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Research paper

# Performance analysis of 1210kW grid-connected solar photovoltaic systems at Bukhara State University

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ABSTRACT

Among renewable energy sources, solar energy clearly stands out due to its wide range of possibilities. Solar photovoltaic (PV) systems are widely used to generate electricity from solar energy. There are a number of standards for evaluating the efficiency of solar PV systems. In this work, the performance of a 1210 kWp solar PV system located on the roof of Bukhara State University (BukhSU) was studied based on the IEC 61,724 standard. The solar PV system produced 1209,638 kWh of electricity in 2024. The electricity generated by solar PV system is linked to solar radiation with a strong linear correlation of $R^2 = 0.7406$. The annual average values of array yield, final yield, and reference yield are 2.79, 2.73, and 4.64 kWh/kWp, respectively. The annual average Array losses were 1.85 kW/kWp, while the total system losses were 1.90 kWh/kWp. According to the economic analysis, the Levelised Cost of Energy is 0.048 USD/kWh and the Simple Payback Period is 9.92 years. The average Capacity Utilization Factor and Performance Ratio of the system are 11.41 % and 65.15 %. The system saves 286,856 tons and 989,626 tons of $CO_2$ compared to natural gas and coal.

## 1. Introduction

According to the International Energy Agency (IEA), global electricity demand in 2025 will be 29,281 TWh (Figs. 1 and 2.), with an average annual growth rate of 3 % for 2023–2025 [1]. Electricity generation accounts for approximately 42 % of energy-related $CO_2$ emissions worldwide [2]. Generating energy using renewable energy systems such as solar, wind, and tidal energy benefits the environment by reducing $CO_2$ emissions [3]. The International Renewable Energy Agency (IRENA) aims for around 85 % of energy generated by 2050 to come from renewable energy, with solar power accounting for 20 % of total energy [4]. Renewable energy sources are being integrated into energy systems as a solution to the problems of depletion of conventional fuel sources and their harmful effects on the environment [5]. Solar energy is gaining importance due to its renewable nature, low environmental impact and potential for use in many devices [6]. According to 2023 data, the global installed capacity of solar energy has exceeded 1200 gigawatts (GW), which is enough to power >300 million homes [7]. Solar energy is the most abundant energy source on earth, allowing electricity generation using PV systems [8]. PV systems have become widely popular due to their ability to generate electricity directly from sunlight, ease of installation, low cost, and long service life [9],[10],. PV systems can operate in both off-grid and on-grid modes [11]. An on-grid system does not require the need to install batteries due to its ability to draw power from the main grid during night hours, cloudy or dusty days, while an off-grid system requires batteries to provide energy at night, during cloudy (shaded) times, and to compensate for the shortage caused by dust [12].

Uzbekistan is the most populous country in Central Asia, with a resident population of 37,355,400 as of October 1, 2024, an increase of 2.1 % compared to the same period in 2023 [13]. According to the United Nations forecast, by 2030 the population of Uzbekistan will reach 40,248,242 people [14]. The volume of electricity consumption by subscribers increased from 53,839.8 GWh to 62,836.3 GWh between 2020 and 2023, respectively, the volume of electricity consumption by subscribers per capita increased from 1572.8 GWh to 1725.7 GWh [13]. Although the share of traditional energy sources in meeting the demand for electricity in Uzbekistan is high (Fig. 3-5), between 2020 and 2023, the volume of electricity generated by solar power plants increased from 0.03 GWh to 1237.3 GWh, while electricity generated by wind power plants reached 7.2 GWh [13].

In 2018–2023, the government implemented a number of projects and initiatives aimed at rapidly developing the use of renewable energy

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**Nomenclature**

| | |
|---|---|
| $C_{IC}$ | investment capital, USD |
| $C_{OM}$ | annual operational and maintenance costs, USD |
| CRF | ratio of a constant annuity to the present value of receiving that annuity for a specified time period |
| $CF_1$ | the annual cashflow for project, USD |
| $E_a$ | annual electricity generated, kWh |
| $E_{AC}$ | actual annual AC (alternating current) energy produced by the system, kWh |
| $E_{AC,m}$ | monthly energy produced by the system, kWh |
| $E_{AC,\ d}$ | daily energy produced by the system, kWh |
| $E_{DC}$ | total daily DC (direct current) energy output from the PV, kWh |
| $E_{ff}$ | thermal efficiency of the conventional heating equipment, % |
| $F_{CO_2}$ | carbon emission factor of various energy sources |
| $G_{STC}$ | irradiance at Standard Test Conditions, kW/m$^2$ |
| $g$ | calorific value of conventional fuel, kWh/kg |
| $H_t$ | total in-plane solar radiation, kWh/m$^2$ |
| $IC_0$ | value of invested capital, USD |
| $L_t$ | total system collection losses, kWh/kWp |
| $L_A$ | array capture losses, kWh/kWp |
| $L_S$ | conversion/system losses, kWh/kWp |
| $LC$ | life cycle, year |
| $P_{PV,rated}$ | maximum rated power of system, kWp |
| $PR$ | performance ratio, % |
| $Q_{CO_2}$ | amount of carbon dioxide emission in the life cycle, kg |
| $Y_r$ | reference yield, kWh/kWp |
| $Y_a$ | array yield, kWh/kWp |
| $Y_f$ | final yield, kWh/kWp |
| $\mu$ | efficiency of the converter, % |

*Abbreviations*

| | |
|---|---|
| AC | Alternating current |
| BukhSU | Bukhara State University |
| *CUF* | Capacity Utilization Factor |
| IEA | International Energy Agency |
| IEC | International Electro-technical Commission |
| IRENA | International Renewable Energy Agency |
| DC | Direct current |
| LCOE | levelised cost of energy |
| PV | Photovoltaic |
| USD | United States Dollar |
| SPP | Simple Payback Period |

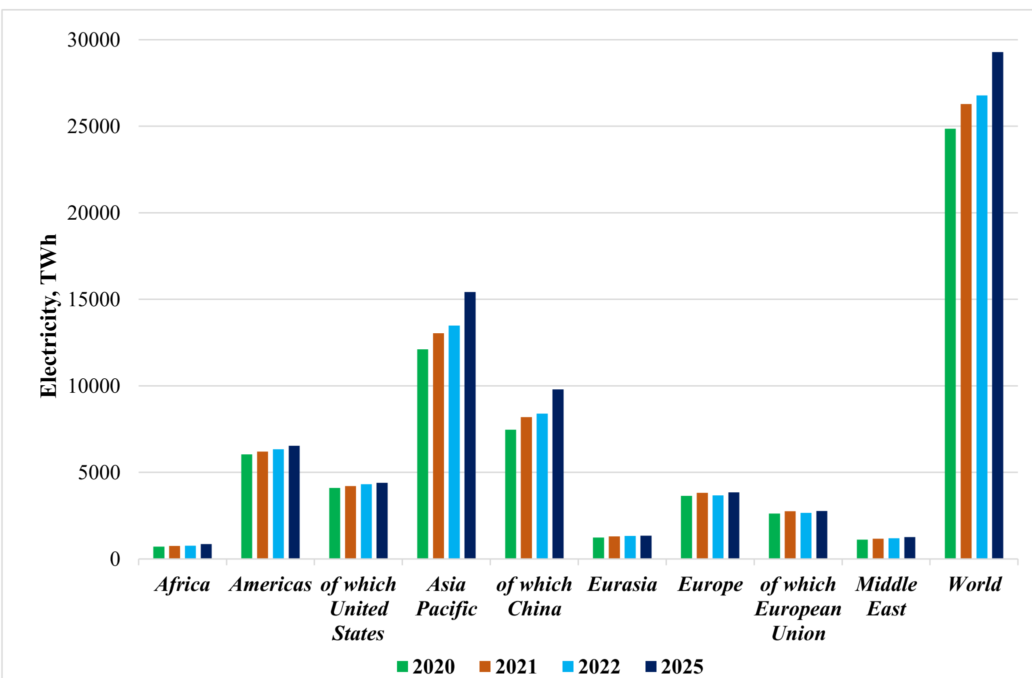



**Fig. 1.** Regional distribution of electricity demand (2020–2025) [1].

sources. A $125 million loan, in partnership with the Asian Development Bank (ADB), will help integrate renewable energy into the country's energy mix and pave the way for generating at least 30 percent of electricity from renewable sources by 2030 [15]. The United Arab Emirates' Masdar Company has signed agreements with international financial institutions worth nearly $396 million to build solar photovoltaic power plants in Uzbekistan: $127 million with the European Development Bank (EDB), $102 million with the ADB, and $167 million with their partner banks. These photovoltaic power plants will have a total capacity of 897 MW and will be able to generate 2 billion kWh of electricity annually. Based on these projects, a 250 MW solar photovoltaic power plant and a 63 MW electricity storage system are being built in the Olot district of Bukhara region, with a project value of $273 million, and a 500 MW solar photovoltaic power plant is being built in the Qarovulbazar district [16]. In addition to large-scale solar photovoltaic power plants, on-grid solar PV systems are also being installed on the roofs of organizations and various buildings. An on-grid solar PV system with a total capacity of 1210 kWp has been installed on the roofs of the academic buildings and student dormitories of BukhSU.

This study aims to determine the performance ratio, capacity factor,

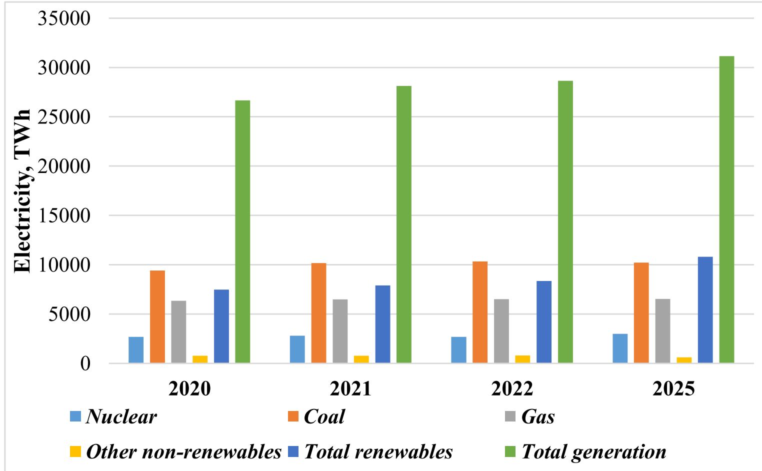



**Fig. 2.** Distribution of electricity generation in 2020–2025 [1].

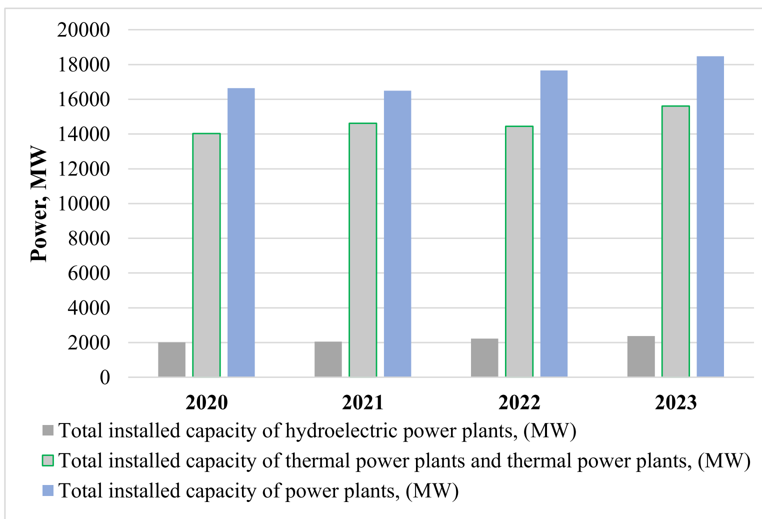



**Fig. 3.** Total installed capacity of power plants in Uzbekistan [13].

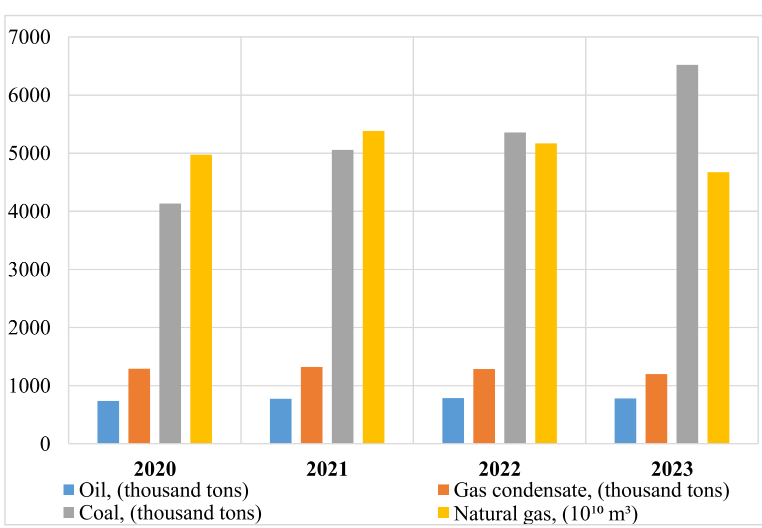



**Fig. 4.** Production volume of oil, coal, gas condensate and natural gas in Uzbekistan [13].

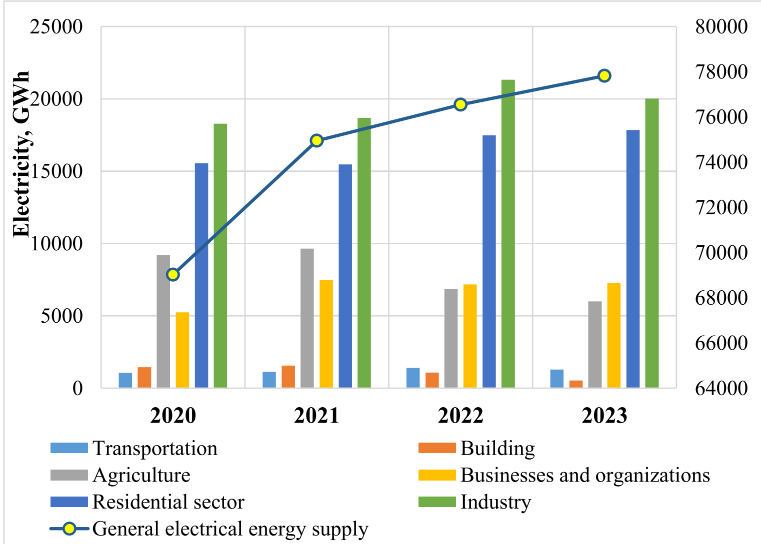



**Fig. 5.** Electricity supply in various sectors in Uzbekistan [13].

**Table 1**
PV systems analyzed based on IEC 61,724 standard.

| References/year | Country | Installation type | PV module type | PV module efficiency, % | PV system capacity | Energy generation | Assesment period |
|---|---|---|---|---|---|---|---|
| Ivan T. Oloya and et al. (2021) [19] | Uganda | Ground | p-Si | 16.16 | 10 MW | 16441MWh<br>16,325 MWh<br>17,342 MWh | 2017<br>2018<br>2019 |
| Emmanuel Ayora and et al. (2023) [20] | Kenya | Rooftop | p-Si | 15.27 | 600 kWp | 735 MWh | 2019 |
| Yibeltal T. Wassie and et al. (2023) [21] | Ethiopia | Fixed ground-mounted racks | m-Si | 18.94 | 375 kWp | 289.607 MWh | 1 May – December 31, 2021 |
| Id omar Nour-eddine and et al. (2020) [25] | Morocco | Rooftop | m-Si<br>p-Si<br>a-Si | 17.47<br>17.47<br>9.87 | 5.94 kW | 3908.9 kWh;<br>3896.7 kWh;<br>3198.0 kWh | June/2018 - May/ 2019 |
| Khalid Mohamed and et al. (2024) [26] | Maldives | Rooftop | p-Si | 17.01 | 6.6 kWp | 9693.492 kWh | 2022 |
| Enrique Fuster-Palop and et al. (2022) [27] | Spain | Ground (PV plant) | m-Si<br>p-Si | 12.21–12.50<br>12.26–14.35 | 50 MW (60.103 MWp) | 91.32 GWh | 2020 |
| Dipankar Pramanick and et al. (2024) [28] | India | - | m-Si<br>p-Si | 17<br>13 | 20 kWp<br>20 kWp | 84.77 kWh<br>78.01 kWh | 2022 |
| Charles K.K. Sekyere and et al. (2021) [29] | Ghana | Ground | p-si | 15.36 | 20 MW | 26,840 MWh | 2018 |
| Said Bentouba and et al. (2021) [30] | Algeria | Ground | p-Si | 15 | 20 MW | 36,364 MWh | 2018 |
| Ali Murat Ates and et al. (2021) [31] | Turkey | Rooftop | p-Si | 16 | 30 kWp | 45.592 kWh | 2018 |
| Abdulhameed Babatunde Owolabi and at al. (2022) [32] | South Korea | Rooftop | m-Si<br>p-Si | 15.62<br>14.22 | 5 kWp<br>4.6 kWp | 9521 kWh<br>8263 kWh | 2021 |
| Omar A. Al-Shahri and et al. (2022) [33] | Oman | Gound | p-Si | 15.4 | 307.7 kWp | 559.23 GWh<br>542.14 GWh | 2017<br>2018 |

reference yield, final yield, annual yield, and system losses of a 1210 kWp PV system based on the IEC 61,724 standard [17]. IEC 61,724 is a standard developed by the International Electro-technical Commission (IEC) to measure the performance of all types of PV technologies, including off-grid, on-grid and hybrid PV systems [18]. sed on this standard, the performance of several PV systems has been analyzed. For example, Ivan T. Oloya and et al. [19] conducted a techno-economic analysis of a 10 MW centralized grid-connected solar PV system in Uganda. Emmanuel Ayora and et al. [20] evaluated the performance of a 600 kWp grid-tied rooftop Solar PV system at Strathmore University in Kenya. Yibeltal T. Wassie and et al. [21] analyzed a small off-grid system in southern Ethiopia. M.M. Samy and et al. [22] conducted a feasibility study and optimized a hybrid PV-biomass microgrid renewable energy system using biomass and solar resources of the selected area to power an independent apple farm located in Albahaa, Kingdom of Saudi Arabia. Jenan Abu Qadourah and et al. [23] studied the economic and energy efficiency of installing PV systems on the roofs of multi-storey buildings located in different climatic zones in Jordan. Wenheng Zheng and et al. [24] simulated and experimentally tested the thermal and electrical performance of rooftop PV with different heights and tiltes using Design Builder software. The study investigated the effects of rooftop PV installation on parameters such as surface temperature, cooling and heating load, climatic conditions.

Table 1 provides information on the performance of PV systems


**Fig. 6.** View of the area where the solar PV system is located at BukhSU (Google Earth, 2/2/2024).
1 - first academic building; 2 - second academic building; 3 - student dormitory.

**Table 2**
Description of solar PV system.

| Parameters | Value |
|---|---|
| PV system nominal power | 1210 kW |
| Tilt | 30° |
| Type of installation | Rooftop |
| Number of PV module | 2201 |
| Number of inverters | 21 |

**Table 3**
PV module specifications.

| Parameters | Value |
|---|---|
| Company name | Ipvisola |
| PV module type | YH550W-36MH |
| Cell type | m-Si |
| Number of cells | 144 |
| Module efficiency | 21 % |
| Weight | 28.4 kg |
| Dimensions | 2279 x 1134 x 35 mm |
| Maximum power rating | 550 W |
| Open circuit voltage | 42.1 V |
| Short circuit current | 13.9 ± 3 A |
| Rated voltage at maximum power | 42.1 V |
| Rated current at maximum power | 13.06 A |
| Maximum system voltage | 50.1 ± 3 V |
| Operating temperature | −40 °C to +85 °C |
| Nominal operating temperature | +25 °C |

analyzed based on the IEC 61,724 standard.

In this work, the performance of the BukhSU rooftop solar PV system was analyzed based on the IEC 61,724 standard. CUF, PR, Array yield, Reference yield, Final yield were determined for the system. LCOE and SPP were determined from the economic indicators. The environmental impact of the system was also studied.

## 2. Materials and methods

### 2.1. Geographic location of Solar PV sytem

The main building of BukhSU is located in the central part of Bukhara city, on its territory there are the first and second academic buildings, a student dormitory (consisting of 6 buildings). BukhSU is located at latitude 39°45′40″N and longitude 64°25′20″E. The city of Bukhara is located at an altitude of 224 m above sea level. Fig. 6 shows the geographical location of the solar PV system located on the roof of the academic and student dormitory buildings on the territory of BukhSU (https://earth.google.com/,2/2/2024) [55].

The solar PV system of BukhSU has a total capacity of 1210 kW and is located on the roofs of the first and second academic buildings, 6 student dormitories. The solar PV system consists of 2201 PV modules (Ipvisola monocrystalline cells), 21 inverters and is connected to the public grid. The standard test conditions (STD) parameters of the PV modules and inverters are shown in Tables 2-4.

### 2.3. Weather data collection and monitoring

Monthly and annual ambient temperature, solar radiation, wind speed, and humidity necessary to evaluate the performance of the solar PV system for the coordinates of the area where BukhSU is located were obtained from the NASA POWER (Prediction of Worldwide Energy Resources) [56] database (Table 5).

**Table 4**
Inverter specifications.

| Parameters | Value of Solis | Value of Sofar |
|---|---|---|
| Model | S5-GS50K | 80KTLX-G3 |
| Max. input voltage DC | 1100 V | 1100 V |
| Mppt voltage range DC | 180–1000 V | 180–1000 V |
| Max. input current DC | 5 × 32 A | 6 × 40 A |
| Max. input short circuit current | 5 × 40 A | 6 × 60 A |
| Rated grid voltage AC | 3/N/PE 220/380 V<br>3/N/PE 230/400 V | 3/N/PE 230/400 V |
| Rated grid frequency | 50/60 Hz | 50/60 Hz |
| Rated output power | 50,000 W/50,000 VA | 80,000 W |
| Max. AC output active power | 55,000 W | |
| Max. AC output apparent power | 55,000 VA | 88,000 VA |
| Max. continuous output | 83.6 A | 133.3 A |
| Max. efficiency | 98.8 % | 98.7 % |
| EU efficiency | 98.4 % | 98.2 % |
| Adjustable cos($\varphi$) | −0.8…1…+0.8 | −0.8…1…+0.8 |
| Operating temperature range | −25…+60 °C | −30…+60 °C |
| Ingress protection | IP66 | IP66 |
| Protective class | I | |
| Overvoltage category | II (PV)<br>III (MAINS) | II (PV) |
| Inverter topology | Non-isolated | Transformerless |
| Weight | 42.1 kg | 50 kg |

**Table 5**
Metrological input data for the coordinates of the territory of BukhSU.

| Months | Horizontal radiation (kWh/m$^2$/day) | Ambient Temperature (°C) | Relative Humidity (%) | Wind velocity (m/s) |
|---|---|---|---|---|
| January | 1,93 | 2,22 | 71,15 | 4,10 |
| February | 2,67 | 2,15 | 59,30 | 4,29 |
| March | 4,09 | 8,96 | 63,20 | 3,95 |
| April | 6,00 | 18,47 | 40,63 | 3,91 |
| May | 6,60 | 22,37 | 39,61 | 4,61 |
| June | 7,84 | 31,38 | 20,93 | 5,37 |
| July | 7,39 | 31,66 | 25,66 | 5,10 |
| August | 6,62 | 30,61 | 21,37 | 5,63 |
| September | 5,28 | 21,61 | 23,40 | 5,25 |
| October | 3,35 | 14,38 | 45,30 | 3,54 |
| November | 2,19 | 7,95 | 64,86 | 3,06 |
| December | 1,70 | 2,17 | 55,83 | 3,46 |
| Average | 4,64 | 16,16 | 44,27 | 4,36 |

### 2.4. Solar PV system performance analysis

The performance of the grid-connected solar PV system of BukhSU was analyzed using the IEC 61,724 standard. The IEC 61,724 standard serves as a basis for comparing the performance of grid-connected solar PV systems installed in different parts of the world. This standard allows for the determination of PV system parameters such as performance ratio, energy output, collection/system losses, reference yield, final yield, and capacity utilization factor [18].

#### 2.4.1. Capacity utilization factor (CUF)

CUF is the ratio of the total energy produced by a solar PV system during a given period to the energy produced during that period when the system was operating at maximum power [34]. The annual value of CUF for a Solar PV system is determined by the following mathematical expression [20]:

$$CUF = \frac{E_{AC}}{P_{PV,rated} \cdot 8760} \tag{1}$$

#### 2.4.2. Total energy output

This represents the total energy that a solar PV system can deliver to the grid over a given period. Total energy output is estimated monthly for grid-connected systems. Total energy output is calculated as the sum of the daily energies produced in a month and is expressed by the following equation [20]:

$$E_{AC,\ m} = \sum_{d=1}^{n} E_{AC,\ d} \tag{2}$$

#### 2.4.3. Reference, array and final yield

The yield is the actual energy produced from a solar panel relative to the nominal power of the solar panel, and is divided into reference yield, array yield, and final yield [32]:

Reference yield is a quantity determined by the ratio of the total solar radiation on the in-plane to the standard solar radiation (1 kW/m$^2$) and depends on the location of the solar PV system [17]. The reason for this is that different amounts of sunlight reach different points on the Earth's surface. This quantity is expressed by the following equation [20]:

$$Y_r = \frac{H_t}{G_{STC}} \tag{3}$$

Array Yield is a quantity defined as the ratio of the DC energy produced by a solar PV system in a day or month to the nominal PV power [17]. This quantity is expressed by the following equation [17,28]:

$$Y_a = \frac{E_{DC}}{P_{PV,rated}} \tag{4}$$

$$E_{DC} = \frac{E_{AC}}{\mu} \tag{5}$$

Final yield - a quantity determined by the ratio of the AC output energy to the nominal power of the PV system under standard test conditions (STC) for a given period [34]. This quantity is expressed by the following equation [17]:

$$Y_f = \frac{E_{AC}}{P_{PV,rated}} \tag{6}$$

#### 2.4.4. Total system collection losses

Total system collection losses ($L_t$) consists of the sum of array capture ($L_C$) and conversion/system losses ($L_S$) [35].

$$L_t = L_C + L_S \tag{7}$$

*Array capture losses* represent the losses in the process of converting total solar energy into DC energy in PV modules and are divided into two types: thermal ($L_{CT}$) and miscellaneous ($L_{CM}$) capture losses [34].

- Thermal ($L_{CT}$) capture losses are caused by higher cell temperatures than STC, which are typically above 25 °C.
- Miscellaneous ($L_{CM}$) capture losses occur due to reasons such as low irradiance, wiring, snow covering, dirt accumulation, spectral losses, mismatching, shading, soling, string diodes, and maximum power tracking errors.

Array Capture losses are found using the following equation using Reference yield ($Y_r$) and Array yield ($Y_a$) [36]:

$$L_C = Y_r - Y_a \tag{8}$$

*Conversion/system losses* occur as a result of the conversion of DC to AC by the system inverters and depend on inverter temperature, input power, voltage variations, and grid voltage [20,34].

This quantity is mathematically equal to the difference between the array yield and the final yield, and is expressed by the following equation [36]:

$$L_S = Y_a - Y_f \tag{9}$$

Using expressions (8) and (9), Eq. (7) can be expressed as follows:

$$L_t = Y_r - Y_f \tag{10}$$

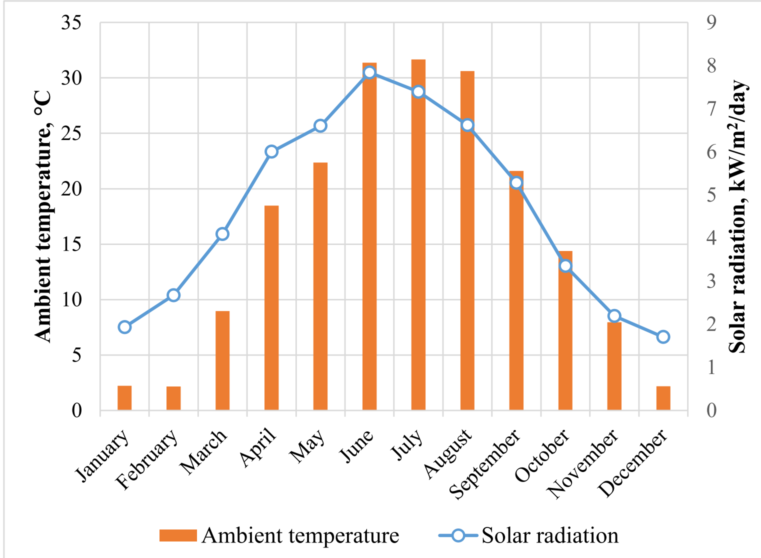



**Fig. 7.** Monthly solar radiation and ambient temperature in 2024.

#### 2.4.5. *Performance ratio*

Performance Ratio is very important in determining details such as temperature changes in PV modules, inverter losses, shading losses, DC cable and AC cable losses, and dust accumulation losses in a PV system at the rated power of a solar PV system [26]. This value is determined by the ratio of Final Yield to Reference Yield [37,38]:

$$PR = \frac{Y_f}{Y_r} \tag{11}$$

#### 2.4.6. *Economic analysis*

The levelised cost of energy (LCOE) basically refers to the minimum price of selling energy and is expressed by the following equation [19]:

$$LCOE = \frac{Life\ Cycle\ Cost\ (LCC)}{Lifetime\ energy\ production} \cdot cost \Big/ kWh \tag{12}$$

or alternatively

$$LCOE = \frac{CRF \cdot C_{IC} + C_{OM}}{E_{AC}} \cdot cost \Big/ kWh \tag{13}$$

where $C_{IC}$ - investment capital, $C_{OM}$ - annual operational and maintenance costs, $E_{AC}$ - annual electricity generated and CRF - ratio of a constant annuity to the present value of receiving that annuity for a specified time period [20]. CRF depends on the discount rate (fraction) $i$ and installation life (years) $n$ and is found through the following mathematical equation [39,50]:

$$CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{14}$$

The simple payback period (SPP) is an economic indicator that compares the income with the investment costs and determines the time required to recover the initial investment (at which the investment reaches the break-even point) [19,40]. The SPP is given as:

$$SPP = \frac{IC_0}{CF_1} \tag{15}$$

where $IC_0$ is the value of invested capital and $CF_1$ is the annual cashflow for project.

#### 2.4.7. *Environmental evaluation*

One of the positive aspects of solar PV systems is their potential to achieve global carbon neutrality. Many countries are preparing action plans for this under the United Nations Framework Convention on Climate Change (UNFCCC) and increasingly focusing on reducing greenhouse gas emissions by reducing fossil fuel-based electricity generation [41]. Uzbekistan joined the United Nations Paris Agreement on Climate Change and committed to reducing $CO_2$ emissions per unit of gross domestic product by 35 percent by 2030 compared to 2010 levels. One of the main advantages of solar PV systems is that they do not emit greenhouse gases during their lifetime [20]. The amount of carbon dioxide gas prevented from being released into the environment by generating electricity in a solar PV system can be determined using the following expression [42]:

$$Q_{CO_2} = \frac{E_{AS} \cdot LC}{g \cdot E_{ff}} \cdot F_{CO_2} \cdot \frac{44}{12} \tag{16}$$

where $F_{CO_2}$ – is the carbon emission factor, which is 0.404 and 0.726 for natural gas and coal, respectively. The value of $g$ per kWh is 10.411 kWh/kg and 6.923 kWh/kg for natural gas and coal, respectively.

## 3. Results and discussion

### 3.1. *Solar radiation and ambient temperature*

Monthly and annual solar radiation, ambient temperature, humidity, and wind speed for the geographical area where BukhSU is located from 01/01/2024 to 31/12/2024 were obtained from NASA POWER [56]. Fig. 7 shows the monthly solar radiation and ambient temperature. The annual average solar radiation for this geographic area is 4.64 kWh/m$^2$/day. The highest solar radiation was in June at 7.4 kWh/m$^2$/day, and the lowest average solar radiation was in December at 1.70 kWh/m$^2$/day. The average annual ambient temperature is 16.16 °C, with a maximum of 31.66 °C in July and a minimum of 2.15 °C in February. Wind speeds were recorded in the range of 3.06–5.63 m/s for 2024.

### 3.2. *Solar radiation and electricity generation*

The 1210 kW solar PV panel system produced a total of 1209,638 kWh of total annual energy in 2024, with a specific energy yield of 999.69 kWh/kWp. Of the energy produced, 697,638 kWh was transmitted to the public grid, while 512,000 kWh was consumed by the university. The total energy consumption of BukhSU for 2024 was

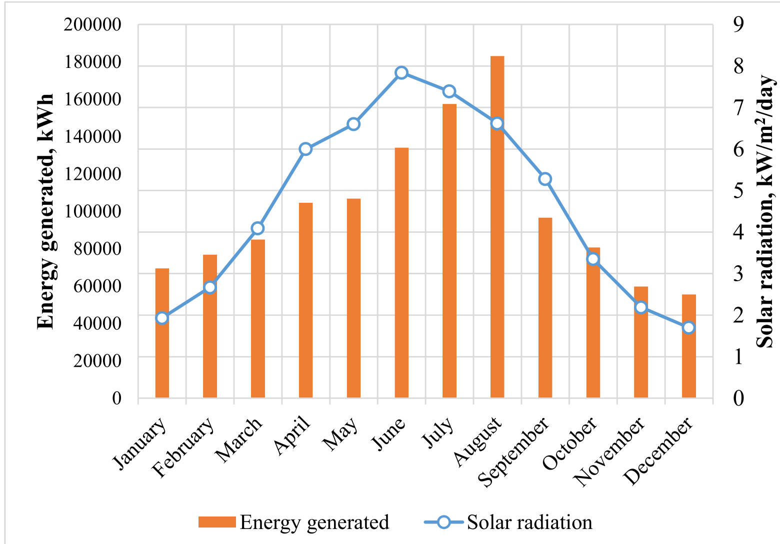



**Fig. 8.** Monthly energy production of solar PV system in 2024.

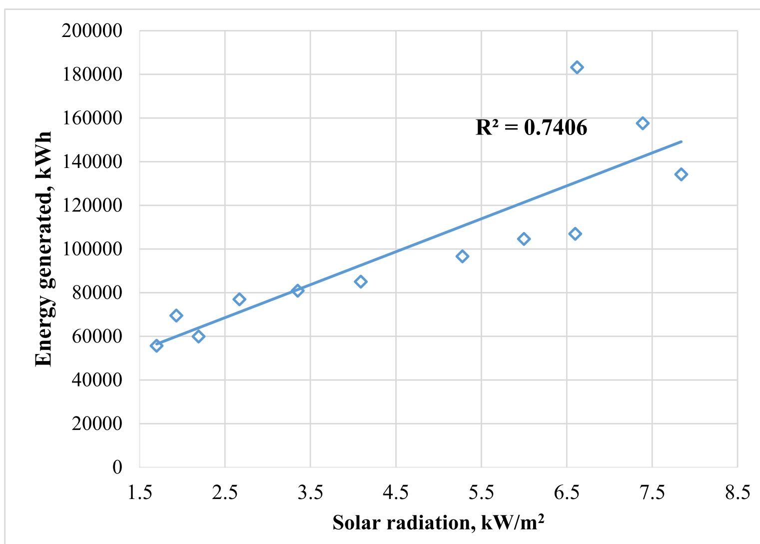



**Fig. 9.** Effect of solar radiation on energy generated.

2179,016 kWh, of which 1667,013 kWh was purchased from the public grid. That is, 76.5 % of the total electricity consumption was purchased from the public grid, while 23.5 % was consumed by the solar PV system.

Fig. 8 shows the electricity generated by the BukhSU solar PV system by month. The solar PV system produced the highest amount of electricity in August, 183,106 kWh. Also, in the months of June and July, when radiation was high, 134,028 and 157,466 kWh of electricity were produced, respectively. In December, the electricity generated was 55,546 kWh, which was the lowest.

The electricity generated by the BukhSU solar PV system is linked to solar radiation with a strong linear correlation of $R^2 = 0.7406$ (Fig. 9).

### 3.3. Capacity utilization factor (CUF)

The CUF of the 1210 kWp BukhSU solar PV system was calculated using Eq. (1) to have an annual average of 11.4 %. The CUF for the PV system was lowest in winter: CUF was 6.2 % in December, 8.5 % in January and February. The highest values were recorded in summer: 15.4 % in June, 17.5 % in July and a maximum of 20.3 % in August. The CUF values were 11.09 % in spring, 17.73 % in summer, 8.96 % in autumn and 7.74 % in winter (Fig. 10).

In the months with the lowest solar radiation, energy production and CUF decreased, respectively. CUF values for solar PV systems are typically reported to range from 10 % to 35 % [43]. In January-March and October-December, the CUF for the system reached values of $<10$ %.

### 3.4. Reference, array and final yield

The reference, array and final yields for the BukhSU solar PV system were determined monthly and annually (Fig. 11). The reference yield ranged from 1.70 to 7.84 kWh/kWp throughout the year. The lowest value was 1.7 kWh/kWp in December and 1.93 kWh/kWp in January. The maximum value was 7.84 kWh/kWp and 7.39 kWh/kWp in June and July, respectively. The highest electricity production was in August, at 6.62 kWh/kWh. The average annual reference yield was 4.64 kWh/kWp.

Array yield was lowest in December at 1.51 kWh/kWp, followed by

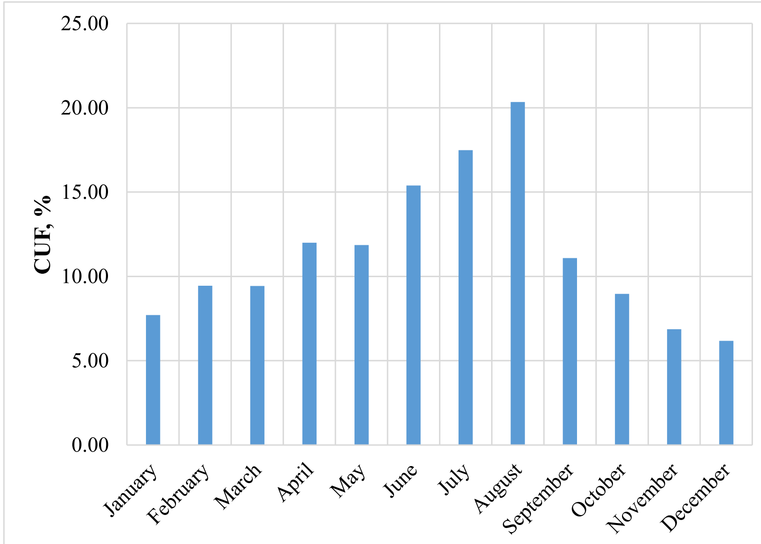



**Fig. 10.** Capacity Utilization Factor (CUF) of solar PV system.

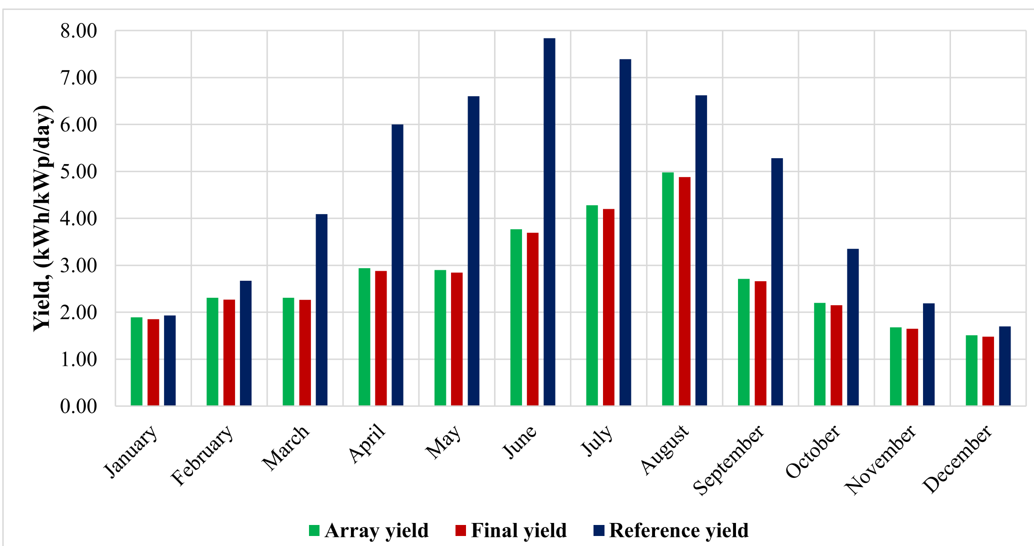



**Fig. 11.** Array, final and reference yield of solar PV system.

1.68 kWh/kWp in November and 1.89 kWh/kWp in January. Array yield ranged from 2.20–2.90 kWh/kWp in February-May and September-October. In June, July and August, when radiation was high, array yield was 3.77 kWh/kWp, 4.28 kWh/kWp, 4.88 kWh/kWp, respectively. The annual average array yield was 2.79 kWh/kWp.

The final yield index was also the lowest in December, at 1.48 kWh/kWp. In November and January, the final yield index was also <2, at 1.65 kWh/kWp and 1.85 kWh/kWp, respectively. In June, July and August, the final yield was 3.69 kWh/kWp, 4.20 kWh/kWp and 4.88 kWh/kWp, respectively. The annual average final yield was 2.73 kWh/kWp.

### 3.5. PV system total collection losses

The losses of the BukhSU solar PV system were determined monthly and annually using Eqs. (8)-(10) (Fig. 12). Conversion/system losses ranged from 0.03 to 0.10 per month. Array capture losses varied from 0.04 to 4.07 kWh/kWp per month. The lowest value was 0.04 in January, and 0.19 and 0.36 kWh/kWp in December and February, respectively. The highest value was 4.07 kWh/kWp in June. The annual average Array capture losses were 1.85 kWh/kWp. The total losses of a solar PV system are equal to the sum of array capture losses and conversion/system losses, and vary in the range of 0.08–4.15 kWh/kWp, with an annual average of 1.90 kWh/kWp.

The closeness of array capture losses to total collection losses indicates that the PV modules have large losses in converting the total solar energy into DC power. These losses are related to the decrease in PV voltage caused by the increase in PV cell operating temperature [19]. The fact that the annual ambient temperature range for the city of Bukhara is very variable, and the high temperatures in May-August cause the temperature in the PV cell to be much higher than normal, is one of the main influencing factors. Each degree increase in PV module temperature leads to a decrease in PV panel efficiency by 0.4–0.65 % [44]. Fig. 13 shows thermal images of the PV module at different times of the day on 13/06/2024. At 08:27 in the morning, the temperature on the surface of the PV module was 32.4 °C. At 10:02, the surface temperature reached 40.6 °C, at 12:00 it reached 46.3 °C, at 14:24 it reached a maximum of 46.8 °C, and at 15:59 it reached 41.3 °C.

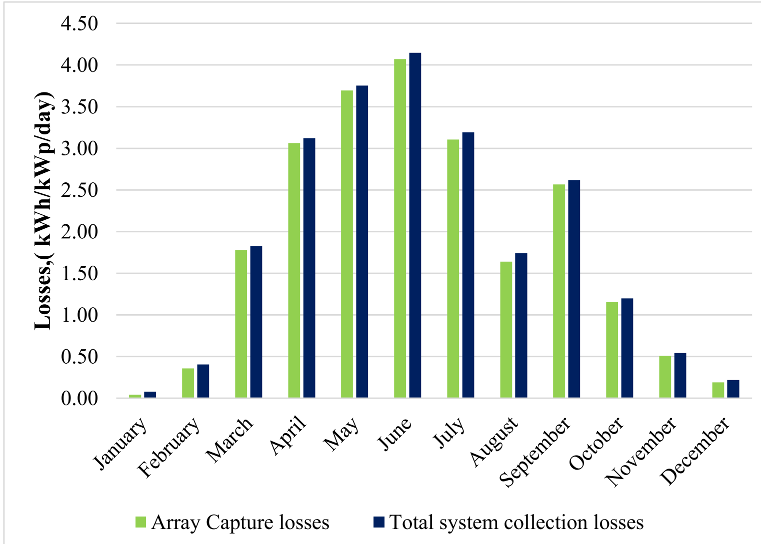
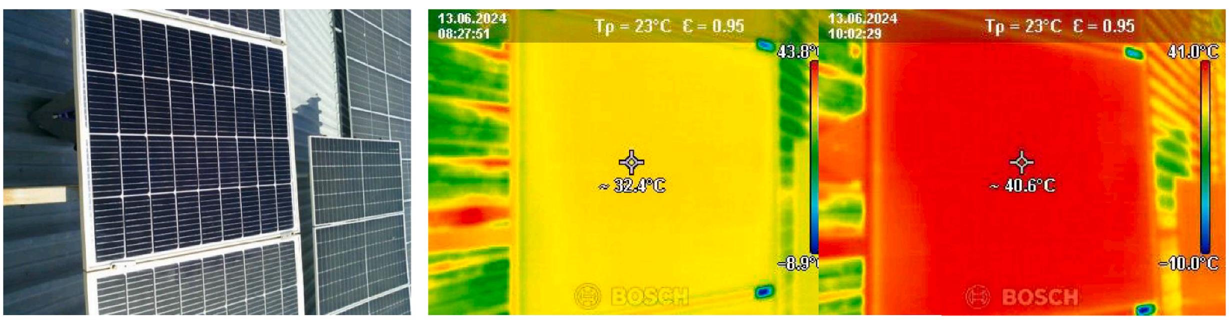


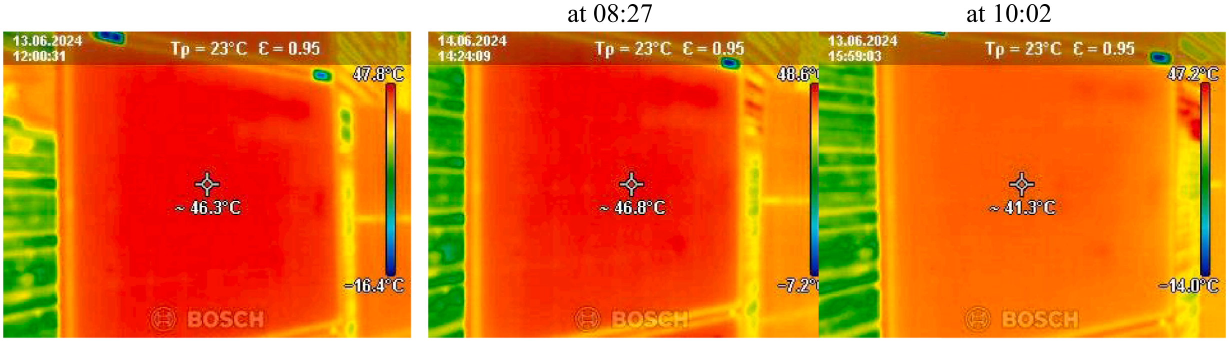

**Fig. 12.** Losses of solar PV system.




a) Image of PV module

b) Thermal image of a PV module at 08:27

c) Thermal image of a PV module at 10:02




d) Thermal image of a PV module at 12:00

e) Thermal image of a PV module at 14:24

f) Thermal image of a PV module at 15:59

**Fig. 13.** Temperature changes on the surface of a PV module at different times of the day (13/06/2024).

**Table 6**
Technical parameters of the thermal imaging camera GTC 600 C.

| Parameters | Value |
|---|---|
| Thermal sensitivity (NETD) | ≤50 mK |
| Measurement range | −20 °C to +600 °C |
| Operating temperature | −10 – 45 °C |
| Storage temperature | −20 – 50 °C |
| Focus distance, minimum | 0.3 m |
| Thermal image refresh rate | 9 Hz |

The thermal images were taken using a thermal camera of the “Thermal imaging camera GTC 600 C” model. The technical parameters of this thermal camera are shown in Table 6.

Also, frequent dust storms in the Bukhara region cause dust coating of PV modules and reduce the efficiency. Despite high solar radiation, in many areas, monthly energy losses due to dust can reach up to 30 % [45].

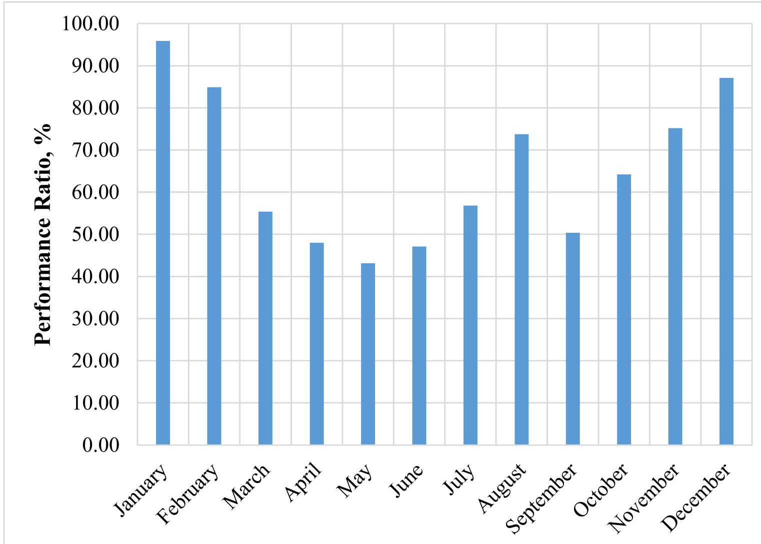



**Fig. 14.** Performance Ratio.

**Table 7**
Performance analysis of PV systems based on IEC 61,724 standard.

| Country | System size | PV type | Specific Energy Yield (kWh/ kWp) | Array yield (kWh/ kWp) | Final yield (kWh/kWp) | Reference yield (kWh/kWp) | PR (%) | CUF (%) | SPP, (years) | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Uganda | 10 MW | p-Si | 1456,8 | – | 4.58 | 5.85 | 75.84 | 19.07 | 9.28 | [20] |
| Morocco | 5.94 kWp | m-Si | | – | 5.25 | 6.15 | 85.51 | 21.87 | - | [21] |
| | | p-Si | | | 5.23 | 6.15 | 85.37 | 21,81 | | |
| | | a-Si | | | 4.71 | 6.15 | 76.66 | 17 | | |
| Maldives | 6.6 kWp | p-Si | 1467,3 | 4.74 | 3.88 | 5.59 | 69.37 | 16.14 | 4.3 | [22] |
| Spain | 50 MW (60.103 MWp) | m-Si p-Si | – | – | 4.28 | 5.44 | 79.24 | 17.83 | 17.61 | [23] |
| Kenya | 600 kWp | p-Si | 1225 | 3.37 | 4.49 | 5.9 | 57.4 | 13.9 | 9.1 | [24] |
| Ethiopia | 375 kWp | m-Si | – | 3.15 | 2.75 | 5.9 | 47.92 | 13 | - | [25] |
| India | 20 kWp | m-SI | - | 4.23 | 4.02 | 5.19 | 77 | 16 | - | [26] |
| | 20 kWp | p-SI | - | 3.74 | 3.55 | 5.19 | 72 | 15 | | |
| Ghana | 20 MW | p-Si | 1324 | 3.68 | 3.63 | 4.98 | 72.8 | 15.1 | - | [27] |
| Algeria | 20 MW | p-Si | – | – | 4.98 | 5.42 | 74.35 | 20.74 | - | [28] |
| Turkey | 30 kWp | p-Si | 1519 | 4.25 | 4.16 | 4.97 | 83.61 | 17.35 | - | [30] |
| Malaysia | 232.5 kWp | m-Si | – | – | – | – | 85.4 | 14.85 | 8 | [47] |
| South Korea | 5 kWp | m-Si | 1904.2 | 5.45 | 5.23 | - | 92.9 | 21.76 | - | [31] |
| | 4.6 kWp | p-Si | 1796.3 | 5.12 | 4.93 | - | 93.5 | 20.52 | | |
| Southern Algeria | 9 MW | p-Si | – | | 5.04 | – | 73 % | 21 % | - | [48] |
| Uzbekistan | 1210 kWp | m-si | 999 | 2,77 | 2,73 | 4.64 | 65,15 | 11,41 | 9.92 | In this stydy |

### 3.6. Performance ratio

The performance ratio is a key measure of the efficiency of a solar PV system, and the higher the PR, the better the system performs [46]. When the Performance Ratio of the BukhSU solar PV system was determined by the magnitude of (11), the annual average PR was 65.15 %. The PR value was highest in the winter months, reaching 87.11 % in December, 95.90 % in January, and 84.88 % in February. The lowest indicator was recorded in May and June, reaching a minimum of 43.13 % (Fig. 14). This can be explained by the fact that the surface temperature of PV modules exceeds STD standards during the summer months. Although the amount of solar radiation in winter is lower than in summer, the lower ambient temperature prevents the PV module surface from heating up, causing the PR to be higher in winter than in summer. According to the analysis, the Performance Ratio for solar PV systems can range from 49 % to 94.6 % depending on different geographical regions and climatic conditions of the world, with an average Performance Ratio of 73.21 % [17]. The PR for the BukhSU solar PV system is close to the world average with an annual average of 65.15 %. However, during the months with the highest solar radiation, the PR values are around 40–60 %, which causes a decrease in the system efficiency.

Table 7 shows the parameters determined for the BukhSU 1210 kWp on-grid solar PV system and other on-grid PV systems.

### 3.7. Economic analysis

The following were taken as a basis for evaluating the economic performance of the BukhSU solar PV system.

(i). The annual average electricity generated is 1209,638 kWh
(ii). The installation life (n) of the PV system is 25 years.
(iii). According to the report of the Central Bank of the Republic of Uzbekistan, the inflation rate and interest rate for 2024 are 9.8 %

and 13.5 %, respectively [57]. Using the Fisher equation [20], the discount rate (i) is 5.98 %.

(iv). The total investment capital for the installation and maintenance of the solar PV system is 12 billion soums. Taking into account that 1 USD = 12,338.7 soums as of January 1, 2024 [57], the investment capital will be equal to 972,549.8 USD.

(v). The fee for each 1 kWh of electricity sold is 1000 soums or 0.081 USD [14].

Considering the above, the LCOE for the BukhSU solar PV system was determined using equation [13]. The LCOE for the system is 593.23 soums/kWh or 0.048 USD/kWh. The revenue from the sale of the generated electricity is 1209,638,000.00 soums or 98,036 USD. The SPP was determined from Eq. (15) and the simple payback period for the system was found to be 9.92 years.

### 3.8. Environmental evaluation

The amount of carbon dioxide saved from the electricity generated by the BukhSU solar PV system is found by the expression [16]. A 1210 kWp solar PV system will save 286,856 tons of carbon dioxide from natural gas and 989,626 tons of carbon dioxide from coal over its entire life cycle.

## 4. Conclusion

The total electricity generated by the 1210 kWp solar PV system of Bukhara State University in 2024 was 1209,638 kWh. The highest electricity was produced in August at 183,107 kWh, and the lowest was in December at 55,547 kWh. The system performance was analyzed based on the IEC 61,724 standard and the following were determined:

- The annual average array, final and reference yields for the solar PV system were 2.77 kWh/kWp, 2.73 kWh/kWp and 4.64 kWh/kWp, respectively.
- The Performance Ratio for the system varied between 43.13–95.90 % over the months, with an annual average of 65.15 %.
- CUF varied within the range of 7.71–20.34 % on a monthly basis, with an annual average of 11.41 %.
- Conversion/system losses for the system varied between 0.03–0.10 per month, while array capture losses varied between 0.04–4.07 kWh/kWp. The lowest value was 0.04 in January, followed by 0.19 and 0.36 kWh/kWp in December and February, respectively. The annual average array capture losses were 1.85 kWh/kWp, and the annual average total system losses were 1.90 kWp/kWh.
- The electricity generated by solar PV system is linked to solar radiation with a strong linear correlation of $\boldsymbol{R}^2 = 0.7406$
- The LCOE for the system was determined to be 593.23 soums/kWh or 0.048 USD/kWh, with a Simple Payback Period of 9.92 years.
- The system will save 286,856 tons of carbon dioxide and 989,626 tons of coal for 286,856 tons of natural gas over its entire life.

In the future work, the authors propose research in several areas to study the problem of improving and optimizing the efficiency of the BukhSU solar PV system:

- Dust and pollution: consider the possibilities of hydrophobic coatings and various innovative cleaning methods [49], the use of pollution sensors [37,50], the use of models based on machine learning (ML) approaches [51,52].
- Tilt angle: study the influence of the installation angle of the PV modules and the air height (for cooling the rear of the module using natural wind) on the system efficiency [24], for example, using simulation programs (PVsyst program) [26].
- PV module temperature control: consider methods for cooling the surface temperature of PV modules (PCM, water, nanofluid, thermoelectric, uniform, active and passive, fin, etc.) [53,54].

## CRediT authorship contribution statement

**Bekhzod Khikmatov:** Writing – review & editing, Writing – original draft, Software, Investigation, Formal analysis. **Mirfayz Mirzaev:** Writing – original draft, Software, Investigation, Formal analysis. **Kamoliddin Samiev:** Writing – review & editing, Methodology, Conceptualization. **Obidjon Khamidov:** Writing – review & editing, Supervision, Resources, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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