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A Technical Analysis of Residential Grid-Connected Photovoltaic System: Design and Simulation

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Abstract

Electricity consumption in the residential sector has steadily increased due to modernization, placing significant pressure on both renewable and non-renewable power sources to keep up with demand. The rising demand for reliable electricity has created challenges in energy production, leading to concerns about sustainability and environmental impacts. Renewable sources, such as solar photovoltaic (PV) systems, offer a practical alternative to non-renewable energy sources and hold promise for sustainable electricity generation. This study examines the feasibility of installing a grid-connected PV system for a typical residential setting, to assess its technical effectiveness in meeting household energy demands. The results demonstrate an effective energy output of 7031.3 kWh annually at the array level, with a global irradiance of 1495.3 kWh/m² on the horizontal plane. Notably, the PV plant supplies 5517.1 kWh of energy to the grid each year, with 1295.2 kWh directly meeting the home's yearly energy requirements. With relevant losses factored in, the system's inverter efficiency stands at 81.9%, indicating a relatively high performance for a residential setup. The analysis also highlights seasonal variations in solar irradiance, which can affect overall energy production. This emphasizes the importance of integrating energy storage solutions, such as batteries, to ensure a consistent power supply throughout the year. This simulation provides valuable insights into both the benefits and challenges of implementing a grid-connected PV system for residential use, highlighting its potential for reducing dependence on non-renewable energy and contributing to a sustainable energy future.

Keywords: Solar energy, Residential sustainable energy, PVsyst software, Grid-Connected Photovoltaic system, technical simulation.

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1. Introduction

The world is becoming increasingly modernized every day, necessitating enormous energy from various sources [1-3], both renewable and non-renewable (fossil) sources. Renewable energy sources are seen as feasible solutions for generating energy to assist economic growth with environmentally friendly influence [4-5] while fossil fuels are quickly running out [6] and having a detrimental influence on the environment [7]. By utilizing both renewable and non-renewable sources, Bangladesh has access to nearly 100% of its electricity needs, including residential applications, which are almost entirely supplied by fossil fuels. To satisfy the fundamental requirements of the residential sector electricity is crucial [8]. Due to the ongoing energy scenario in Bangladesh [9], the expansion of the global economy, and environmental degradation, the importance of utilizing energy from sustainable (renewable) sources has increased as a reliable and environmentally friendly alternative to fossil fuels [10]. In

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Bangladesh, solar photovoltaic energy is the most accessible and effective renewable energy source, considering its abundant solar irradiance, technological advancements, and decreasing costs.

The photovoltaic system, which is required to be used as efficiently as possible, is the most plentiful energy source on Earth [11]. Solar Photovoltaic (PV) technology has been used to design grid-connected, off-grid, and hybrid energy systems for various applications. Grid-connected solar PV systems play a crucial role in promoting sustainable energy practices, enhancing energy security, reducing costs, and fostering economic growth while contributing positively to environmental conservation. The advantage of a grid-connected PV power-generating system is that the generated electricity is used more efficiently [12]. Grid-connected solar photovoltaic (PV) systems can be categorized into several types based on their configuration, energy storage capabilities, and intended applications. Each type of grid-connected solar PV system has its unique advantages and is suitable for different applications, helping to promote the use of renewable energy in various contexts.

Despite favourable climatic conditions, quantitative studies on optimizing grid-connected PV designs for residential use in Bangladesh are limited. However, several studies have explored the potential of grid-connected PV systems in different contexts, from residential areas to commercial facilities. Feasibility analysis [13] and GHG emissions reduction analysis [14] using RETScreen Software were conducted to meet the demand for electricity with economic and environmental considerations in Bangladesh. The techno-economic analysis [15] for PV systems using PVsyst software was conducted to meet the household demand in Bangladesh. Techno-economic analysis of the potential for electricity generation from floating photovoltaic solar power systems has been performed and accentuates the potential contribution these plants may provide to the national grid in Bangladesh [16]. The paper [17] discussed the planning and economic evaluation of a system that generates electricity from sunlight for a sports complex in Oman, which can fulfil the demand for energy from the playgrounds and send surplus energy to the grid, taking advantage of Oman's high solar irradiation and varying temperatures. The rooftop system [18] is subjected to technical examination using the photovoltaic system (PVsyst) software to compute the energy provided by solar panels, inverter losses, and other data. The research has been completed [19] to assess the viability of a rooftop solar power system integrated with a small-scale on-grid system in Semarang City in terms of both technical and financial aspects. The PVsyst, PVGIS, and HOMER renewable energy simulation tools were utilized for modelling and design of grid-connected Solar PV systems in Afghanistan [20]. This literature review underscores the potential of grid-connected rooftop PV systems as a sustainable energy solution like Bangladesh.

To promote sustainable energy generation from clean sources, several studies have been published in Bangladesh, focusing on the potential of grid-interactive systems. However, there is limited research assessing the efficiency and viability of grid-connected rooftop PV systems specifically in Rangpur city. This paper presents a design for a grid-connected solar energy system tailored for residential use in Rangpur, supported by technical simulations. The simulation aims to demonstrate both the benefits and challenges associated with constructing a grid-connected photovoltaic (PV) system for residential applications in Bangladesh.

The rest of this paper is organized as follows: Section 2 details the research methodology, covering site characteristics, simulation software, and the configuration of the solar power system. Section 3 presents and analyses simulation results, including performance metrics, energy output, and system losses. Finally, Section 4 summarizes the study's findings and discusses the potential of grid-connected PV systems for residential applications in Bangladesh, with supporting references and materials provided at the conclusion.

2. Research method

The technique of the study consists of constructing and modelling a grid-connected photovoltaic (PV) system customized for residential energy requirements. Site characteristics, simulation software, solar panel orientation, solar power plant layout, PV system schematic design, and consumer energy consumption analysis are important elements of this technique.

With these elements, the study methodology offers a thorough way to assess the viability and effectiveness of a home grid-connected photovoltaic system in a particular urban setting.

2.1. Site parameters

The proposed grid-connected residential PV solar system has been considered at the Rangpur City of Bangladesh. A capacity of 5 kWp has been considered for the proposed system. The GPS position of Rangpur City of 25° 44' 41.4960" N and 89° 16' 32.1204" E, is situated in Bangladesh presented in Figure 1 [21]. The monthly average global horizontal solar irradiance with temperature is shown in Figure 3. The annual average solar radiation is found to be 4.12 kWh/m^2/day. The highest solar irradiance is in March and April at 5.14 kWh/m^2/d and the lowest solar irradiance is in December at 3.06 kWh/m^2/d.

2.2. Tools used in this study

The simulation tool PVsyst was developed in Geneva initially to assist in calculating the operation and performance of PV systems. This simulation tool assists in system configuration design and enables evaluation of the quantity of the produced electricity. The result is derived from a simulation of the measuring system, which is more reliant on the geographic position of the site for the PV system. Numerous simulation variables that can be shown as hourly, daily, or monthly values may be present in the results [3].

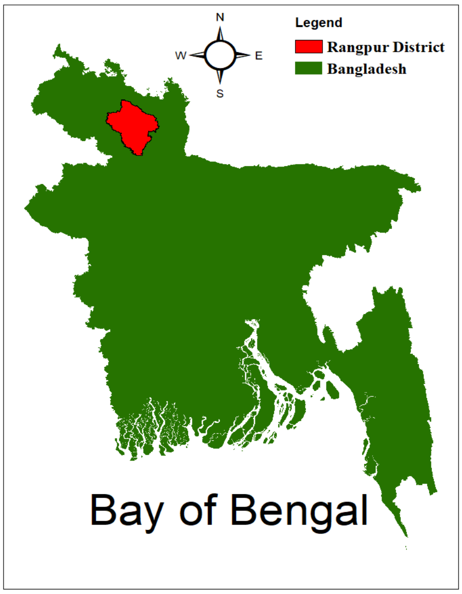

Figure 1. Rangpur District of Bangladesh

2.3. Solar panel orientation

The arrays have been regarded as being positioned at a fixed tilted position with a 26º tilt angle and oriented toward the south with zero azimuth as shown in Figure 2. The latitude of the location equals the optimal module tilt angle for a fixed tilt configuration. According to the specified perspective, the annual meteorological output has been computed using 1.07 as the transposition factor (FT) with 0% loss to the optimal. A total of 1608 kWh/m^2 of radiation will be received by the collector plane (modules) arranged in the specified configuration. Figure 2 depicts the FT and loss-optimized diagrams to the plane direction and plane tilt optimal for the given configuration.

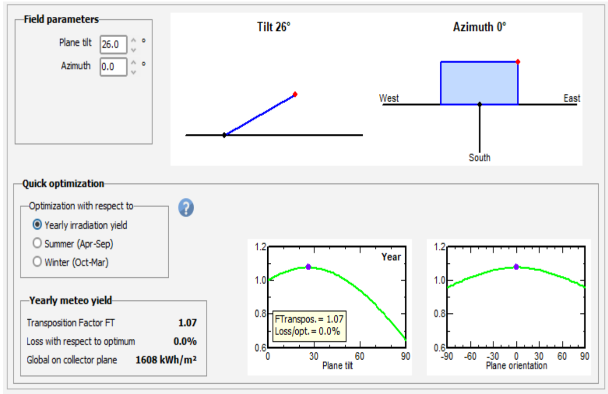

Figure 2. Orientation (tilt and azimuth) and Optimization graph of FT and loss with respect to optimum

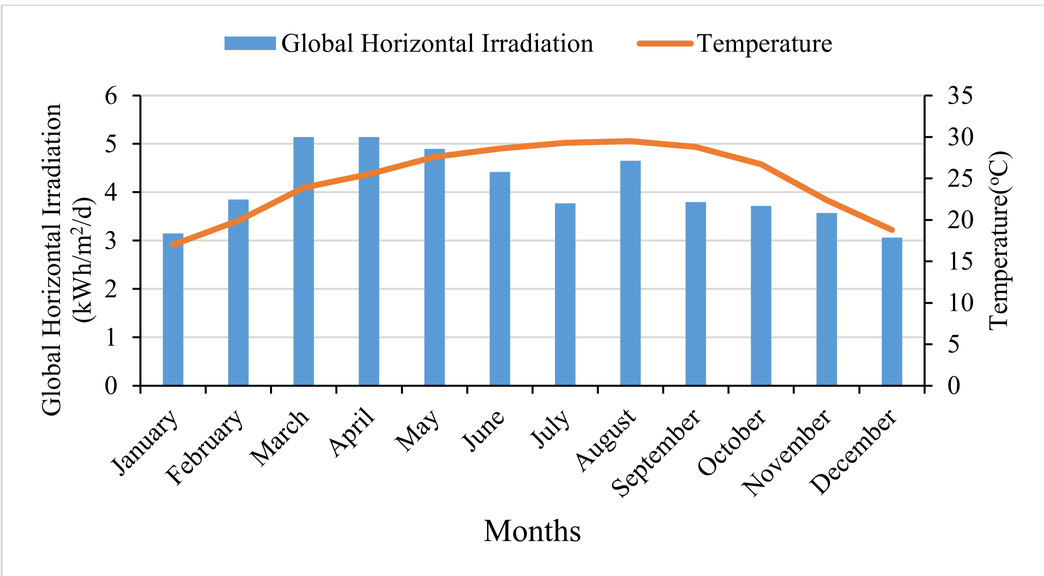

Figure 3. The annual average global horizontal irradiation of Rangpur City

2.4. Solar power plant configuration

A single photovoltaic panel, also known as a solar panel or solar module, is a collection of attached solar cells. Solar cells utilize the energy from sunlight (solar irradiance) as a source to generate electrical energy. The relevant factors, including the type and quantity of PV modules, inverter, control of series and parallel module placement, and intended power output, are covered in this section. Table 1 shows the characteristics of the Axitec Energy (AXIpower AC-325P/72S) PV module.

Table 1. Solar panel specifications of the system

Parameter	Specification
Manufacture	Axitec Energy
Model	AXIpower AC-325P/72S
Type	Monocrystalline
Power maximum (P_{max})	325 Wp
Open circuit voltage (V_{oc})	45.9 V
Short circuit current (I_{sc})	9.15 A
Maximum point voltage (V_{mp})	37.6 V
Maximum point current (Imp)	8.64 A
Temperature coefficient	3.7 mA/°C
Tolerance	0-1.5%
Module area	1.940 m^2

The Efficiency curves of the PV module under various irradiance is demonstrated in Figure 4. According to Figure 4, the efficiency at a given radiation level declines as the temperature of the PV module rises. The photovoltaic panel has a 16.75% efficiency rating at STC.

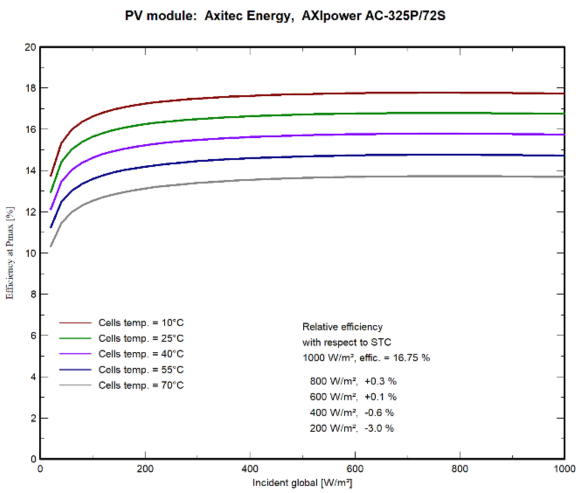

Figure 4. The efficiency curves of PV module under varying irradiation conditions

Table 2. Inverter specifications of the system

Parameters	Specifications
Manufacture	Delta Energy
Model	AXIpower AC-325P/72S
Inverter Input (DC)	
Minimum voltage (MPP)	100 V
Minimum voltage for nominal power	220 V
Maximum current/MPPT	11.7 A
Nominal voltage (MPP)	350 V
Maximum voltage (MPP)	500 V
Maximum photovoltaic voltage	600V
Power threshold	25 W
Inverter Output (AC)	
Grid voltage	230 V
Frequency	50 Hz
Maximum efficiency	97.50%

An electrical power inverter referred to as a solar inverter or a photovoltaic (PV) inverter converts direct current (DC) into a utility frequency alternating current (AC). The converted alternating current (AC) can be utilized for many different purposes or supplied into a national grid, or off-grid electrical network. One of the crucial pieces of the photovoltaic solar system hardware is an inverter. Table 2 shows the inverter characteristics of Delta Energy (Solar Inverter RPI H5A) for the proposed system.

2.5. Schematic of PV system

The basic schematic concept of the grid-tied solar energy system has been presented in Figure 5. The PV array, system, and user (load) are the three components that make up the overall system. The PV array is made up of PV modules that are linked together in series and a blocking diode that is connected in series to stop the grid from powering the PV modules in the other direction. The PV array includes two (2) strings, each of which has eight (8) modules with a series connection. The solar inverter receives the DC electricity produced by the array, which is converted into AC power that is subsequently supplied to the grid.

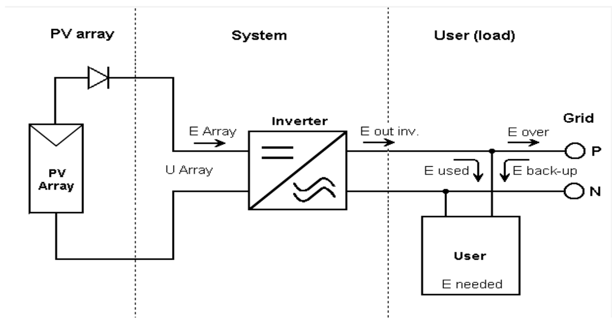

Figure 5. Simplified schema design of the grid-connected PV system

2.6. Energy used by consumer

This section calculates the monthly energy consumption by the user which is the actual value of a single house in Rangpur City. The monthly energy consumption of a house is shown in Table 3. The highest energy used of 349 kWh in May and the lowest energy used of 197 kWh in January with an average of 244 kWh/month. The total energy used by a single house is almost 2926 kWh/year. This data has been collected from July 2022 to June 2023.

Table 3. Monthly Energy consumption by a single house of Rangpur City.

Month	Energy Used (kWh)
January	197
February	260
March	323
April	281
May	349
June	275
July	202
August	210
September	219
October	207
November	198
December	205
Total	2,926

3. Result and discussion

To comprehensively evaluate the performance of a residential energy system in Rangpur City, key performance metrics are employed, including balance and main result, normalized production, performance ratio (PR), and loss diagram analysis. The balance and main result metric offers a holistic view of energy production and consumption, providing insight into the net energy surplus or deficit within the system. Normalized production, typically expressed in kilowatt-hours per kilowatt (kWh/kW), standardizes energy output relative to the installed capacity, facilitating meaningful comparisons across systems of various sizes. The performance ratio (PR), a fundamental efficiency metric, quantifies the actual energy output as a percentage of the theoretical output, accounting for localized environmental conditions, such as solar irradiance for photovoltaic systems. A high PR indicates optimal system efficiency with minimized losses. The loss diagram visually depicts specific points of energy loss within the system, such as transmission, shading, or conversion losses, providing targeted insight for potential enhancements. Collectively, these metrics offer a standardized framework for assessing system performance, enabling more precise evaluation and improvement opportunities in residential energy applications.

3.1. Balance and main results

The balance and main results for this study incorporate key variables, including global irradiance on the horizontal plane, global irradiance on the collector plane (without optical adjustments), average ambient temperature, shading losses, and effective global irradiance considering for soiling effects. These simulations considered each of these variables, alongside the direct current (DC) energy generated by the mono-crystalline solar array, representing the energy supplied to the grid after considering photovoltaic array losses, electrical component losses, and overall system efficiency. Each variable included in the balance calculations was simulated, and the most important outcomes were obtained on a monthly and annual basis. Annual data for these parameters are presented as average values for temperature and efficiency and as cumulative values for irradiance and energy.

Table 4. Monthly Key Energy Measurements

Months	E_Solar (kWh	EArray (kWh)	E_User (kWh)
January	79.9	562.4	197
February	107.1	569.0	260
March	143.1	764.2	323
April	129.9	675.4	281
May	163.4	619.8	249
June	130.4	529.7	275
July	95.5	462.4	202
August	101.4	602.1	210
September	95.4	509.0	219
October	86.5	571.9	207
November	79.1	602.5	198
December	83.5	562.9	205
Year	**1295.2**	**7031.3**	**2926**

Table 5. Monthly Grid Energy Summary

Months	E_Grid (kWh)	EFrGrid (kWh)
January	465.5	117.1
February	444.8	152.9
March	598.8	179.9
April	525.3	151.1
May	437.1	185.6
June	381.7	144.6
July	350.1	106.5
August	481.8	108.6
September	396.4	123.6
October	467.3	120.5
November	505.7	118.9
December	462.6	121.5
Year	**5517.1**	**1630.8**

Energy from the sun (E_Solar), effective energy at the output of the array (E_Array), and energy supplied to the user (E_User) are summarized in the Monthly Key Energy Measurements (Table 4) and the Monthly Grid Energy Summary (Table 5). The yearly effective energy at the output of the array is 7031.3 kWh with this effective irradiance. The highest energy produced by the PV plant was found to be 764.2 kWh in March, and the lowest energy generation was found to be 462.4 kWh in July. The yearly energy demand that is directly met by the solar PV system is 1295.2 kWh. The rest of the energy (5517.1 kWh) generated by the PV plant was supplied to the grid every year. However, since the energy demand by the building was 2926 kWh/year, the energy taken from the grid by the load was found to be 1630.8 kWh/year. Thus, a balance of 3886.3 kWh/year will be supplied to the grid if the PV system is installed.

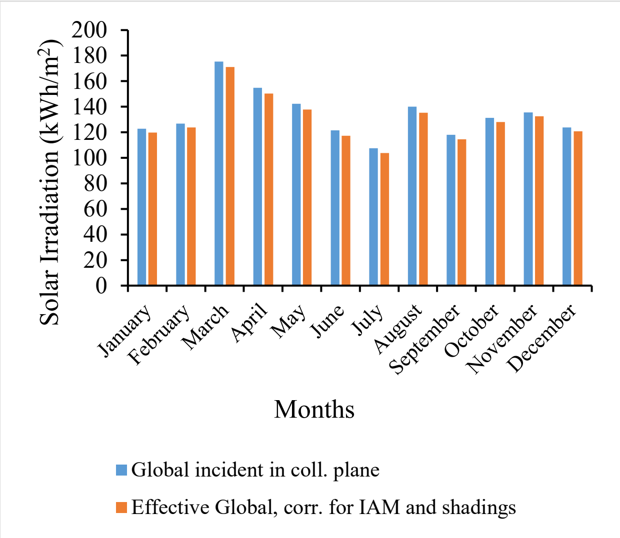

Figure 6. Monthly Global vs. Effective Irradiation

Figure 6 presents a detailed comparison between Monthly Global Irradiation and Effective Irradiation. This comparison provides a clear visualization of the influence of these factors on usable irradiance throughout the year, highlighting the variations in energy availability and efficiency losses every month. Every year the global irradiance is 1495.3 kWh/m^2 on the horizontal plane, the global incident energy is 1599.9 kWh/m^2 on the collector without optical corrections, and the effective global irradiance is 1555.1 kWh/m2 after optical losses.

The monthly variation in solar irradiation and temperature plays a crucial role in determining the energy production of solar systems. Solar irradiation directly influences the amount of energy that can be harvested, while temperature affects the efficiency of photovoltaic panels, as higher temperatures generally lead to lower efficiency. The combined effect of these two factors is essential for understanding seasonal performance variations in solar energy systems.

Table 6: Monthly Solar Irradiation and Temperature of the system

Months	GlobHor (kWh/m^2)	DiffHor (kWh/m^2)	T_Amp (°C)
January	97.7	56.7	17.01
February	107.9	62.19	19.89
March	159.3	81.17	23.93
April	154.1	92.43	25.45
May	151.9	99.93	27.62
June	132.5	92.85	28.58
July	116.9	72.59	29.92
August	144.2	88.7	29.5
September	113.9	68.45	28.21
October	115.2	66.03	26.74
November	107	55.12	22.39
December	94.9	52.77	18.76
Year	**1495.3**	**888.95**	**24.81**

The data Table 6 provides monthly values for Global Horizontal Irradiation (GlobHor), Diffuse Horizontal Irradiation (DiffHor), and Average Ambient Temperature (T_Amp). Global Horizontal Irradiation reaches its peak in March, with a minimum in December, totalling of 1495.3 kWh/m² annually. Diffuse Horizontal Irradiation exhibits seasonal variation, with the highest value recorded in May (99.93 kWh/m²) and the lowest in December (52.77 kWh/m²), reflecting changes in cloud cover and atmospheric conditions. The average ambient temperature is highest in June and July, with an annual average of 24.81°C, which influences both solar energy generation and the efficiency of photovoltaic systems.

3.2. Normalized production

PV array collecting losses, system losses, and significant inverter output are all included in the normalized production of the PV power plant. The generation and losses of monthly productive electricity per kWh are displayed clearly by the graph of normalized production. These normalized productions correspond to standard variables used to evaluate the performance of PV systems and are prescribed by the IEC regulations [22]. The normalized production of the PV power plant is illustrated in Figure 7. The collection loss of the system is 15.5% with the system loss of 2.6%. The produced useful energy from the inverter is 81.9%.

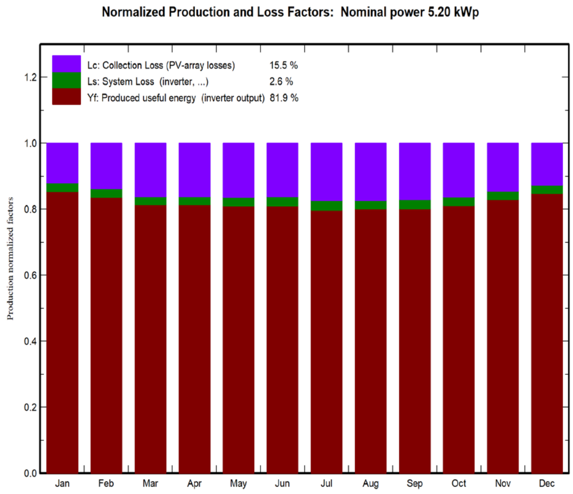

Figure 7. Normalized energy productions per installed kWp

3.3. Performance ratio

The performance ratio (PR) is the ratio between the energy supplied and the nominal energy of the solar-PV array as specified by the manufacturer. This ratio of performance generally serves as a quality factor to evaluate the level of quality of a PV plant. The PR represents the amount of energy after all energy consumption and losses have been subtracted. The performance ratio (PR) of the PV plant for the estimated 5 kWp Si-poly photovoltaic solar system is 81.9%, which is the yearly average PR value, as shown in Figure 8 on a monthly basis [23].

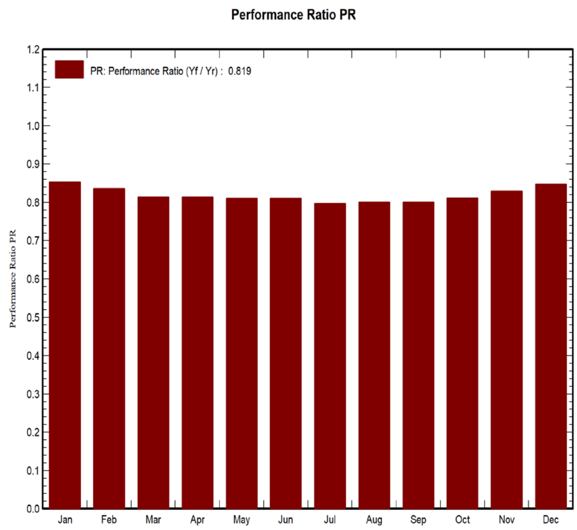

Figure 8. Performance ratio of 5 kWp solar system in Rangpur City

3.4. Loss diagram

The array loss diagram has been generated using simulation techniques, which help in the study of different losses that might happen during the construction of PV plants or restrictions to consideration. The array loss diagram, shown in Figure 9, demonstrates the different losses in the system. Global irradiance in the horizontal plane is 1294 kWh/m^2 and the optimum irradiation of the system's collection is 1325 kWh/m^2. Due to the irradiance level, this causes an energy loss of 1.1%. A solar module or array generates electricity or electrical energy when this effective irradiance reaches its surface. The nominal energy of the array at standard testing conditions (STC) after the PV conversion is 11930 kWh. The PV array at STC has an efficiency of 18.45%. At MPP, the yearly virtual energy from the arrays is 10239 kWh. The many losses that happen at this step include 5.4% losses from temperature, 2% losses from light-induced degradation, 2.7% losses from mismatched module arrays, and 0.9% losses from ohmic writing. Every year, the amount of electricity accessible at the inverter output plant is 10029 kWh, with 9843 kWh fed into the grid. It is conceivable for an inverter to lose 2% of its power while operating.

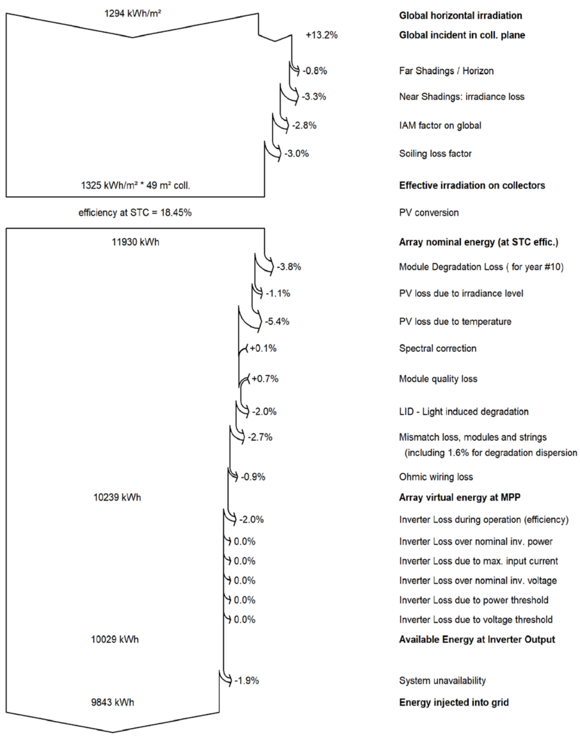

Figure 9. Loss diagram of 5 kWp solar system in Rangpur City

4. Conclusion

The PVsyst software was used in this study to conduct an analysis of a 5 kWp grid-connected PV plant for the Rangpur city of Bangladesh. The geographical location and local meteorological information have been considered while analysing performance of the proposed PV plant. In order to optimize the yearly energy generation from the plant, the PV plant's optimum design was completed with the right orientation, components selection, and scale as well. The energy generation, performance ratio, and system losses have all been used to analyse efficiency of the PV plant. The array produces 7031.3 kWh of effective energy annually. The solar PV system directly meets 1295.2 kWh of the annual energy consumption, while the remaining energy (5517.1 kWh) is sent to the grid on a yearly basis. After the collection and system losses are included, the useable energy produced by the inverter is 81.9%. As a result, the geographical region may be suitable for the building of PV power plants that are connected to the grid.

To further improve the system's performance, future research should focus on the integration of advanced tracking systems, which can significantly increase energy production by adjusting the panel orientation in real-time. Additionally, incorporating energy storage solutions such as batteries can enhance the system's efficiency by ensuring energy availability during periods of low sunlight or grid failures. Exploring hybrid solar systems, combining PV with other renewable sources like wind, could also be valuable for enhancing energy reliability. Lastly, on-going monitoring and adjustments based on long-term performance data will help in identifying and mitigating unforeseen losses, further improving the system's viability for widespread residential adoption.

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