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Determination Of Optimal Tilt Angle For Solar Photovoltaic Panels In The Southern Regions Of Uzbekistan

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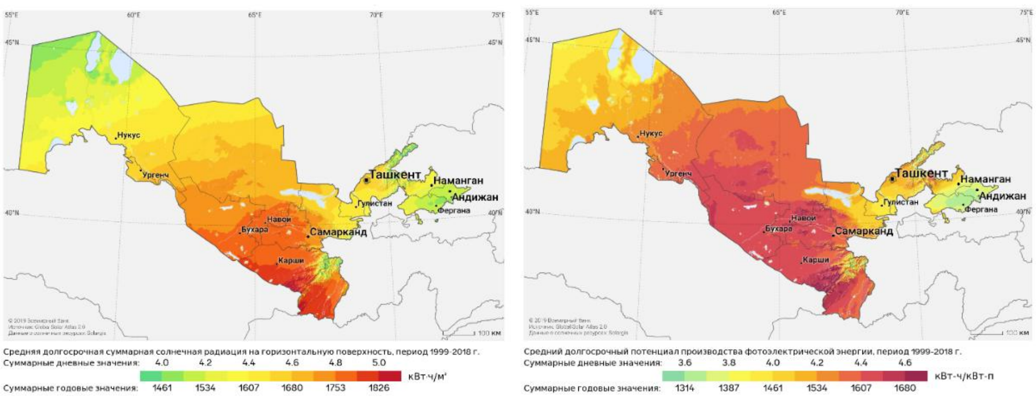
Abstract
This article examines the trends in the development of solar energy in Uzbekistan, the solar energy potential, and the methodology for determining the optimal installation angles of solar panels. The optimal tilt angles of solar photovoltaic panels relative to the horizontal surface in Bukhara province were determined. The results showed that the average optimal tilt angle for summer months is 5° (≈ φ – 35°), while for winter months it reaches 65° (≈ φ + 25°). When using seasonally adjusted tilt angles are applied, the total annual collected solar energy amounts to 9252 MJ/m²·year. The annual average optimal tilt angle for south-facing solar panels was evaluated as 36°.
Keywords: solar panel, temperature, optimal tilt angle, total solar radiation, solar declination angle.

1. Introduction

In addressing global ecological challenges and energy security issues, significant attention is being paid worldwide to the use of renewable energy sources, particularly solar energy. In 2024, solar energy accounted for approximately 6.9% of global electricity generation, with solar photovoltaic power plants producing a total of 2131 TWh of electricity [1].

Uzbekistan is actively developing its solar energy potential as a means of diversifying its energy mix and reducing dependence on fossil fuels. By 2030, the country plans to increase the installed capacity of renewable energy sources to 25 GW, raising their share in total electricity generation to over 40% [2]. Key ongoing solar projects include: 220 MW PV plant in Kattakurgan district, Samarkand province (project cost: $150 million), 220 MW PV plant in Gallaorol district, Jizzakh province (project cost: $150 million), 457 MW PV plant in Sherabad district, Surkhandarya province (project cost: $260 million), 500 MW PV plant in Karavulbazar district, Bukhara province (project cost: $400 million), 500 MW PV plant in Nishan district, Kashkadarya province (project cost: $400 million) [3].

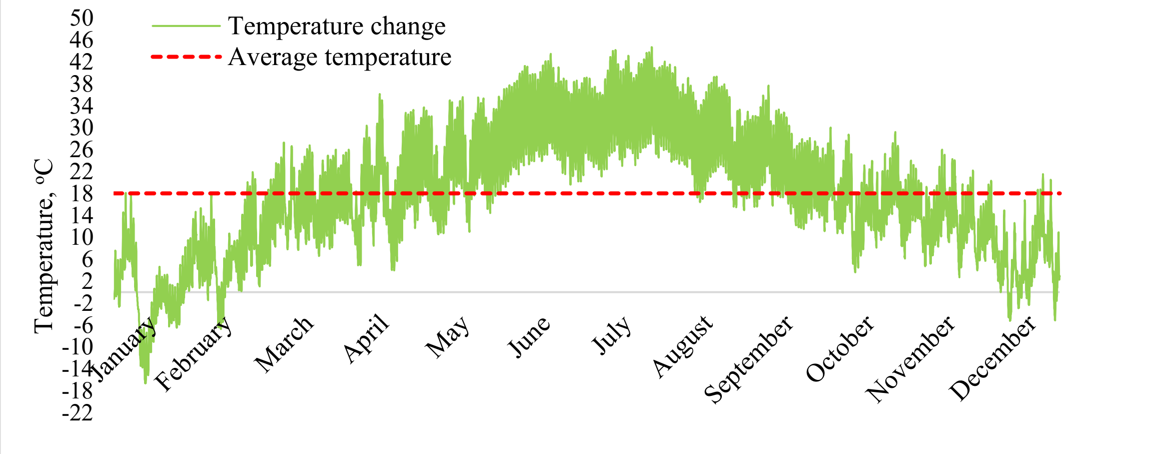
Figure 1 presents an assessment map of solar energy utilization potential across Uzbekistan's regions. In Bukhara province, the daily total solar radiation on a horizontal surface ranges from 4.8–5 kWh/m², with an annual total of 1750–1800 kWh/m² [4].



a) b)

Fig. 1. Solar energy potential assessment map of Uzbekistan. (a) Total solar radiation on horizontal surface. (b) Specific electricity yield of photovoltaic systems

Figure 2 shows the 2024 temperature and horizontal solar radiation dynamics for the city of Bukhara (latitude 39.86°N, longitude 64.80°E). The maximum temperature reached 45°C, the average annual temperature was 18°C, the minimum temperature was –17°C, and the peak solar irradiance was 1030 W/m² [5].



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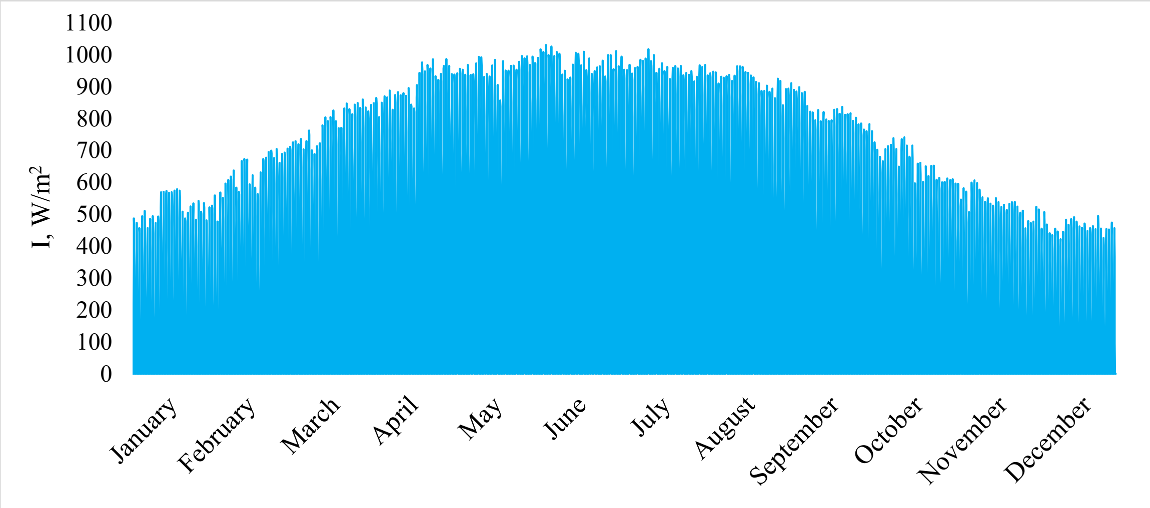

b)

Fig. 2. Dynamics of (a) temperature and (b) horizontal solar radiation in Bukhara city during 2024

Alongside large-scale solar power plants, Uzbekistan places great emphasis on the development of small- and medium-capacity photovoltaic systems. However, insufficient research has been conducted on determining the optimal fixed tilt angles for solar panels in Bukhara province.
The objective of this study is to determine the monthly, seasonal, and annual optimal tilt angles of solar panels relative to the horizontal surface in Bukhara province.

2. Material and methods

The optimal tilt angles of solar photovoltaic panels relative to the horizontal surface in Bukhara province were determined. The total solar radiation incident on a horizontal surface (H_T) consists of beam radiation (H_B), diffuse radiation (H_D), and reflected radiation from the ground (H_R). The total solar radiation incident on an inclined surface at an angle β relative to the horizontal is expressed as follows [6,7]:

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

where: H – total solar radiation on horizontal surface; R_b – geometric factor (ratio of beam radiation on tilted surface to that on horizontal surface); ρ – ground albedo (taken as 0.2)
The solar declination angle (δ) for a given day of the year (n) can be calculated using the following equation [8]:

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

The geometric factor Rb is a function of atmospheric transmittance and depends on cloudiness, water vapor, and particulate concentration. Liu and Jordan [9] proposed calculating Rb as the ratio of extraterrestrial radiation on the tilted surface to that on a horizontal surface for each month:

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

where ωs' is the sunset hour angle for the tilted surface:

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

The hourly clearness index (KT) is defined as the ratio of terrestrial horizontal radiation to extraterrestrial horizontal radiation:

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

The hourly extraterrestrial radiation is calculated as [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} = 1367 W/m² is the solar constant.

The correlation for the diffuse fraction as a function of the hourly clearness index is [11]:

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

3. Result and Discussion

The average daily total solar radiation incident on a south-facing surface was calculated using Equation (1) by varying the tilt angle from 0° to 90° in 1° increments. In June, the optimal tilt angle reaches its minimum of ~0°, yielding an average daily radiation of 8.25 kWh/m²·day. In winter months, the optimal angle increases, reaching a maximum of 68° in December, with a monthly average of 5.81 kWh/m²·day. When monthly optimal tilt angles are applied, the annual total solar radiation reaches 2570 kWh/m²·year.

Figure 3 presents the monthly average daily solar energy potential on surfaces with different tilt angles relative to the horizontal in Bukhara province.

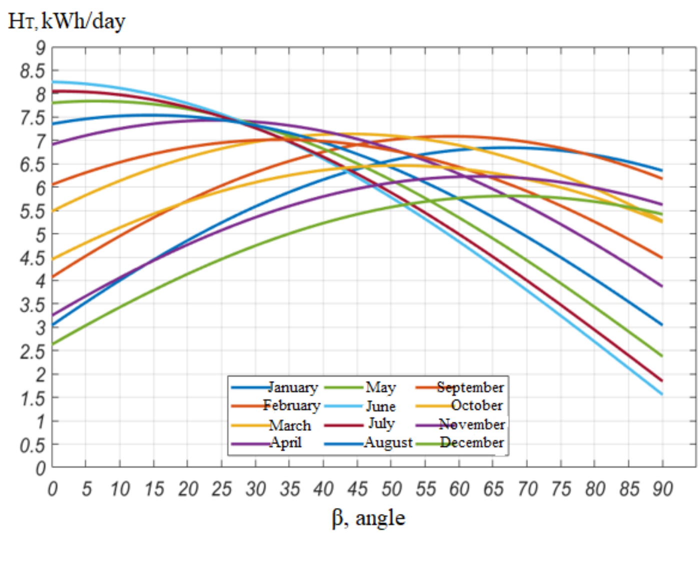

Fig. 3. Solar energy potential indicators for Bukhara province at various tilt angles

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Table 1 summarizes the results of determining the optimal tilt angles and corresponding energy yields for fixed solar panels.

Table 1. Optimal tilt angles and energy yield indicators

Month	Season	Optimal Tilt Angle, β			H_T, kWh/m²/day		
		Monthly	Seasonal	Annual	Monthly	Seasonal	Annual
December		68°			5.81		
January	Winter	67°	65°		6.84	6.57	
February		59°			7.08		
March		44°			7.14		
April	Spring	24°	25°	36°	7.43	7.47	7,14
May		7°			7.84		
June		0°			8.25		
July	Summer	1°	5°		8.05	7.95	
August		14°			7.54		
September		34°			7.02		
October	Autumn	51°	49°		6.46	6.57	
November		63°			6.23		

The results indicate that the average optimal tilt angle for summer is 5° (≈ φ – 35°), while for winter it is 65° (≈ φ + 25°). With seasonal tilt adjustment, the annual collected solar energy reaches 9252 MJ/m²·year (2570 kWh/m²·year). The annual average optimal fixed tilt angle for south-facing panels was determined to be 36°.

4. Conclusion

In Bukhara province, the daily total solar radiation on a horizontal surface ranges from 4.8 to 5 kWh/m², with an annual total of 1750–1800 kWh/m². The optimal tilt angles of solar photovoltaic panels relative to the horizontal surface were determined. The calculations showed that the average optimal tilt angle for summer months is 5° (≈ φ – 35°), while for winter months it reaches 65° (≈ φ + 25°). When seasonally adjusted tilt angles are used, the annual collected solar energy amounts to 9252 MJ/m²·year (2570 kWh/m²·year). The year-round fixed optimal tilt angle for south-facing solar panels in Bukhara province was evaluated as 36°.

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