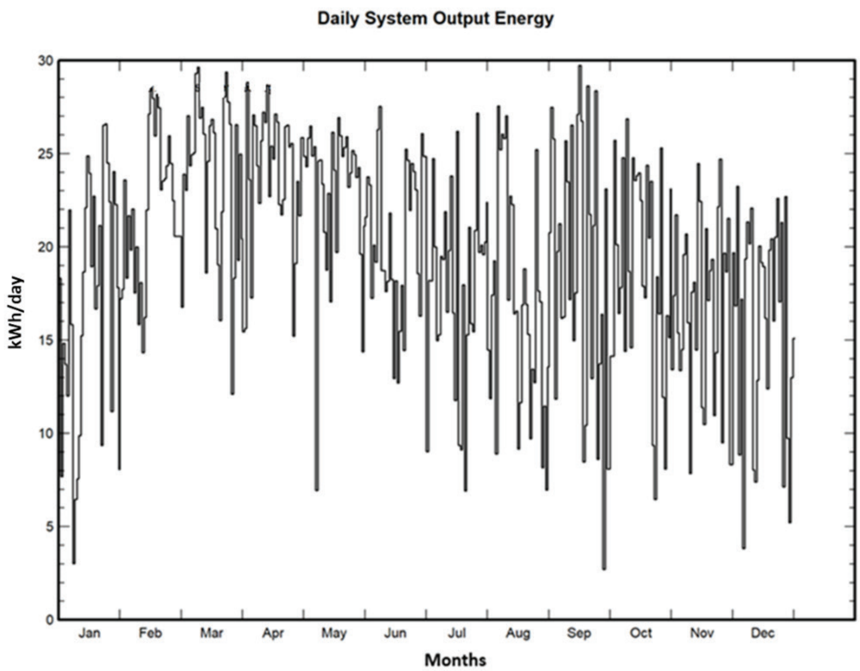


Figure 12. Monthly system output energy.

system is quite good. Table 3 indicates the balance sheet of PVsyst results including the global energy hor, diff hor., Glob Inc.., ambient temperature, E array & Figures 10-11 shows the trends of normalized energy generation, Glob Inc. Eff, irradiation in coll. Plane, and monthly output energy respectively. Figure 12 shows the daily energy produced by the installation. The maximum electrical energy generated was from June to Aug.

Analysis of Yield performance

Figure 13 demonstrate monthly average values of array yield, final yield, as well as daily reference yield respectively.

The lowest values were noted during the winter months, specifically in Dec and Jan. In the month of Dec, the array yield, final yield, and reference yield were calculated as 4.2, 4.0, and 4.8 kWh/kWp/day, respectively. In contrast, the maximum values were recorded in the month of June, reaching 6.15, 6.0, and 7.80 kWh/kWp/day, respectively. The annual average values were noted as 5 for array yield, 4.91 for final yield, and 6.25 kWh/kWp/day for reference yield. Vignola et al. [12] observed that inverter efficiency reduces by approximately 1% for every 13°C increase in ambient temperature. When comparing the final yield of the experimental system at an annual average temperature of 31°C to the simulated PVsyst results at 25.5°C, the annual average final yields were recorded as 4.91 kWh/kWp/day for the experimental system and 5.41 kWh/kWp/day for the simulation. This small difference highlights the strong performance of the actual system. Since PVsyst operates as a clear-sky model, it does not account for atmospheric effects such as dust, clouds, and rain. However, despite the hot summer climate of Madhya Pradesh, the PV solar system performed exceptionally well. This demonstrates its potential as a promising solar technology for India.

Determination of Losses

PV modules and arrays experience various kinds of losses, including wiring losses (1.5%), module quality losses (2.5%), and module mismatch losses (2%). These all losses primarily result from temperature variations, module inconsistencies, as well as wiring inefficiencies. After accounting for inverter losses, the total amount of energy delivered to grid is computed. The final energy output from the PV system for load/grid is evaluated to be 7153.6 kWh. This value is attained after applying multiple loss corrections within PVsyst software, as presented in Figure 14.

The loss diagram provides a step-by-step breakdown of all the losses occurring throughout the system. Despite these losses, the system successfully delivers 596.2 kWh/m of usable energy.

Figure 15 presents monthly average value of daily losses for the overall system, array, and inverter. In the month of July, the maximum value of daily array loss was noted as 1.59 kWh/kWp/day, primarily due to the high ambient temperatures. In contrast, the minimum array losses were calculated in January and December, as 0.61 kWh/kWp/day. These values represent 21.56% and 13.01% of monthly daily average reference yield, respectively. System losses (primarily due to inverter inefficiencies) varied in the range of 0.15 kWh/kWp/day in Dec to 0.23 kWh/kWp/day in June. This increase in losses during June is because of the higher solar radiation, which leads to greater DC-to-AC conversion demands. These losses account for 3.1% and 3.0% of daily reference yield, respectively. When comparing annual averages, the real system's daily array losses were 1.2 kWh/kWp/day at an annual average temperature of 31°C, whereas the PVsyst simulation estimated 0.731 kWh/kWp/day at 25.5°C. The difference is relatively small, at only 0.469 kWh/kWp/day. Similarly, annual average daily system losses were 0.181 kWh/kWp/day for experimental system and 0.18 kWh/kWp/day for the simulated system. The close agreement in system losses is attributed to the similar inverter efficiencies, as the experimental system's inverter was installed indoors, minimizing temperature-related losses. The highest value of overall losses was

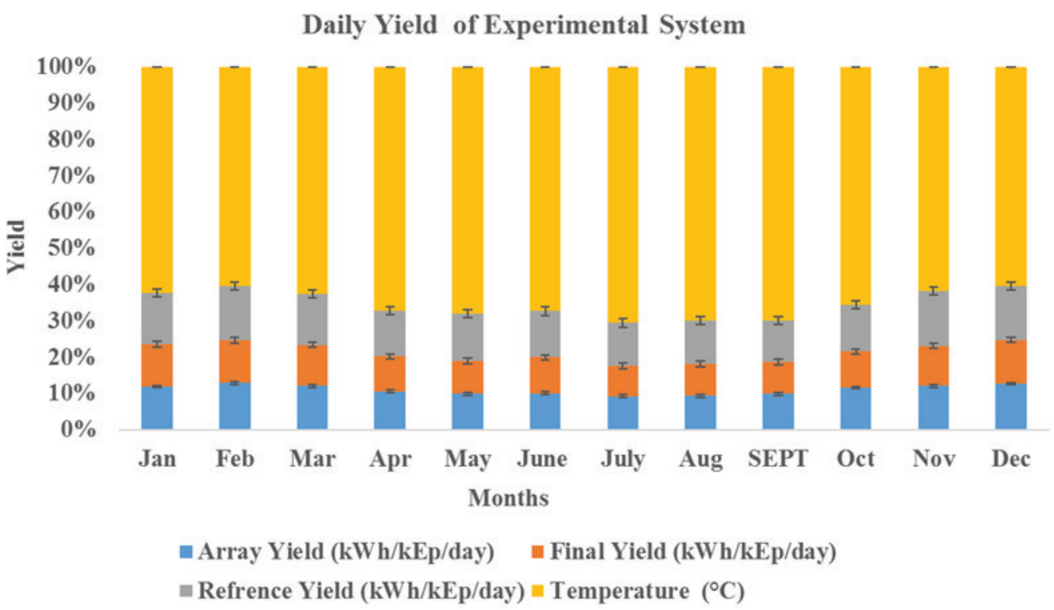


Figure 13. Monthly yield performance of actual system.

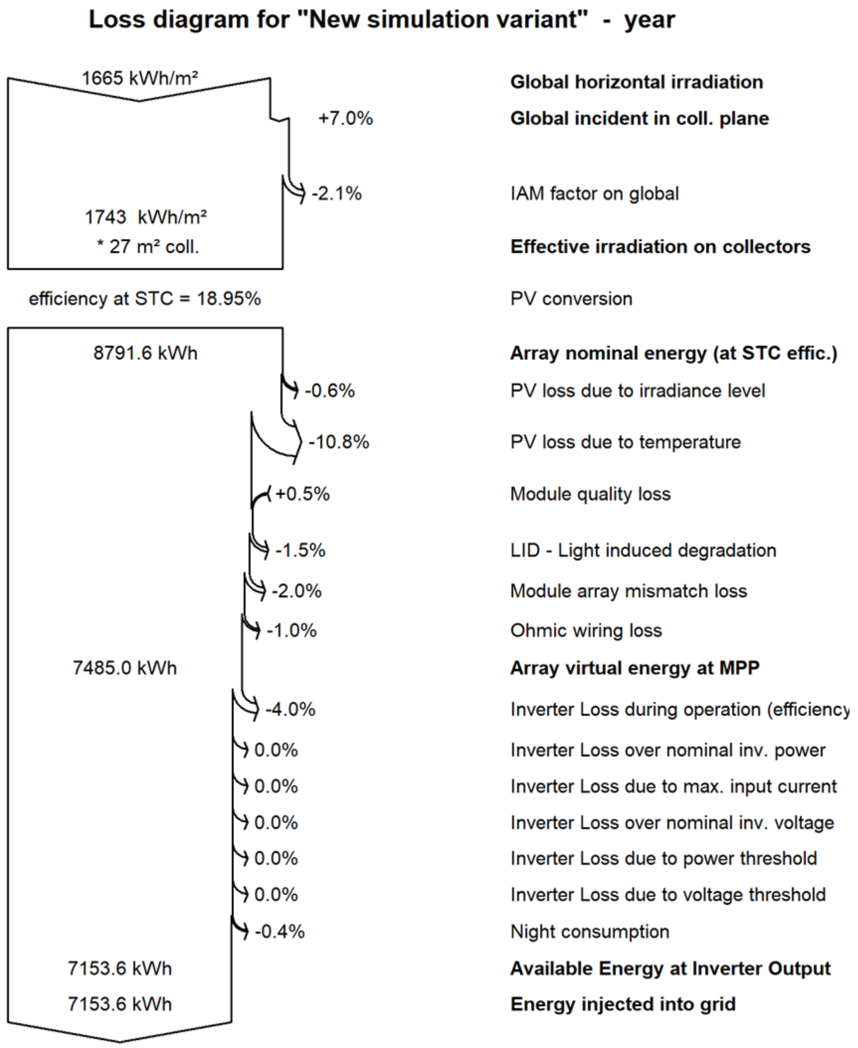


Figure 14. Simulated Energy losses.

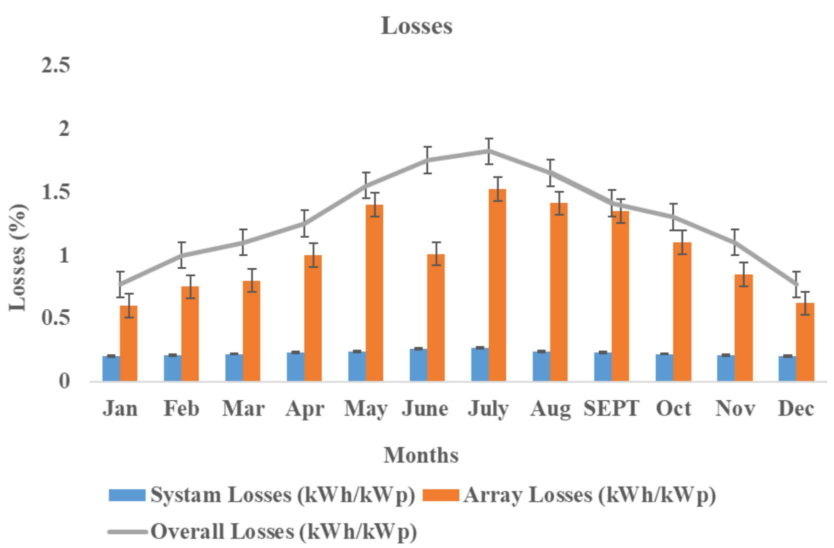


Figure 15. Monthly Solar Energy Losses.

observed in July at 1.84 kWh/kWp/day, while lower losses were in Jan and Dec, as 0.764 kWh/kWp/day. These losses accounted for 25.1% and 17.1% of the daily reference yield, respectively.

Evaluation of Performance Ratio and Capacity Factor

Figures 16 and 17 indicates monthly average capacity factor (CF) and performance ratio (PR) of actual system and PVsyst software respectively. The annually average PR for experiment system was 81.01%, with maximum values recorded in Jan and Dec (84.1%) and the minimum in July (77%). PR serves as an indicator of how closely the experimental system operates to its theoretical maximum performance. PR of the system tends to drop in May, June, July, and Aug, mainly because of high temperatures throughout these months. When comparing annually average PR of the experimental system (81.01%) at an annual average temperature of 31°C with the PVsyst simulation result (79.7%) at 25.5°C, the difference is small. This suggests that the experimental system performs very well despite the higher atmospheric temperature, indicating that it is not significantly affected by extreme heat. The annual average capacity factor (CF) for the system was 21.02%, with a maximum of 25.21% in June and a minimum of 15.9% in December. The CF indicates the percentage of time the PV system operates at full capacity. In this case, the system generates power at full capacity for approximately 92 days (2,208 hours) per year, mainly during June, July, and Aug. CF also has a direct impact on the cost of electricity generation, making it an essential parameter for evaluating grid-connected PV systems. When comparing the yearly average CF of the experimental system (21.2%) with the PVsyst simulation result (23.02%), the difference is only 1.82%. This small gap indicates the strong performance of the experimental system, even though the PVsyst model does not account for cloud cover, rain, or dust.

Solar Energy Efficiency

The comparative analysis of simulated and experimental energy data are presented in Table 4.

Figure 18 indicates the monthly average efficiencies of the inverter, system, as well as array over the observation time.

The annual average efficiencies were noted as: Inverter efficiency (96.7%), System efficiency (12.2%), and Array efficiency (12.8%). The highest value of efficiencies was observed in the month of January, with values of 96.8% (inverter), 12.8% (system), and 13.2% (array). Conversely, the minimum efficiencies were noted in the month of July, as 96.7% (inverter), 11.6% (system), and 12.1% (array). For comparison, the PVsyst simulation program (at an annual average temperature of 25.5°C) reported the following efficiency values: Inverter efficiency (97%), Array efficiency (13.16%), and System efficiency (12.72%). Despite the experiment system operating at a higher annual average temperature (31°C), the measured efficiency values were very close to the PVsyst simulation results. This highlights the strong performance and reliability of the experimental system, even under higher temperature conditions.

Economic and Environmental Analysis

The economic analysis of the 5.0 kWp solar rooftop system considered different key parameters such as, initial investment (II), savings, return on investment (ROI), payback period among others as summarized in Table 5.

Initial Investment Costs (IIC): The initial cost of installing a 5.0 kWp solar rooftop system may differ depending on the region, quality of the PV panels, charges of installation, as well as government subsidies. The average

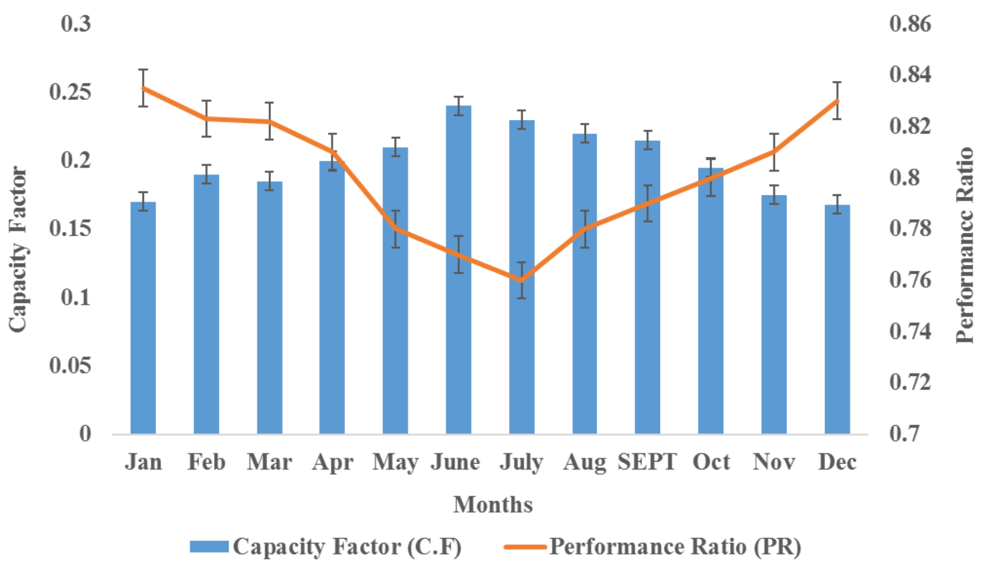


Figure 16. Monthly performance ratio and capacity factor of the system.

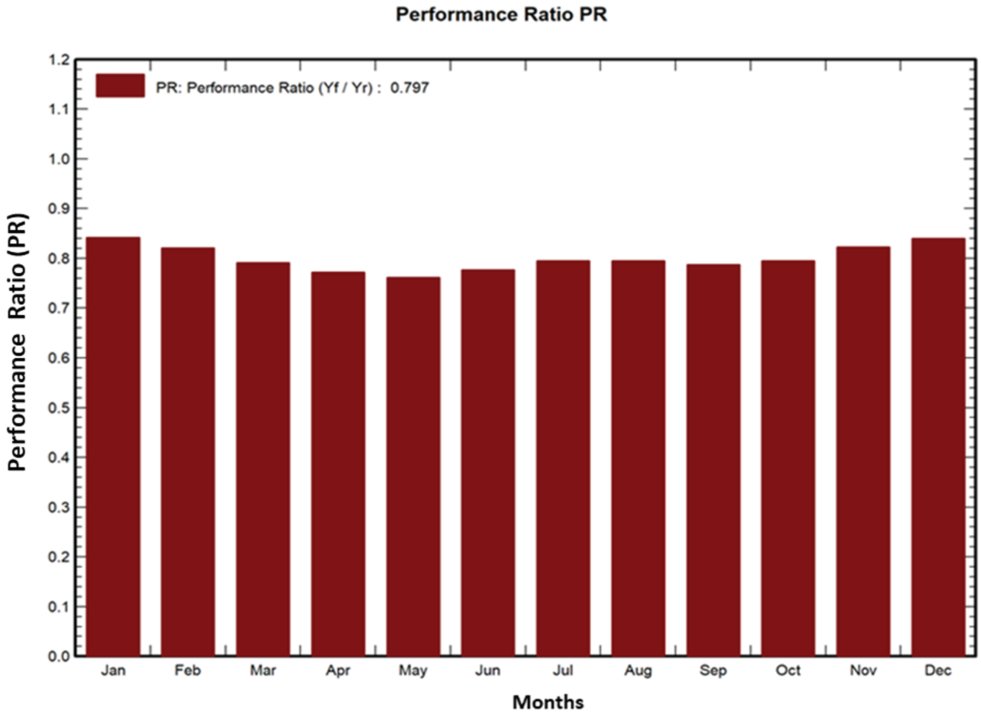


Figure 17. Monthly performance ratio simulated by PVsyst software.

Table 4. Simulated vs. Experimental Solar Energy

Metric	Experimental	PVsyst Simulated	Difference
Array Yield (kWh/kWp)	5.00	5.46	+0.46 (approx. +9.2%)
Reference Yield (kWh/kWp)	6.25	6.39	+0.14 (approx. +2.2%)
Final Yield (kWh/kWp)	4.91	5.32	+0.41 (approx. +8.4%)
Annual Energy Output(kWh/kWp)	6910.2 kWh	7485 kWh	+574.8 kWh (+8.3%)

This shows/demonstrates that …….

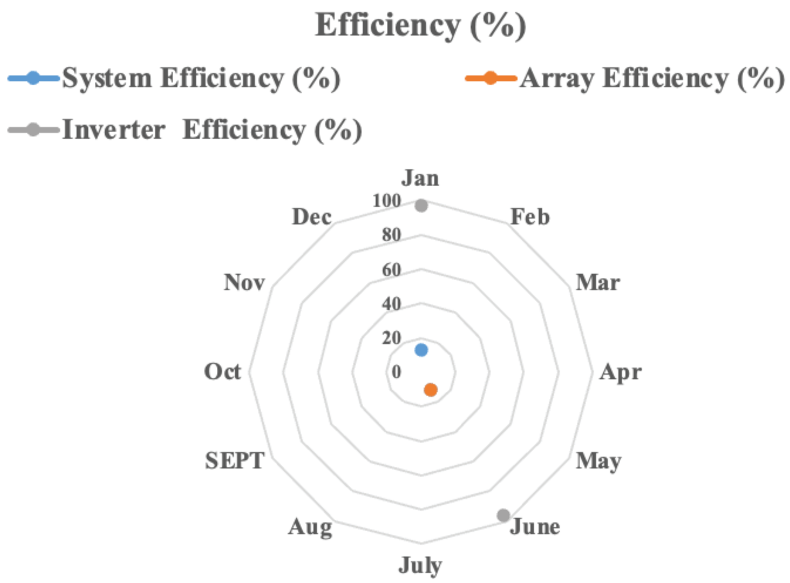


Figure 18. Demonstration of average monthly efficiencies.

Table 5. Summarized value of environmental and economic analysis

Parameter	Unit	Lower Estimate	Upper Estimate
System Size	kWp	5	5
Installation Cost		$5,000	$12,500
Annual Energy Generation		9,125 kWh	9,125 kWh
Electricity Rate		$0.12/kWh	$0.12/kWh
Annual Savings		$1,095	$1,095
Annual Maintenance Cost		$150	$150
Government Incentive (30%)		$1,500	$3,750
Net Initial Investment		$3,500	$8,750
Payback Period (years)		4.57 years	8 years
Net Savings over 25 years		$22,375	$14,875
ROI		447.5%	119%
CO_2 Savings (per year)		7,756.25 kg	7,756.25 kg
Total CO_2 Savings (25 years)		193,906.25 kg	193,906.25 kg

price per kWp of solar rooftop installation is around $1,000 to $2,500 in many regions (this could vary widely).

Annual Energy Generation

A 5.0 kWp PV solar roof top system can generate an average of about 4 - 5 kWh/day/installed kW (normally depending on the location and sunlight hours). For a location with virtuous sunlight (average of 5 hours per day), it can generate as:

Daily energy generation: 5 kWp x 5 hours = 25 kWh/day

Annual energy generation: 25 kWh/day x 365 days = 9,125 kWh/year

Savings of electricity

The price of electricity be different depending on the region and location, therefor this analysis, let's assume an average electricity rate of $0.12 per kWh.

Yearly Savings: 9,125 kWh/year x $0.12 = $1,095/year.

Maintenance Costs

PV solar systems involve minimal maintenance, typically just cleaning the PV panels as well as monitoring the system's performance annually. Maintenance costs are usually low, estimated at around $100 to $200/year. Annual Maintenance Costs: Assume $150/year.

Payback Period

The payback period is usually defined as the time it takes for the savings from the PV solar system to cover the initial investment cost.

Lower Estimate (if system cost is $5,000):

Payback period = Initial Investment / Annual Savings = $5,000 / $1,095 = 4.57 years

Upper Estimate (if system cost is $12,500):

Payback period = Initial Investment / Annual Savings = $12,500 / $1,095 = 11.41 years

Return on Investment (ROI)

Subsequently the payback period, the system will continue to produce savings. Therefore, to compute the ROI, will consider the system's lifespan, which is normally around 25 years.

Net savings over 25 years:

Lower estimate (after incentives):

Total savings = $1,095/year x 25 years = $27,375

Net savings after initial investment = $27,375 - $5,000 = $22,375

Upper estimate (after incentives):

Total savings = $1,095/year x 25 years = $27,375

Net savings after initial investment = $27,375 - $12,500 = $14,875

ROI:

Lower estimate: ROI = ($22,375 / $5,000) x 100 = 447.5%

Upper estimate: ROI = ($14,875 / $12,500) x 100 = 119%

Environmental Effect

CO_2 Savings: The average PV solar panel system emits about 0.85 kg of CO_2/kWh. Therefore, in a case of 5.0 kWp solar system generating 9,125 kWh/year, the whole PV solar system would save 9,125 kWh/year x 0.85 kg CO2 = 7,756.25 kg of CO_2 per year. Over 25 years, that would be 193,906.25 kg of CO_2.

CONCLUSION

A Photovoltaic solar system was designed using PVsyst software to assess the energy requirements for an institutional building›s total load of 5.0 kWp. The PVsyst simulation provided valuable insights into the performance of the PV modules. The results indicated that as load demand decreases, the performance ratio increases, and power generation remains proportional to load. Further analysis confirmed that the system performs well and is capable of reliably supporting a load of approximately 5.0 kWp. A comparative study was also conducted to evaluate the effect of different parameters on the performance of actual system in term of energy output, yield, efficiencies, and losses. The results indicate that when the system is installed with a zero-azimuth angle, it attains the maximum specific production with higher efficiency, making this orientation the preferred choice. The feasibility of the actual system was validated through simulation results, demonstrating its suitability for PV solar array installation.

- The variance between the PVsyst simulation results and the actual performance of the experimental system was minimal, despite the PVsyst model assuming an annual average temperature of 25.5°C, while the experimental system operated at 31°C.
- In terms of efficiency, the experimental system closely matched the performance of PVsyst simulation, with comparable energy losses between the two.
- The results demonstrate that the PV solar system performs effectively under real-world conditions, despite the PVsyst model representing an ideal scenario unaffected by factors like clouds, rain, and dust. The experimental system, operating at a higher average temperature of 31°C, showed strong performance and resilience in Gwalior, Madhya Pradesh, India.
- The payback period for a 5.0 kWp PV solar rooftop system ranges from about 4.57 years to 11.41 years, depending on the cost.
- The ROI ranges from 119% to 447.5%, with the system providing substantial long-term savings.
- The environmental impact is significant, with reductions in CO_2 emissions contributing to sustainability.

Future research should investigate long-term performance variations of rooftop PV systems under diverse seasonal and environmental conditions. It can also focus on integrating storage solutions, optimizing tilt and orientation dynamically, and improving simulation accuracy. Expanding studies across different Indian regions would strengthen national strategies for effective solar energy deployment.

NOMENCLATURE

PV	Photovoltaic
CF	Capacity factor
PR	Performance Ratio
L_a	Array losses
Y_a	Array yield
Y_r	Reference yield
η_{sys}	System efficiency
η_{PV}	Photovoltaic efficiency
η_{inv}	Inverter efficiency

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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.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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