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METHODOLOGY FOR DETERMINING THE OPTIMAL INSTALLATION ANGLE OF PHOTOVOLTAIC SOLAR PANELS

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Abstract. The article presents the development trends of solar energy in Uzbekistan, the solar energy potential, and a methodology for determining the optimal installation angles of photovoltaic solar panels. The optimal installation angles of photovoltaic solar panels relative to the horizontal surface were determined for the Bukhara Region. The results showed that the average optimal tilt angle for the summer months is 5° (≈ φ − 35°), while for the winter months it is 65° (≈ φ + 20°). When seasonally adjusted tilt angles are used, the annual accumulated solar energy is estimated to reach 9252 MJ/m²·year, while the annual average optimal tilt angle for south-facing solar panels is estimated at 36°.
Keywords: solar panel, temperature, optimal angle, total solar radiation, solar declination angle.

1. Introduction.

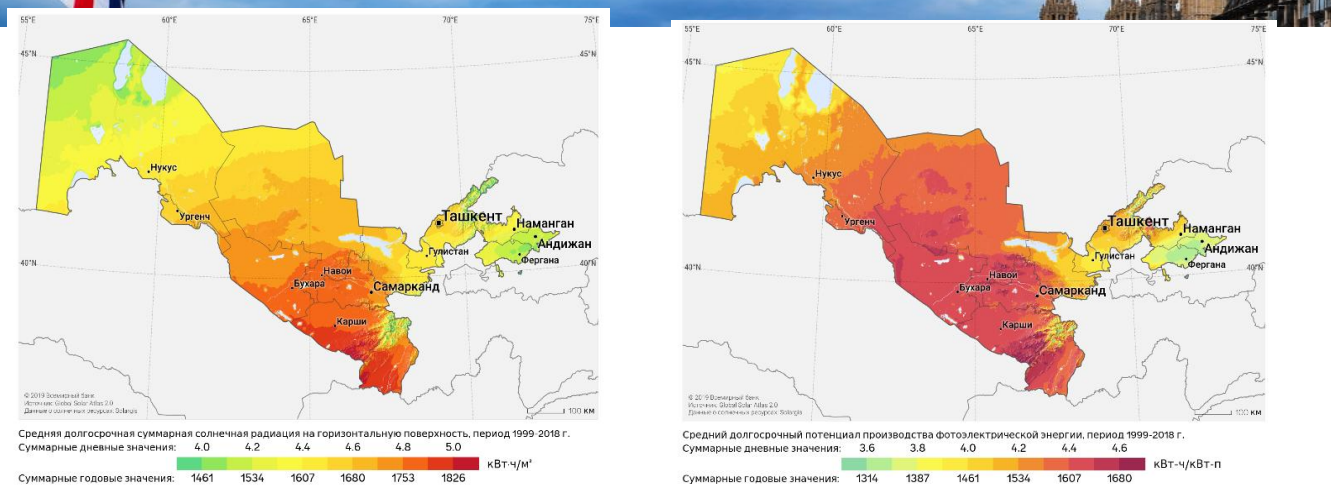
In addressing global environmental and energy security challenges, considerable attention is being paid to the use of renewable energy sources, particularly solar energy. In 2024, solar energy accounted for approximately 6.9% of global electricity generation, while the total electricity generated by solar photovoltaic power plants during this period reached 2,131 TWh [1].

Uzbekistan is developing its solar energy potential as a means of diversifying its energy mix and reducing dependence on fossil fuels. Strategic plans have been adopted to increase the installed capacity of renewable energy sources to 25 GW by 2030 and to increase their share to more than 40% of total electricity generation [2].

The following projects are being implemented for the utilization of solar energy: a photovoltaic power plant (PV plant) with a total capacity of 220 MW and a project cost of USD 150 million in Kattaqo‘rg‘on District, Samarkand Region; a 220 MW PV plant with a project cost of USD 150 million in G‘allaorol District, Jizzakh Region; a 457 MW PV plant with a project cost of USD 260 million in Sherobod District, Surkhandarya Region; a 500 MW PV plant with a project cost of USD 400 million in Qorovulbozor District, Bukhara Region; and a 500 MW PV plant with a project cost of USD 400 million in Nishon District, Kashkadarya Region [3].

Figure 1 presents indicators for assessing the potential for solar energy utilization across the regions of Uzbekistan. It has been determined that the total solar radiation received on a horizontal surface in the Bukhara Region is 4.8–5 kWh/m² per day and 1,750–1,800 kWh/m² per year [4].

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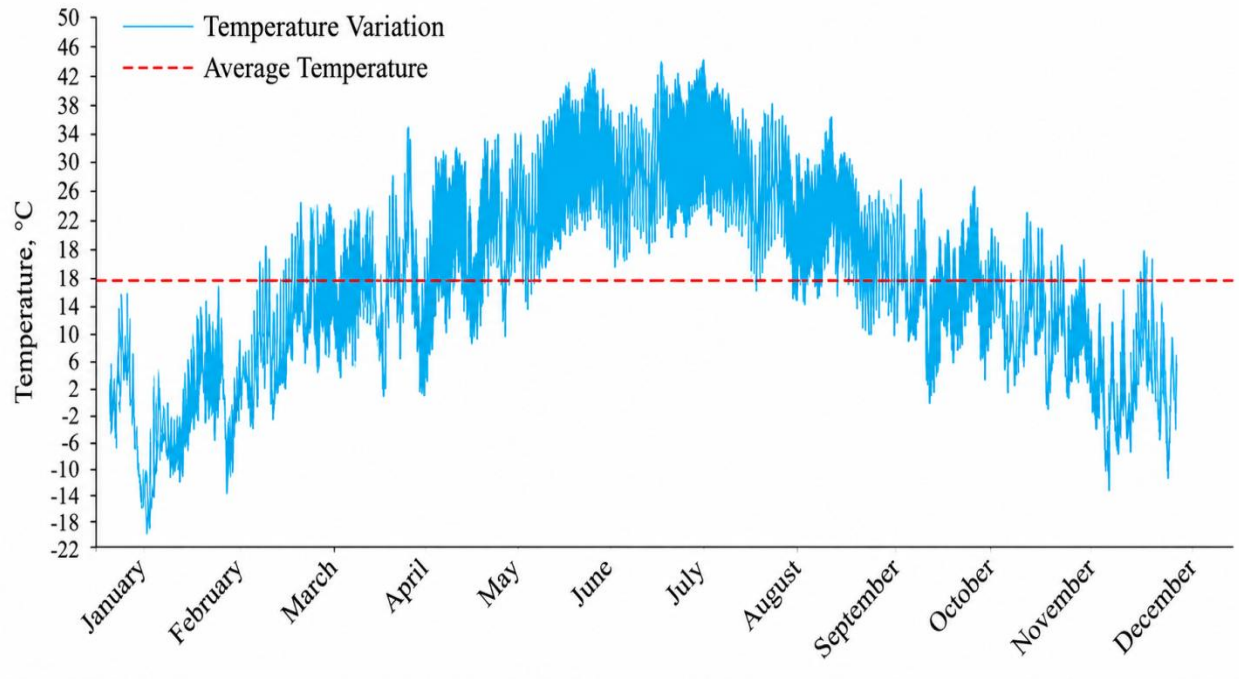
a) **b)**

Figure 1. Map of Solar Energy Potential Assessment in the Regions of Uzbekistan

a — Global solar radiation incident on a horizontal surface

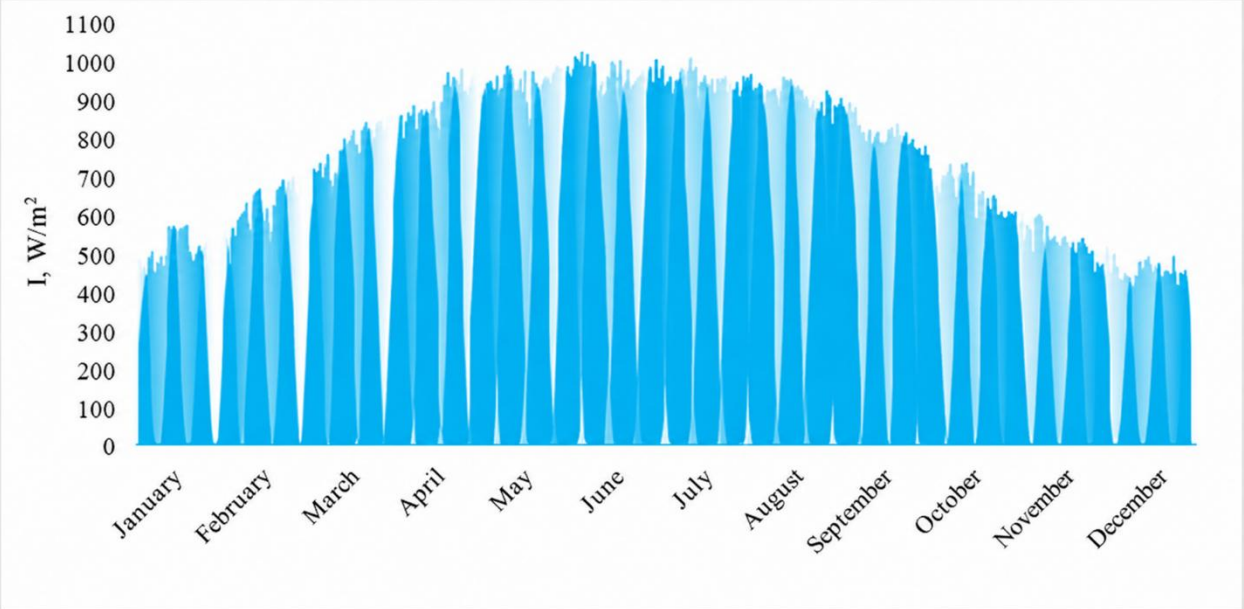
b — Electricity generation indicators of photovoltaic solar systems

Figure 2 shows the variation dynamics of temperature and horizontal solar radiation in Bukhara City (longitude 39.86°, latitude 64.80°) in 2024. The maximum temperature was 45 °C, the average temperature was 18 °C, and the minimum temperature was −17 °C, while the maximum solar radiation reached 1,030 W/m² [5].



a)

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b)

Figure 2. Variation dynamics of temperature (a) and solar radiation incident on a horizontal surface (b) in Bukhara City.

Currently, in Uzbekistan, significant attention is being paid not only to the development of large-scale solar power plants but also to small-scale solar power plants. Insufficient research has been conducted to determine the optimal fixed installation angles of solar panels in the Bukhara Region.

The aim of this study is to determine the monthly, seasonal, and annual optimal installation angles of solar panels relative to a horizontal surface in the Bukhara Region**.**

2. Material and methods.

The optimal installation angles of photovoltaic solar panels relative to the horizontal surface were determined for the Bukhara Region. The total solar radiation incident on a horizontal surface (H_T) consists of direct solar radiation (H_B), diffuse solar radiation (H_D), and ground-reflected solar radiation (H_R). Thus, the total solar radiation incident on an inclined surface at an angle β relative to the horizontal surface can be expressed as follows [6,7]:

$$H_T=H_B+H_D+H_R=(H-H_D)\cdot R_b+H_D\cdot\left(\frac{1+\cos\beta}{2}\right)+H\cdot\rho\cdot\left(\frac{1-\cos\beta}{2}\right) \quad (1)$$

Here, H_T denotes the total solar radiation incident on a horizontal surface**;** R_b is the ratio of the amount of solar radiation incident on an inclined surface to that incident on a horizontal surface**;** and ρ\rho is the ground reflectance coefficient**,** which is equal to 0.2.

It is well known that the apparent position of the Sun relative to a horizontal plane on the Earth varies depending on several geometric parameters. The solar declination angle (δ) can be determined from the following equation as a function of the selected day of the year (n) [8]:

$$\delta=23.45\cdot\sin\left(\frac{360\cdot(n+284)}{365}\right) \quad (2)$$

R_b is the atmospheric transmittance function**,** which depends on atmospheric cloudiness, water vapor, and particulate matter concentration. However, Liu and Jordan proposed evaluating R_b for each

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month as the ratio of extraterrestrial radiation incident on an inclined surface to that incident on a horizontal surface. It can be determined using the following equation [9]:

$$R_b = \frac{\cos(\varphi-\beta)\cdot\cos\delta\cdot\sin\omega_s' + (\pi/180)\cdot\omega_s'\cdot\sin(\varphi-\beta)\cdot\sin\delta}{\cos\varphi\cdot\cos\delta\cdot\sin\omega_s' + (\pi/180)\cdot\omega_s\cdot\sin\varphi\cdot\sin\delta} \quad (3)$$

Sunset hour angle for an inclined surface:

$$\omega_s' = \min\begin{bmatrix} \omega_s = \cos^{-1}(-\tan\varphi\cdot\tan\delta) \\ \cos^{-1}\left(-\tan(\varphi-\beta)\cdot\tan\delta\right) \end{bmatrix} \quad (4)$$

he hourly clearness index k_T is determined as the ratio of the measured hourly solar radiation incident on a horizontal surface to the hourly extraterrestrial solar radiation:

$$k_T = \frac{H}{H_o} \quad (5)$$

The hourly extraterrestrial solar radiation H_o is determined using the following equation [10]:

$$H_o = \frac{24}{\pi}\cdot I_{sc}\cdot\left(1+0.033\cdot\cos\left(\frac{360\cdot n}{365}\right)\right)\cdot\left[\cos(\delta)\cdot\cos(\varphi)\cdot\sin(\omega_s)+\frac{\pi\cdot(\omega_s)}{180}\cdot\sin(\delta)\cdot\sin(\varphi)\right] \quad (6)$$

where I_{sc} is the solar constant, equal to 1367 W/m².

The correlation for the diffuse solar radiation factor as a function of the hourly clearness index is given by the following equation [11]:

$$\frac{H_d}{H} = \begin{cases} 1-0.09\cdot k_T & \text{if } 0.22>k_T \\ 0.9511-0.1604\cdot k_T+4.388\cdot k_T^2-16.638\cdot k_T^3+12.336\cdot k_T^4 & \text{agar } 0.22<k_T<0.8 \\ 0.165 & \text{if } 0.8<k_T \end{cases} \quad (7)$$

3. Result and Discussion.

When the tilt angle of the solar panel was varied from 0° to 90° at 1° intervals, the average daily total solar radiation incident on a south-facing surface was determined using Equation (1). In June, the optimal tilt angle reached 0° (minimum), at which the monthly average daily total solar radiation was 8.25 kWh/m²·day. Subsequently, the tilt angle increased during the winter months, reaching a maximum of 68° in December, at which the monthly average solar energy received was 5.81 kWh/m²·day.

When the optimal tilt angles for each month were used, the total solar energy received throughout the year amounted to 2,570 kWh/m²·year. Figure 3 presents the monthly average daily solar energy received by a surface installed at an angle relative to the horizontal surface in the Bukhara Region.

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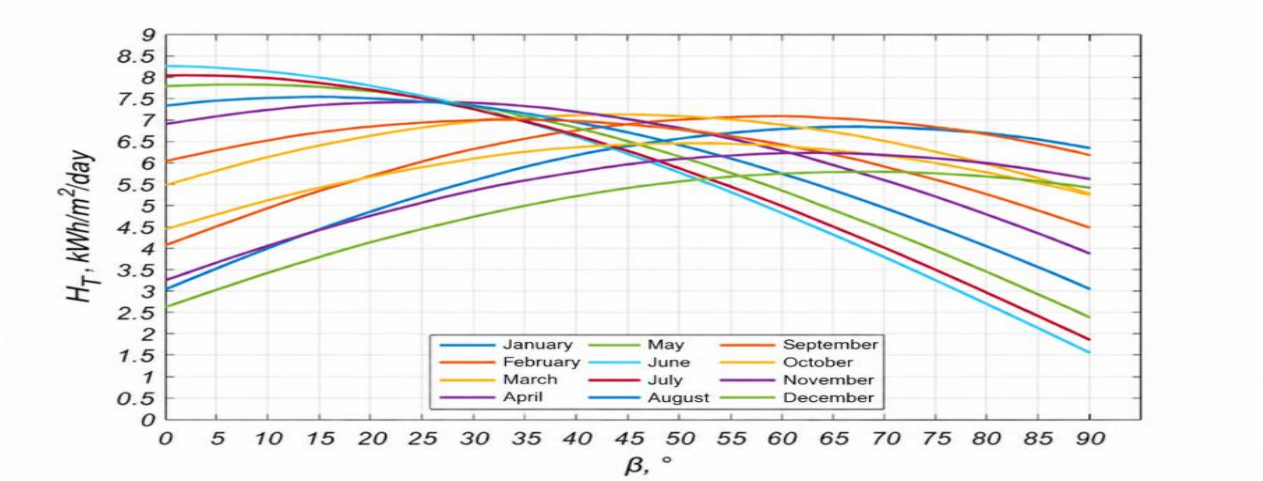


Figure 3. Solar Energy Potential Indicators of the Bukhara Region

The results of determining the optimal tilt angles and corresponding energy values for fixed solar panels are presented in Table 1**.** The results show that the average optimal tilt angle for the summer months is **5°** (≈ φ − 35°)**,** whereas for the winter months it is 65° (≈ φ + 20°)**.** When seasonally adjusted tilt angles are used, the total solar energy received throughout the year amounts to 9252 MJ/m²·year**.** Finally, the annual average optimal tilt angle for south-facing solar panels was determined to be 36°**.**

Table 1.

Optimal Tilt Angles and Energy Indicators

Months	Seasons	Optimal Tilt Angle, β			H_T, kWh/m²/day		
		Monthly	Seasonal	Annual	Monthly	Seasonal	Annual
December	Winter	68°	65°	36°	5,81	19,73	2570
January		67°			6,84		
February		59°			7,08		
March	Spring	44°	25°		7,14	22,41	
April		24°			7,43		
May		7°			7,84		
June	Summer	0°	5°		8,25	23,84	
July		1°			8,05		
August		14°			7,54		
September	Autumn	34°	49°		7,02	19,71	
October		51°			6,46		
November		63°			6,23		

4. Conclusion.

It has been determined that the total solar radiation incident on a horizontal surface in the Bukhara Region is 4.8–5 kWh/m² per day and 1,750–1,800 kWh/m² per year. The optimal installation angles of photovoltaic solar panels relative to the horizontal surface were determined for the Bukhara Region. The results showed that the average optimal tilt angle for the summer months is 5° (≈ φ − 35°)**,** while

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for the winter months it is 65° (≈ φ + 20°). When seasonally adjusted tilt angles are used, the total solar energy received throughout the year is estimated to be 9,252 MJ/m²·year, and the annual average optimal tilt angle for south-facing solar panels is estimated to be 36°.

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