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INTEGRATED PERFORMANCE MODELING AND LIFE CYCLE CARBON ASSESSMENT OF A RESIDENTIAL GRID-CONNECTED PHOTOVOLTAIC SYSTEM

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Photovoltaic power forecasting; Grid-connected PV systems; Performance ratio analysis; PV system modeling; Life cycle carbon assessment

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Abstract
Accurate power forecasting of grid-connected photovoltaic (PV) systems is critical for performance evaluation, financial planning, and grid stability. This study investigates the predictive accuracy of two industry-standard simulation platforms PVsyst and HelioScope by benchmarking their outputs against one year of measured operational data from a 24.64 kWp residential rooftop PV installation in Islamabad, Pakistan (33.53°N, 73.15°E). The system comprises 56 monocrystalline modules (440 Wp each) coupled with a 20-kW inverter operating at a DC/AC ratio of 1.23. Meteorological inputs, including global horizontal irradiance (GHI), diffuse irradiance, and ambient temperature, were analyzed to quantify their influence on energy yield. Key performance indicators reference yield, array yield, final yield, performance ratio (PR), capacity factor, and system losses were evaluated. PVsyst estimated annual energy production of approximately 44 MWh prior to system losses, with nearly 80% delivered after capture and conversion losses. HelioScope predicted annual grid injection of 36.20 MWh after accounting for optical, thermal, mismatch, soiling, and inverter losses. Seasonal trends from both models showed strong agreement with measured data, particularly during high-irradiance summer months. Life cycle assessment indicates that although manufacturing emissions amount to approximately 45 tCO_2-eq, the system offsets nearly 340 tCO_2 over a 25-year operational lifespan. The results confirm the robustness of both modeling platforms for reliable PV performance forecasting under semi-arid climatic conditions.

INTRODUCTION

Carbon emissions are a significant and growing environmental issue, with major implications for the future of our planet [1]. Addressing this issue will require a concerted global effort, with a focus on reducing emissions from all sectors of the economy and transitioning to a more sustainable and low-carbon future [2], [3]. In the process of generating electricity from conventional sources such as coal, natural gas, and oil, carbon emissions are released into the atmosphere. These emissions are a major contributor to climate change, which has serious environmental, economic, and social impacts [4]–[6]. In contrast, solar PV systems generate electricity with no direct carbon emissions [7]–[11]. According to the International Energy Agency (IEA), the deployment of solar PV systems could potentially avoid 2.6 billion tons of CO_2 emissions by 2024, which is equivalent to taking more than 580 million cars off the road [6].

Though, the production of solar PV systems does require energy and materials, the emissions associated with this production are typically offset within a few years of operation by the carbon emissions avoided from the generation of electricity [12]. In addition, advances in solar PV technology are reducing the environmental impact of manufacturing solar PV systems, including the use of more sustainable materials, more efficient manufacturing processes, and better recycling practices [13], [14]. Despite the environmental benefits of solar PV, the widespread deployment of these systems still faces challenges, including high upfront costs and the need for a supportive policy environment. However, as the costs of solar PV systems continue to decline and public awareness of the need to address climate change grows, it is expected that the deployment of solar PV systems will continue to expand, contributing to a more sustainable and low-carbon energy system [15].

Rooftop solar has attracted much attention in recent years due to its easy maintenances especially in the areas where there is enough amount of solar radiation. Pakistan has significant solar photovoltaic (PV) potential, thanks to its geographical location in the sun belt. The country is blessed with abundant sunshine throughout the year, making it an ideal location for solar energy production. According to estimates, the total solar energy potential in Pakistan is around 2.9 million megawatts (MW) [16]. Despite this however, Pakistan's solar energy potential remains largely untapped. The country still relies heavily on fossil fuels, and only a small fraction of its energy comes from renewable sources. However, there is growing interest in solar energy in Pakistan, and the government has set a target of generating 30% of the country's electricity from renewable sources by 2030, which could create opportunities for further solar development [17].

The performance of the PV system measured in the number studies [18]–[25]. The energy generation through the solar PV system is mainly dependent on the environmental factors. The other factors include the systematic parameters that are installation of the PV system, inverter type [26]. The environmental factor includes the solar radiation, wind speed, ambient temperature, humidity ratio and dust accumulation on the solar panels [27]–[29]. The energy production is dependent of the which region the PV solar system is installed i.e., humid region, arid zone. The problem associated with the solar system is vary as the region varies i.e., dust storm in the semi-arid reduces the energy generation of the PV system [30], [31].

In certain condition it is difficult of the measure the effectiveness of the PV system as mentioned in the IEC 61274 standards. Furthermore, the knowledge to run the PV system is mandatory [32]. Properly monitoring the input parameters help to tackle the different uncertainties which will ultimately improve the performance of the PV system [24]. The monthly, seasonal and annual performance of the grid connected PV system was examined The annual average daily array yield, reference yield, and final yield of the solar PV system was 2.62, 2.85 and 2.41 kWh/kWp/day, respectively [19]. In another study the authors find that the performance ratio and the final yield ranges from the 1.96 to 6.42 kW h/kWp and 58-98% respectively [25].

This study aims to comparative analysis of the estimated results by theoretical models with real time performance of the solar PV system. The one-year experimental data is compared with the data of the two-modelling software's i.e., PVsyst, HelioScope. The performance parameter, losses in the PV system are also considered to provide the best agreement with theoretical and experimental.

Methodology

The PV system is installed at the Islamabad having the longitude and latitude of the site 33.531847° and 73.152894° respectively. Figure 1 shows the location of the site. The number of PV module that are installed are 56 with the azimuth angle of 15°.

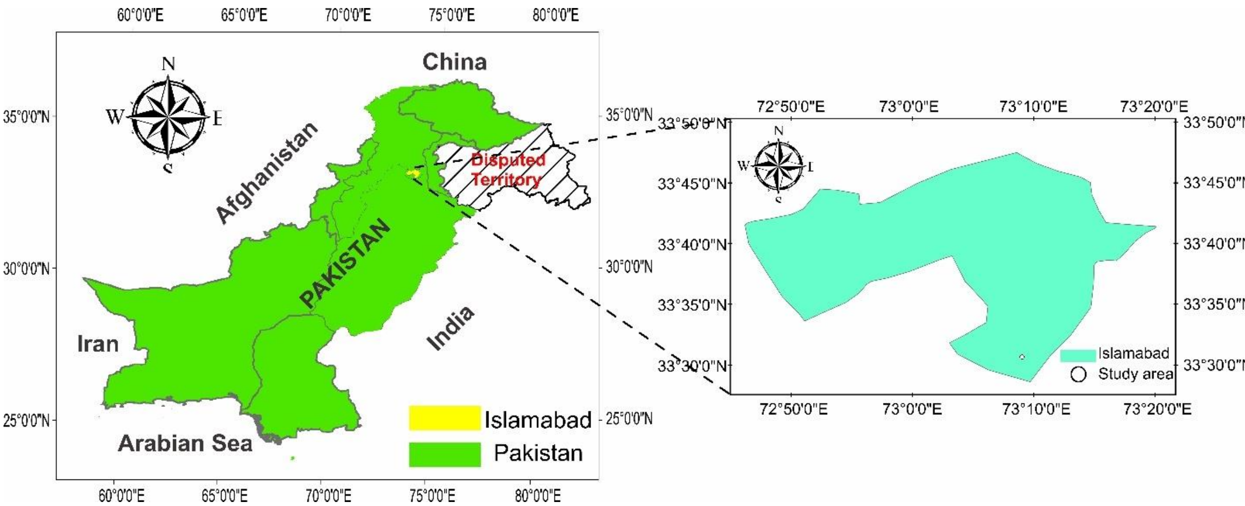

Figure 1 Location of the PV system installed.

Climatic parameters for energy generation

The climatic parameters of the study area is given below which actually shows the potential of the solar photovoltaic. Figure 2 shows the global horizontal and the global diffuse radiation on the monthly basis. Furthermore, the maximum horizontal radiation are in the month of the June and July where the maximum diffuse radiation are in the month of the July and August. The horizontal radiation varies from the 79 to 200 kWh/m^2 whereas the diffuse radiation varies from 34 to 100 kWh/m^2. Figure 3 shows the daily global radiation in the study area which is varies from the 33 to 334.3 w/m^2. This shows a comprehensive potential of the solar photovoltaic especially in the summer months.

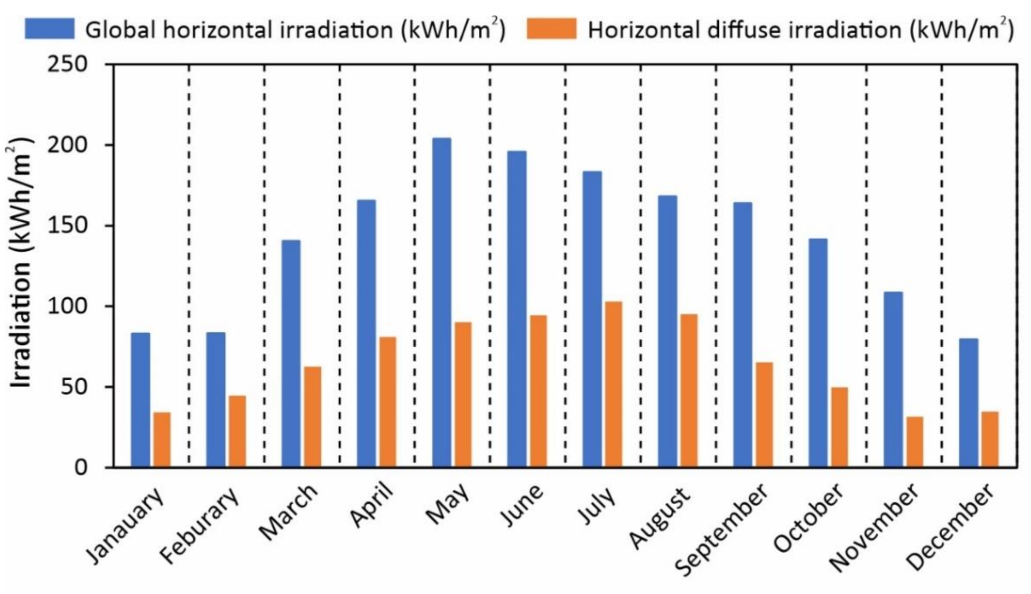

Figure 2 Monthly global horizontal and diffuse radiation in Islamabad.

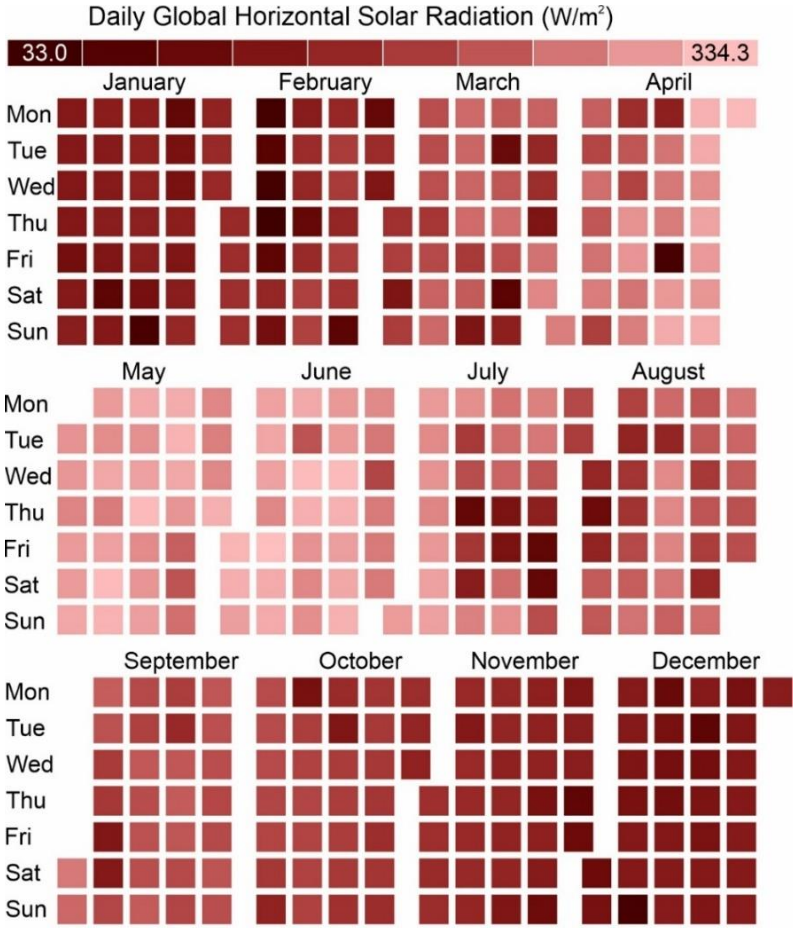

Figure 3 Daily global horizontal radiation in Islamabad.

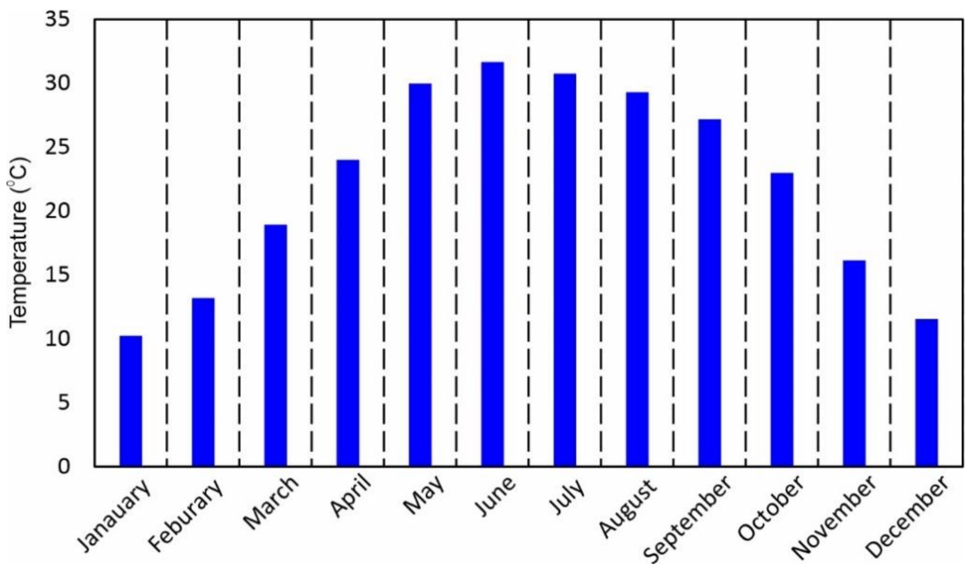

Figure 4 Monthly temperature in Islamabad.

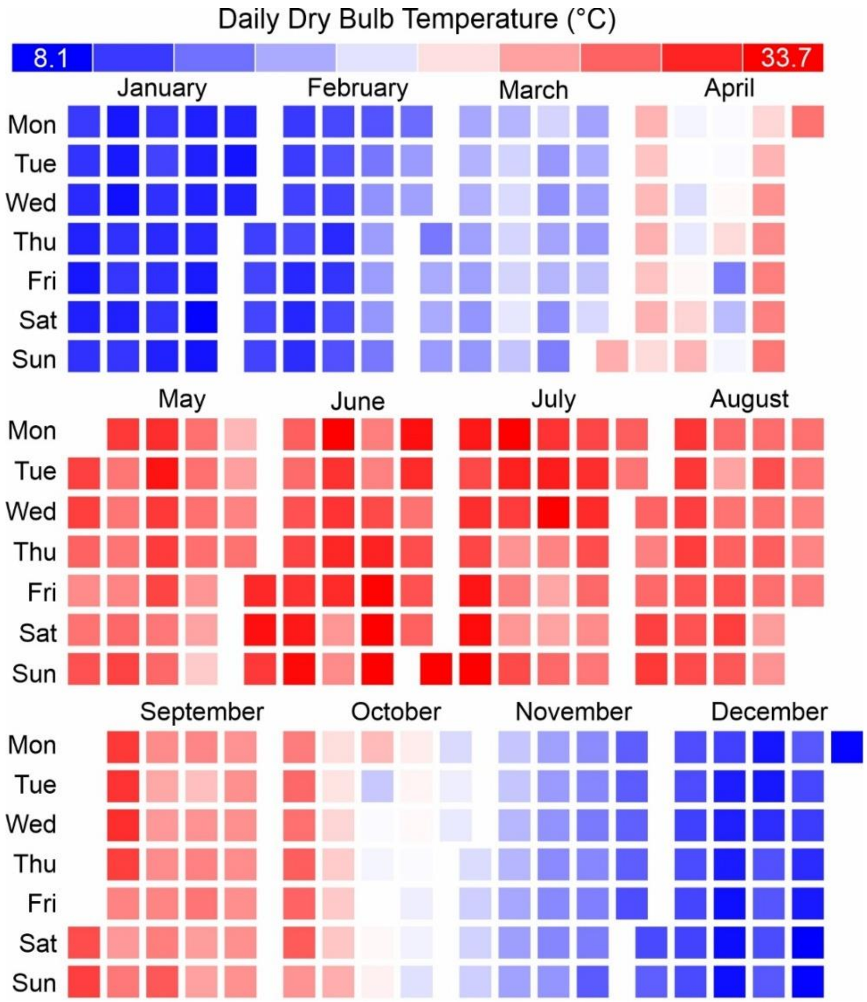

Figure 5 Daily dry bulb temperature in Islamabad.

Figure 4 shows the monthly average temperature in the study area which varies from the 30 to 10°C.As mentioned above the temperature average is also greater in the summer months. Figure 5 shows the daily temperature in the study area which varies 8.1 to 33.7 °C. Greater temperature leads toward the more solar irradiation which ultimately results in higher electricity generation. Therefore, the solar photovoltaic is completely dependent on the climatic parameters.

Performance analysis

The performance of the PV system is comprised on the yields (array yield, reference yield, and final yield), performance ratio (P_R), and capacity factor. Table 1 and Table 2 shows characteristic of the Photovoltaic module and inverter.

The reference yield is the measure to determine the peak sunshine hour per day. It is the ratio of total solar inplane solar insolation to the solar array unit irradiance. Equation 1 shows the reference yield Y_R. Where G_T (kWh/m^2) and I_u (1 kW/m^2) shows the solar insolation and unit irradiance respectively [33], [34].

$$Y_R = \frac{G_T}{I_u}$$

Table 1 Characteristics of the photovoltaic module

1	Unit Nom. Power	Wp	440
2	No. of PV modules	-	56
3	Nominal (STC)	kWp	24.64
4	Modules	-	4 strings × 14 in series
5	Total area	m^2	122
6	Azimuth angel	Degree	15

Table 2 Characteristics of the inverter

1	Unit Nom. Power	kWac	20
2	No. of inverters	-	1
3	Total Power	kWac	20
4	Operating voltages	V	200-950
5	Max. Power	kWac	22
6	Pnom ratio (DC:AC)	-	1.23

The array yield is ratio of the DC energy (E_{DC}) generated by the PV array over a time period to the peak energy generated E'_{PV} at STC (standard condition). Equation (2) shows the array yield Y_A. The daily and monthly array yield is given in the equation (3 & 4) [19], [35].

$$Y_A = \frac{E_{DC}}{E'_{PV}}$$

$$Y_{DA} = \frac{E_{DDC}}{E'_{DPV}}$$

$$Y_{MA} = \frac{1}{n}\sum_{d=1}^{n} Y_{DA}$$

The final yield is given as the ratio of the AC energy generated over a period of time to the peak energy generated at STC. The final yield is the measure of the same power at different geographical locations [19], [34], [35].

$$Y_F = \frac{E_{AC}}{E'_{PV}}$$

The capacity factor is the performance measure as per the geographical location of the PV system. It is the ratio of the annual AC energy generated (E_{Ac}^{a}) to the maximum energy that a system can generate in consequence of rated power in one power year (E'_{PV}). If a system supplies full rated power so the capacity factor could be considered as the unity. Equation shows the capacity factor C_F [18], [19], [33], [34]

$$C_F = \frac{E_{Ac}^{a}}{E'_{PV} * 24 * 356} * 100$$

Performance ratio is the dimensionless performance parameter. It is the ratio of the energy that a PV system can deliver at STC condition [36]. Equation shows the performance ratio (P_R).

$$P_R = \frac{E_{AC}}{\eta_{STC} * G_T} * 100$$

Where E_{AC} shows the AC energy generated in kWh, η_{STC} shows the system effectiveness at STC and G_T shows the irradiation of solar module area at given period (kWh). Furthermore, the performance ratio can be calculated by the ratio of the final yield to reference yield.

$$P_R = \frac{Y_F}{Y_R}$$

Performance ratio could be also explained as ratio of the effectiveness of the PV system to the effectiveness' at STC [33], [37].

$$P_R = \frac{\eta_{PV}}{\eta_{STC}}$$

Losses in PV systems

Mainly the losses in PV system is classified as array capture losses and the system conversion loses. The array capture losses show the uncaptured radiations in the arrays due to the panel temperature, improper wiring, spectral losses, partial shading, searching in the maximum power point. It is given as the difference of the reference yield to the actual yield [38]. Equation shows the capture loses.

$$L_c = Y_R - Y_A$$

The system conversion losses are due to converting the direct current (DC) to alternating current (AC) using the inverter. System conversion losses is the difference between the actual yield and final yield. Equation shows the system conversion loses.

$$L_{sys} = Y_A - Y_F$$

PV systems efficiencies

The PV system efficiencies are classified as the PV module efficiency, inverter efficiency, and system efficiency. PV module efficiency can be calculated by the using the equation () [19], [33].

$$\eta_{PV} = \frac{P_{VM}}{R_T A_m} * 100$$

Where the η_{PV} shoes the effectiveness of the solar module, A_m shows the solar radiation on the module (W/m^2). Furthermore, the cell temperature is dependent on the effectiveness of the solar module given in equation () [39]–[41].

$$\eta_{PV} = \eta_{PVSTC} [1 - \zeta (T_{cell} - T_{ref})]$$

Where η_{PVSTC} is the efficiency of the module at STC, ζ temperature coefficient of the power, T_{cell} shows the cell temperature and T_{ref} shows the temperature at STC.

The inverter efficiency is ratio of the energy output (alternating current output) to the energy input (Direct current input) [33]. Equation shows the inverter efficiency whereas the equation shows the monthly efficiency of the inverter is shown in the equation () [42].

$$\eta_{INV} = \frac{E_{AC}}{E_{DC}}$$

$$\eta_{M,INV} = \frac{\sum_{d=1}^{N} E_{D,AC}}{\sum_{d=1}^{N} E_{D,DC}}$$

The system efficiency of the system is the product of the PV module efficiency (how much irradiation is captured by the module) inverter efficiency (how much DC is converted into AC). Equation ( ) shows the system efficiency [33], [41].

$$\eta_{SYS} = \eta_{PV} * \eta_{INV} = \frac{P_{VM}}{R_T A_m} * \frac{E_{AC}}{E_{DC}}$$

Annually, the system efficiency can also be measured by using the equation ().

$$\eta_{SYS} = \frac{E_{A,AC}}{A_m \sum_{d=1}^{365} G_{T,d}}$$

Modeling of PV system

The amount of the energy produced from PV system depends upon the sunshine hours. The modelling has the various steps to simulate that are Site Survey: The first step in modeling a PV system using is to conduct a site survey to collect data about the location, orientation, shading, and other factors that may impact the performance of the PV system. After the site survey is conducted, the create a detailed 3D model of the PV system. The user inputs the site data and then creates a model of the solar panels, inverters, batteries and other components of the system. The next step is design the PV system by selecting the type and number of solar panels, the inverter, and other components of the system. The software optimize the design of the PV system, such as a database of solar panels and inverters from different manufacturers. The last step is performance analysis tools that allow users to analyze the performance of the PV system under various conditions. This includes analyzing the energy output of the system based on the site's location, the orientation of the panels, shading, and other factors that impact the system's performance. Two modelling software's are used to check the performance of the photovoltaic system one is PVsyst and Helioscope. Figure 6 shows the setup of the PV system on location. Figure 6a, 6b, and 6c shows the setting of the geometry for the PVsyst, Helioscope and installed PV system on site.

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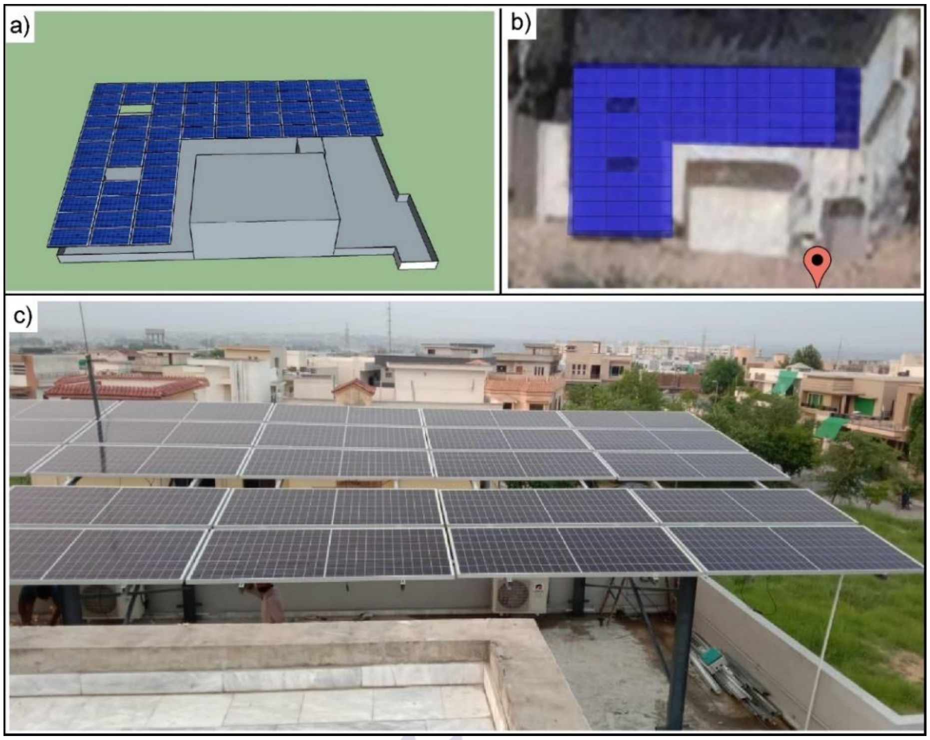

Figure 6 Setting of the PV system on the study area for a) PVsyst b) Helioscope c) Experimental setup.

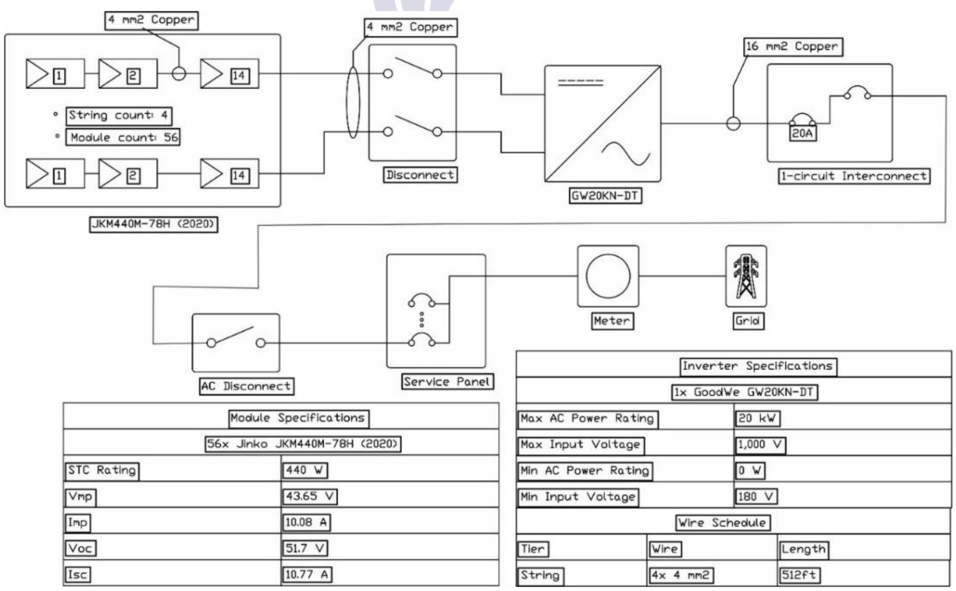

Figure 7 Block diagram of the installed PV system.

Results and discussion

In the current study by using the meteorological data the performance of the PV system is determined and compared with the two-modelling software (PVsyst and Helioscope) and the experimental data.

PVsyst results

The irradiation is one of the most significant factor in the performance of the solar photovoltaic system. The irradiation that incident on the solar plate is dependent on the setting up the angel of the plate to capture the maximum solar radiation. Figure 8 shows the incident the solar radiation on the solar plate. So, the more effective solar irradiation means more generation of the output electricity. After the solar radiation incident on photovoltaic plate there are also some losses in the in the energy before we get the results. Figure 9 shows the annual global irradiation, diffuse irradiation, effective irradiation, GHI incident to solar and temperature on the site. As mentioned above the losses are classified as the system capture losses and conversion losses. Figure 10 shows the losses in the PV system. After the capture losses the due to incident of the radiation into the collection solar plate complete energy is 44 MWh. So as this current pass through the array loss, inverter loss and DC to AC the complete 80% of the 44MWh.

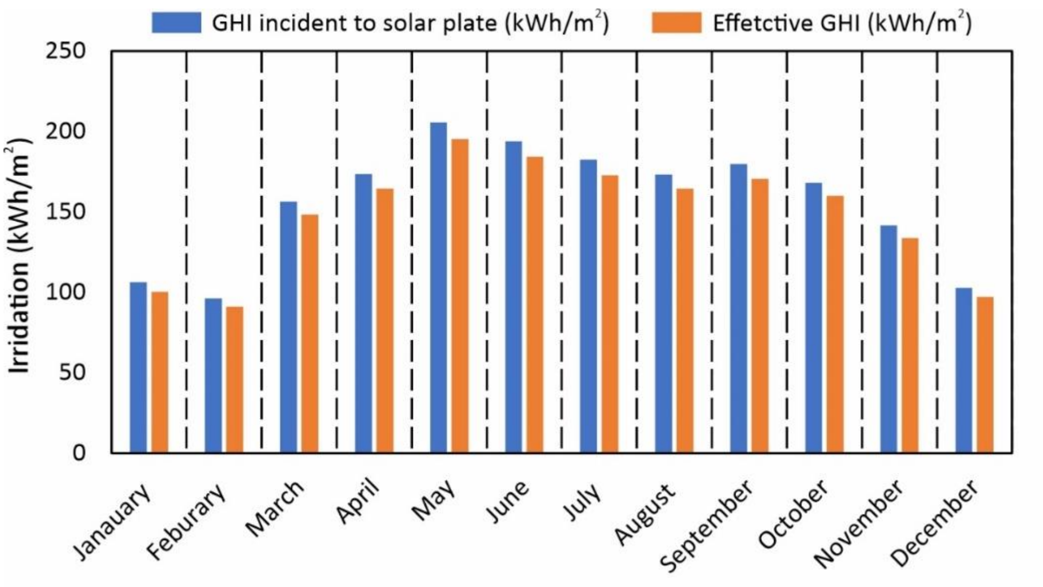

Figure 8 Global Horizontal irradiation incident and effective global horizontal irradiation on the solar plate.

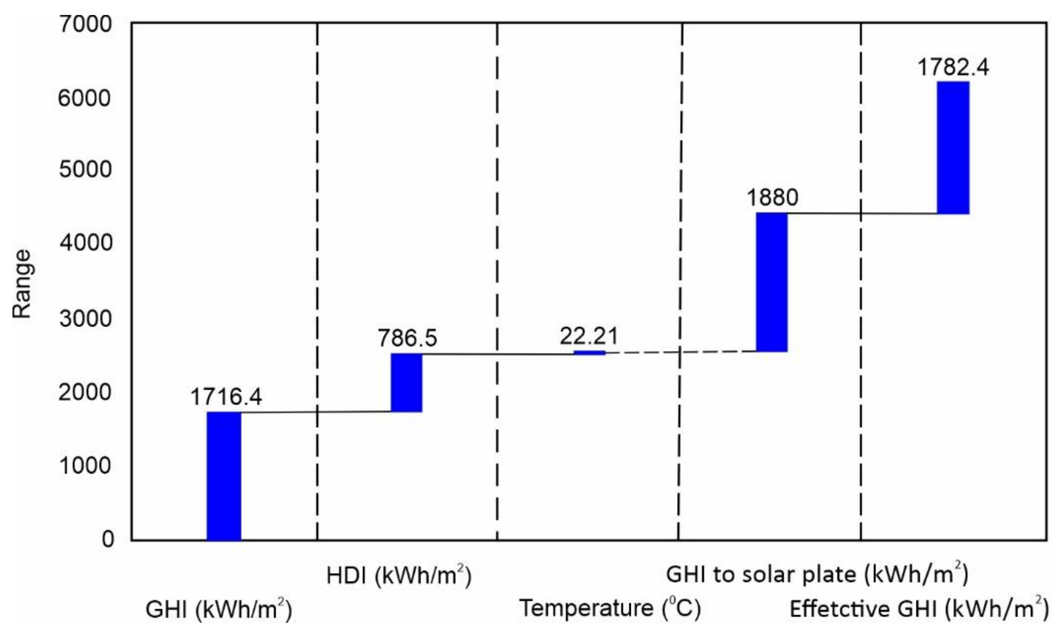

Figure 9 Annual global irradiation, diffuse irradiation, effective irradiation, GHI incident to solar and temperature on the site.

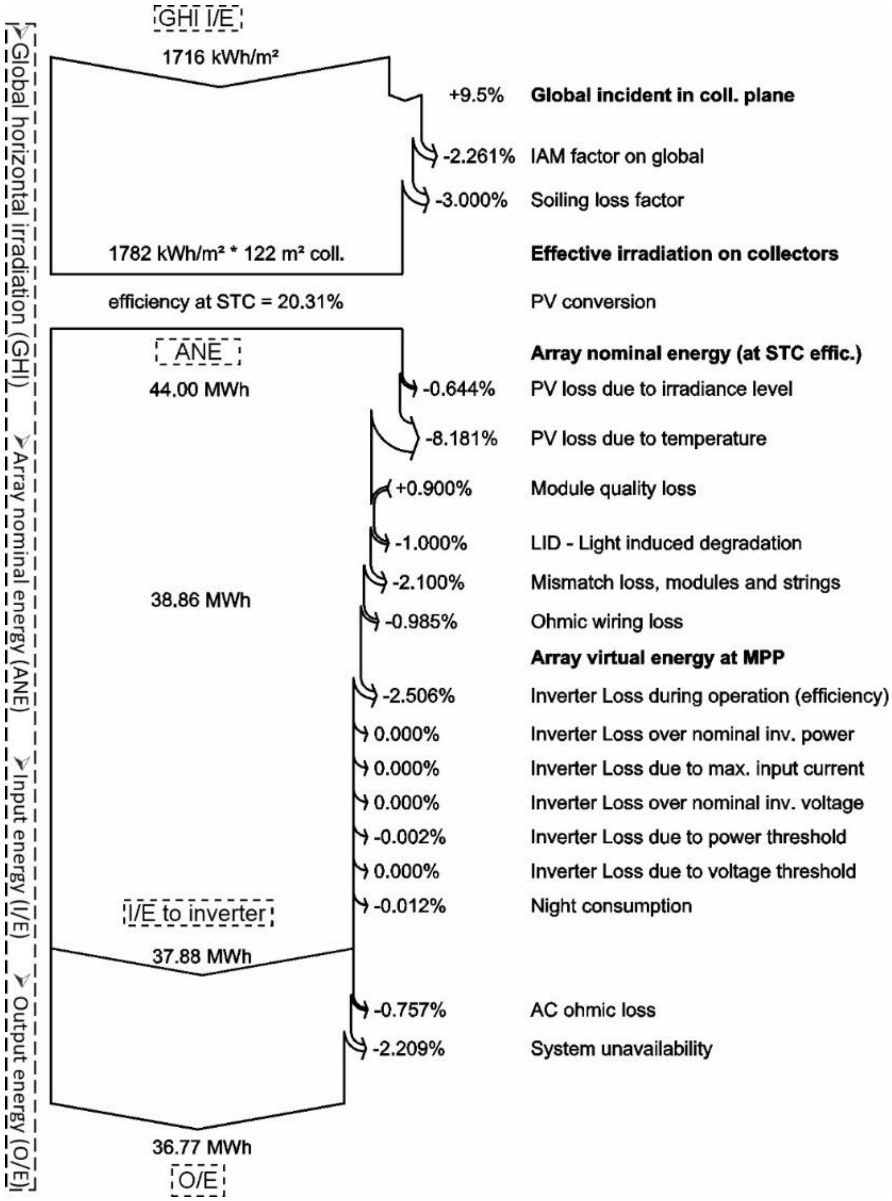

Figure 10 Losses in the PV system

Figure 11 shows the global incident irradiation to the solar plate and energy entered into grid on the annual basis. As the global incident irradiation increases the power generation of the system also increases. It possesses the linear relationship. So, the more radiation to the collection plate leads towards the higher energy generation. Figure 12 shows the annual system output power distribution.

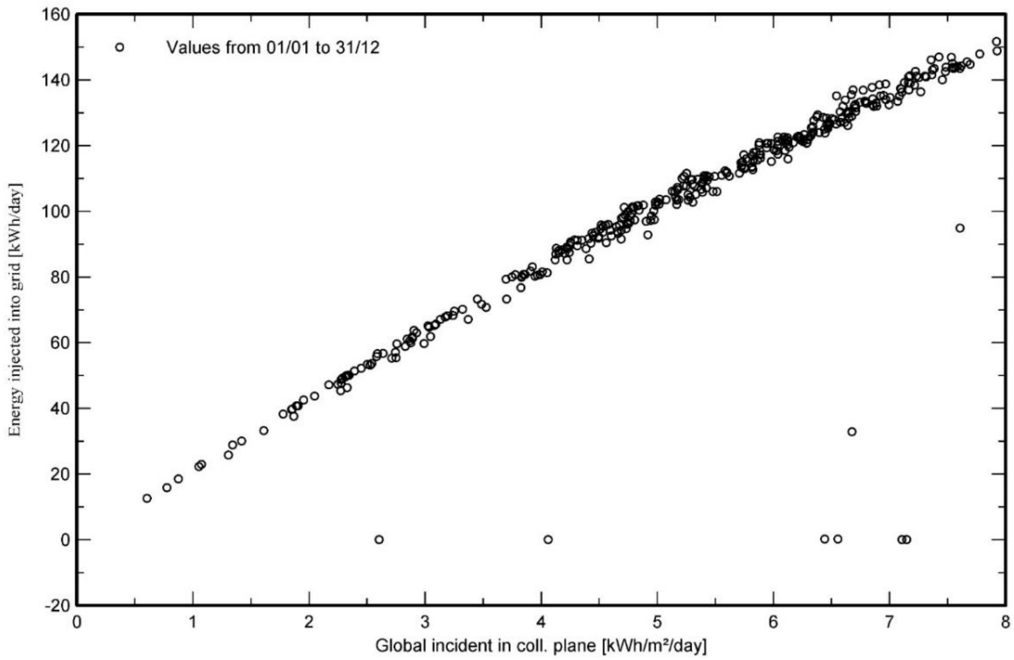

Figure 11 Global incident irradiation to the collection plate and energy injected into grid.

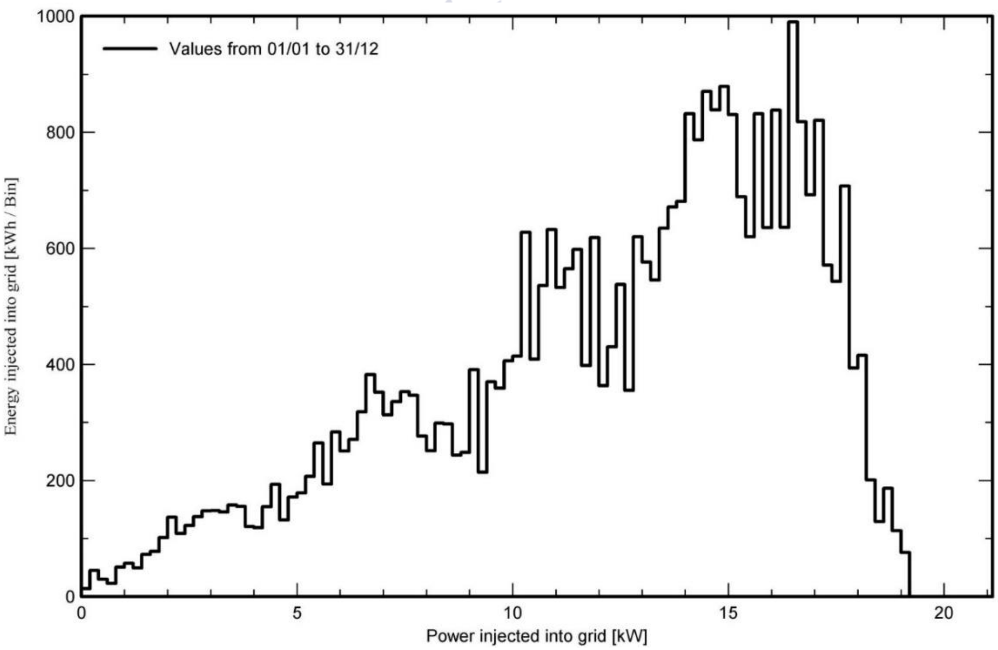

Figure 12 Global incident irradiation to the collection plate and energy injected into grid.

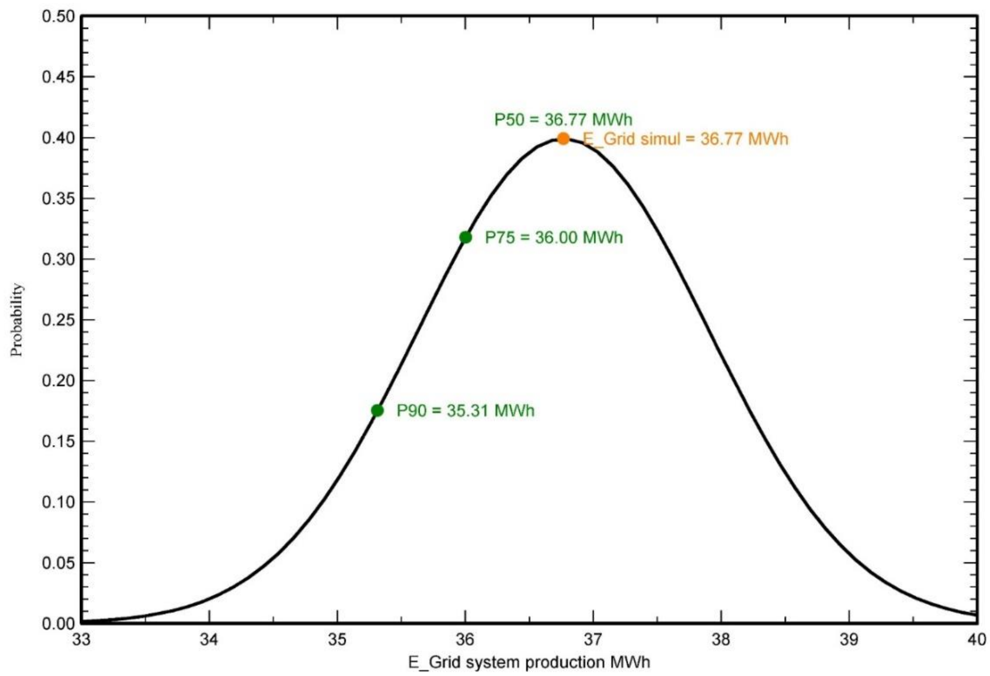

Figure 13 Probability curve of the energy production.

Figure 13 shows the probably curve based on the Gaussian probability distribution corresponding to the monthly average of the yearly data (2002-2011). It shows the energy supplied to the grid to with the maximum probability of P50 including all possible uncertainties, year to year variability and excluding the climate change factor. The annual variability considered as the 1.13 MWh. The minimum energy supplied to the gird is at P90 whereas the optimal energy supplied to the grid is P75. Furthermore, P75 is preferred due to its range between the minimum and maximum energy supplied to the grid.

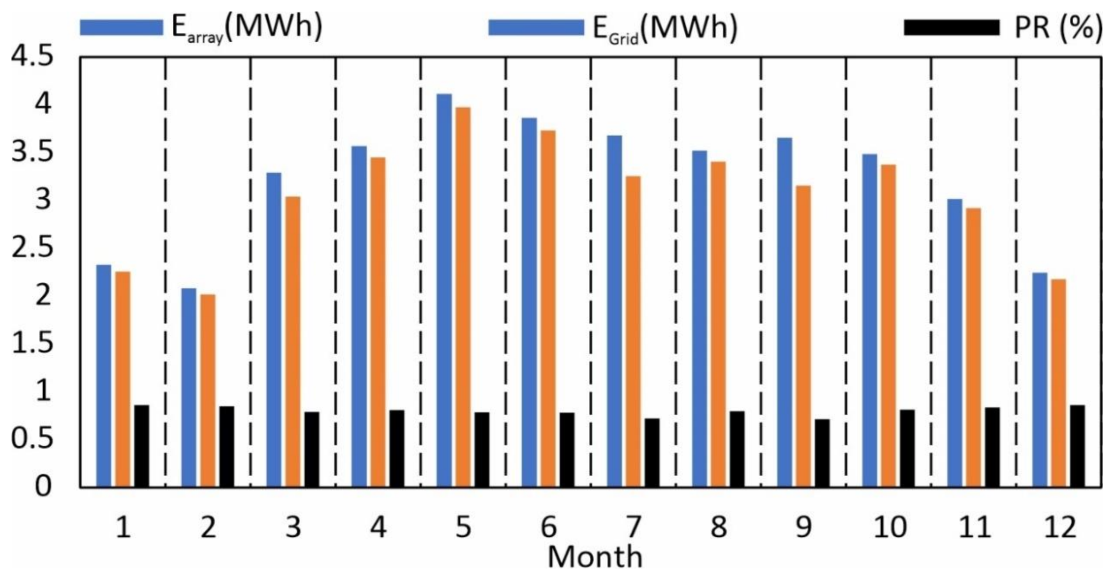

Figure 14 Energy from to array, energy supplied to grid and performance ratio.

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Figure 14 shows energy supplied from the to the array to the grid and the performance ratio. Furthermore, performance ratio is the ratio of the energy delivered from the array and energy supplied to the gird. The more performance ratio shows the more electricity delivered to the system.

HelioScope results

Table 3 shows the annual energy production of the setted photovoltaic system. Furthermore, it shows the losses and the gain of the output energy. It shows the sequence of the energy reduction in the in % at every step. Minus sin show the energy deduction in the next step where plus sign shows the energy addition in the next step. The total energy collected or transferred to grid are 36195.5 after all loses. Figure 15 shows the loses of the PV system using the Heliscope software.

Table 3 Annual energy production from the PV system

Irradiance (kW/m^2)	Annual GHI	1723.5	-
	POA irradiance	1896.2	+10
	Shaded irradiance	1896.2	0
	Irradiance after reflection	1834.1	-3.3
	Irradiance after soiling	1779.1	-3
	Total Collector Irradiance	1779.1	0
Energy (kWh)	Nameplate	43842.2	-
	Output at irradiance level	43760.1	-0.4
	Output at irradiance level Derate	38416	+12
	Output after mismatch	37112	-3.4
	Optimal DC Output	36934.1	-0.5
	Constrained DC Output	36934	0
	Inverter Output	36232.2	-1.9
	Energy to Grid	36195.5	-0.1

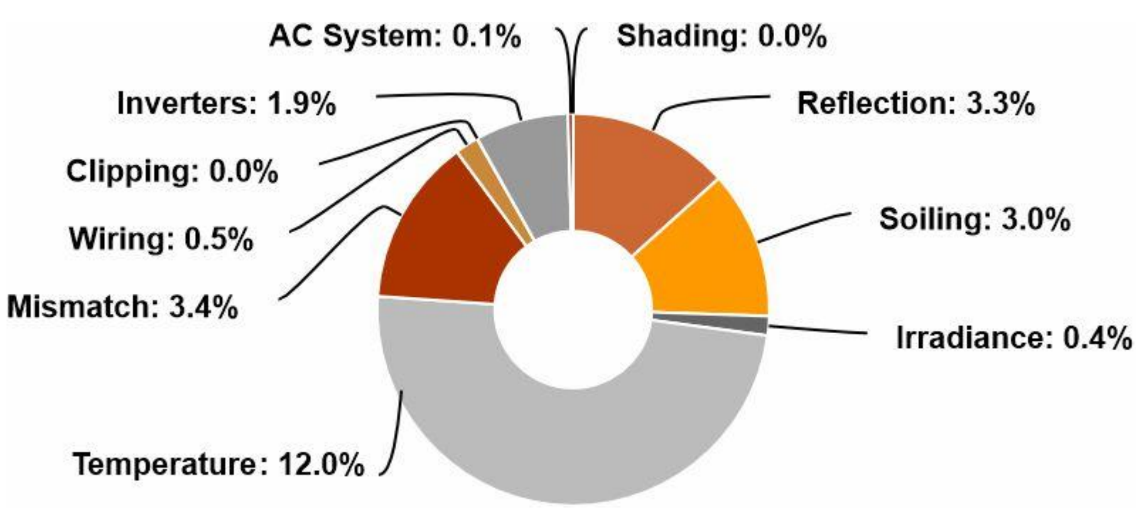

Figure 15 Loses in the PV system in Helioscope.

CO$_2$ emission

Table 4 Life cycle carbon emission of the installed PV system.

[redacted]				
1	Module	1713 ($kgCO_2/kWp$)	24.6 kWp	42201
3	Supports	2.97 ($kgCO_2/kg$)	560 kg	1662
3	Inverters	294 ($kgCO_2/unit$)	1 unit	294

The carbon emission footprint of the solar photovoltaic system is much smaller than conventional energy generation technique. Table 4 shows the complete emission of the CO_2 in the complete life cycle. It is obvious that the solar photovoltaic system only produces the ~45 tons of carbon from production of each unit to assembling. Figure 16 shows the simulation of the carbon emission in next 25 years. The analysis represents that we can save ~340 tons of the CO_2 generation by employing the solar photovoltaic system. Furthermore, it will also help us to gain sustainable development goals. In figure 15 below the lines from 0 to -50 shows the generation of the energy.

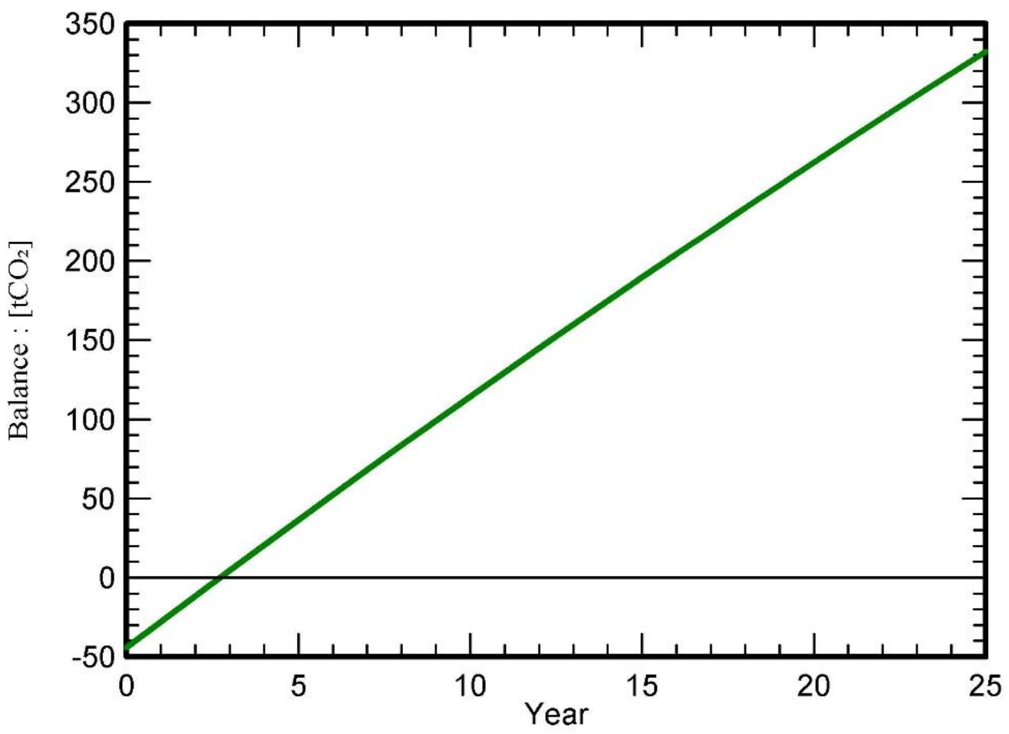

Figure 16 Loses in the PV system in Helioscope.

Validation of the above results

The validation of the results is shown in the figure 17. The simulation results of both software's are compared with the each other and also with the experimental results. In all three performance tools the maximum energy generation is in the summer months due to more sunlight and irradiation as per the geographical area of the study area. Furthermore, it shows the in all months there is enough potential of the energy generation.

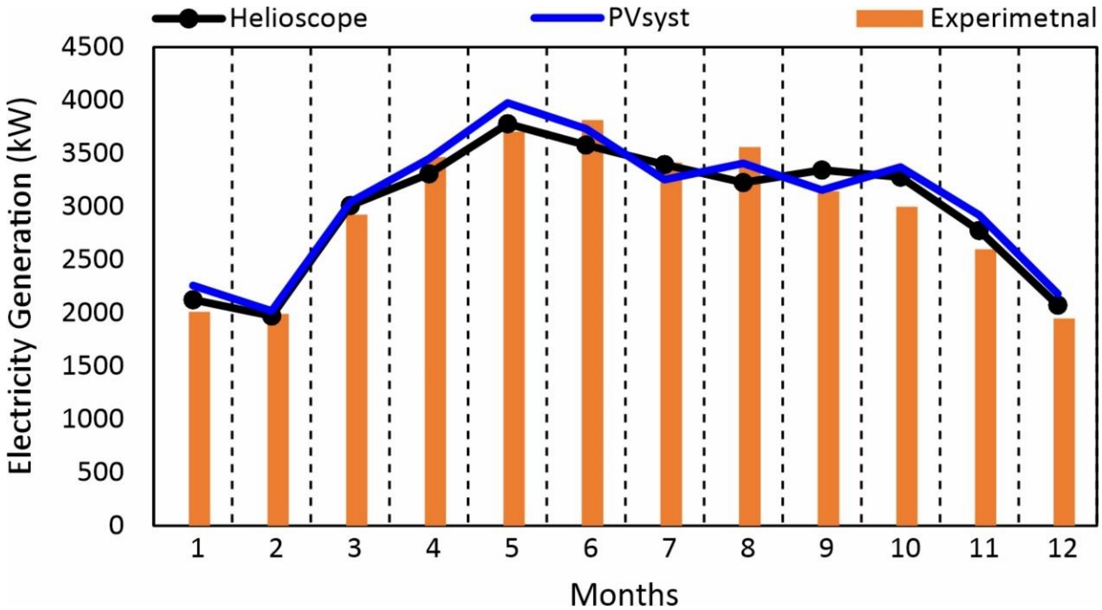

Figure 17 Comparison of the results the simulated results.

Conclusions

This study presented a comparative validation of PVsyst and HelioScope against measured operational data for a 24.64 kWp grid-connected residential PV system installed in Islamabad. The analysis confirms that solar irradiance is the dominant driver of energy yield, with peak generation observed during summer due to elevated incident radiation levels.

PVsyst predicted approximately 44 MWh annual DC energy prior to losses, with roughly 80% conversion to usable AC output after accounting for array capture and inverter losses. HelioScope estimated 36.20 MWh annual energy delivered to the grid following detailed loss modeling, including reflection, soiling, mismatch, and conversion effects. Both tools demonstrated strong consistency with experimental observations across seasonal variations, validating their applicability for system design and performance forecasting in similar climatic regions.

Performance ratio trends indicated stable system operation, while loss decomposition highlighted the significance of temperature effects and inverter efficiency in overall yield reduction. Life cycle carbon analysis revealed that initial embodied emissions (~45 tCO_2-eq) are substantially offset during operation, yielding an estimated 340 tCO_2 mitigation over 25 years.

Overall, the findings demonstrate that both PVsyst and HelioScope provide reliable and technically robust predictions for residential PV systems in Pakistan, supporting optimized design, grid integration planning, and long-term sustainability assessments.

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