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INTEGRATION OF RENEWABLE ENERGY SOURCES INTO AGRICULTURE IN UZBEKISTAN

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ABSTRACT
The electrification of agriculture is increasing demand for electricity. One way to meet this demand is through agrivoltaics (AV), an innovative technology in which photovoltaic panels are installed above or alongside crops so that electricity generation and agricultural production can occur on the same land. Because AV is only beginning to be introduced in Uzbekistan, this study examines its prospects for the country's agricultural sector. Uzbekistan's high solar radiation and high air temperatures in many regions create favorable conditions for AV, which can generate electricity while moderating crop and soil heat loads. This paper presents a methodology for estimating the technical, economic, and environmental indicators of an AV system per hectare of land and provides recommendations for implementing modern solar systems under regional climatic conditions. The results indicate that AV may help reduce farmers' dependence on external power grids and fossil fuels while improving the efficiency of land, water, and energy use in Uzbekistan.

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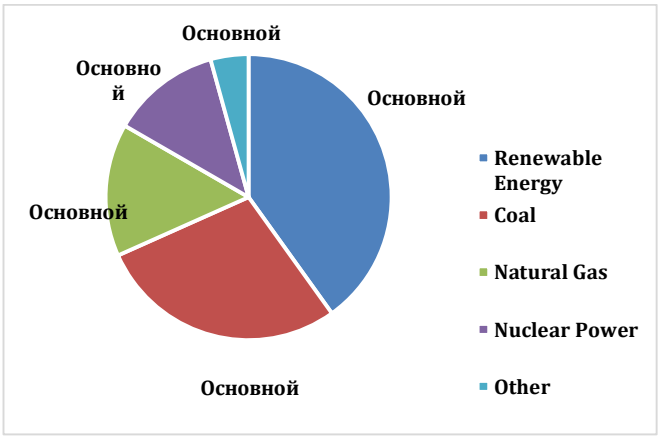
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Keywords: *agrivoltaics, agriculture, electricity, photovoltaic panels, renewable energy, shading, soil moisture, solar energy, crop yield.*

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Introduction

Systematic electrification of agricultural production requires substantial electrical capacity. At present, centralized power-supply systems may not fully meet the growing electricity demand of the agricultural sector (Ministry of Energy of the Republic of Uzbekistan, 2024; World Bank, 2023; Allaev, 2021). Therefore, energy-efficient technologies for decentralized or autonomous electricity generation are increasingly important. One promising option is agrivoltaics (AV), which combines electricity generation with agricultural production on the same land (Kostyuchenko, 2016; Kostik & Bobyl, 2021; Fraunhofer Institute for Solar Energy Systems ISE, 2020; Lytle et al., 2021). AV systems generate electricity from solar energy while providing partial shading to crops. As a renewable-energy technology, AV can reduce dependence on external power grids and fossil fuels and, under suitable crop and climatic conditions, may improve crop performance. The technology is based on photovoltaic conversion of solar radiation into electrical energy while modifying the light and thermal environment beneath the panels (Fraunhofer Institute for Solar Energy Systems ISE, 2022; Liu et al., 2020; Bellos, 2025). Comparative data indicate that renewable energy sources (RES) accounted for about 40% of Germany's electricity generation by 2019 (Figure 1), whereas RES accounted for less than 1% of Uzbekistan's energy balance at the beginning of 2019 (Figure 2) (World Bank & Solargis, n.d.; Korzhovov, 2024).



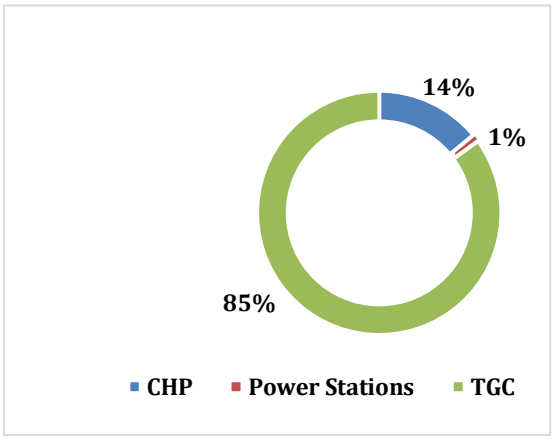


Figure 1. Renewable-energy generation in Germany by 2019. Figure 2. Renewable-energy generation in Uzbekistan by 2019.

Examples of AV implementation reported in different countries include the following:

• In India, AV systems have been deployed in vineyard areas, illustrating the potential for combining agricultural production with large-scale solar generation.

• In the United States, studies in arid environments such as Arizona have reported that partial shading from AV systems can reduce crop water use under certain conditions.

• Large AV power plants have also been developed in China, where the technology is presented as a means of reducing fossil-fuel use and associated emissions (Fraunhofer Institute for Solar Energy Systems ISE, 2022; Bellos, 2025; World Bank & Solargis, n.d.; Republic of Uzbekistan, 2024b).

Practical examples from companies and organizations active in the AV market include projects associated with policy and market initiatives described in Uzbekistan's electricity-supply planning documents (Republic of Uzbekistan, 2019; Cabinet of Ministers of the Republic of Uzbekistan, 2024):

• VALOREM Group is an independent operator in the field of "green" energy and AV projects in France, generating 12.4 GWh of electricity per year.

• Next2Sun has launched an AV solar park called "Agri" with an area of 11 hectares, which generates 4,800 MWh of electricity per year and supplies electricity to about 1,400 households.

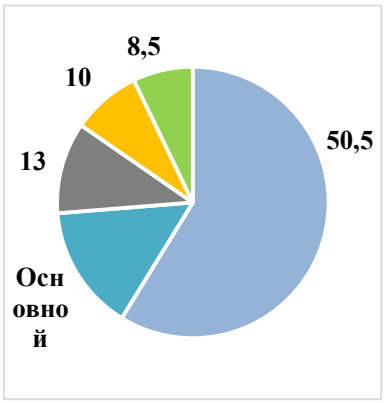
• Cero Generation Limited commissioned the 70 MW solar AV power plant "Pontinia," which supplies electricity to more than 47,000 homes.

The global AV market has expanded rapidly, although published market-size and growth estimates vary by source and methodology. Therefore, market forecasts should be interpreted cautiously and should be tied to a specific market-research source when used quantitatively (World Bank, 2023; Kostyuchenko, 2016; Kostik & Bobyl, 2021).

Data and Methods

In recent decades, shortages of water and land resources, soil degradation, rising energy consumption, and dependence on fossil fuels have created environmental and economic challenges for Uzbekistan (Ministry of Energy of the Republic of Uzbekistan, 2024; World Bank, 2023; Allaev, 2021; Republic of Uzbekistan, 2024a). To address these challenges, Uzbekistan adopted the Concept for Providing the Republic of Uzbekistan with Electricity for 2020–2030 and legislation on energy saving, rational energy use, and energy efficiency. According to the national electricity-supply concept, electricity generation from RES is planned to reach 18.5 billion kWh per year by 2030, including 10 billion kWh from solar power plants (Figure 3). Total installed generation capacity is projected to reach 29.3 GW by 2030, including 8 GW of RES capacity and 5 GW of solar capacity (Figure 4) (Republic of Uzbekistan, 2019; Cabinet of Ministers of the Republic of Uzbekistan, 2024; Begmatov & Aleksandrov, 2025).

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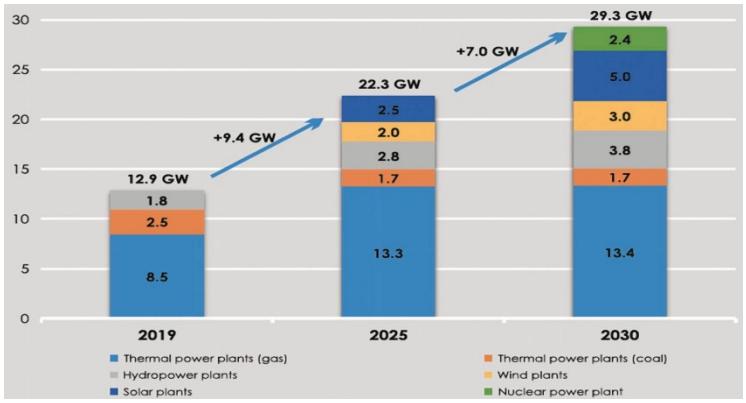
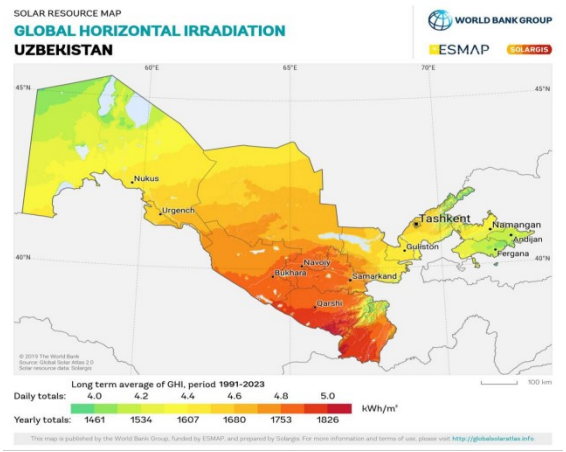


Figure 3. Electricity generation in Uzbekistan by 2030 (billion kWh/year). Figure 4. Installed power-generation capacity in Uzbekistan by 2030 (GW).

The aim of this study is to examine Uzbekistan's solar-energy potential and the feasibility of implementing AV systems in agriculture. According to the solar-resource map of Uzbekistan, which summarizes long-term average daily and annual solar irradiation, daily global horizontal irradiation (GHI) in different regions ranges from approximately 4.0 to 5.0 kWh/m²/day, while annual GHI ranges from approximately 1,461 to 1,826 kWh/m²/year (Figure 5).

The air-temperature and precipitation data shown in Figure 6 indicate that Uzbekistan has approximately 270–300 sunny days per year and 2,800–3,000 sunshine hours. Monthly or seasonal temperature and precipitation values vary substantially by region; therefore, the plotted values should be interpreted in the context of the specific locations and periods represented in Figure 6.

According to the calculations used in this study, this solar potential could support electricity generation of more than 50 billion kWh per year, making solar energy an important area for renewable-energy development in Uzbekistan (Ministry of Energy of the Republic of Uzbekistan, 2024; World Bank, 2023; Allaev, 2021).



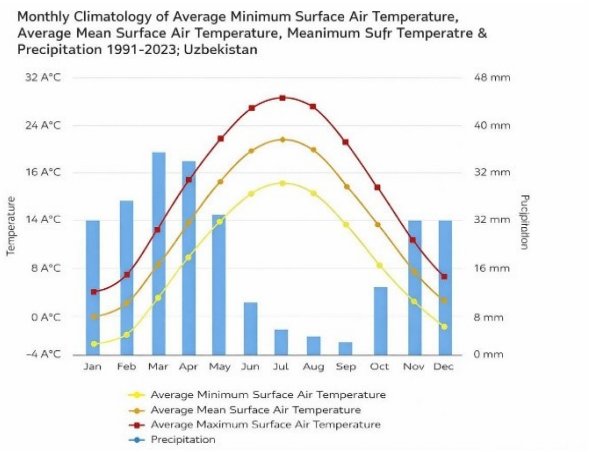


Figure 5. Solar-energy resources of Uzbekistan. Figure 6. Air temperature and precipitation in Uzbekistan.

Results and Analysis

Across many regions of Uzbekistan, the period of strong solar irradiation and warm temperatures extends for much of the growing season. Based on the solar-resource map, potentially suitable regions for AV implementation include Khorezm, Bukhara, Kashkadarya, Surxondarya, Samarkand, Sirdarya, Fergana, Jizzakh, and the Republic of Karakalpakstan (Figure 7). Implementing AV systems in these regions could provide electricity for farms and, where grid rules permit, allow surplus electricity to be exported to the centralized grid. Panel shading may also reduce soil and crop overheating and help moderate the field microclimate.

Table 1

Modeled GHI Values for Selected Agricultural Crops in Uzbekistan

Crop type	Crop	Average GHI over 1 hour (W/m²)
Fiber crop	Cotton	327
Fiber crop	Wheat	304
Cereal crop	Barley	326
Cereal crop	Rice	176
Tuber crop	Potato	98
Tuber crop	Tomato	64

Note. GHI = global horizontal irradiance. Values are simulation-model results reported in the manuscript and should not be interpreted as universal crop thresholds.

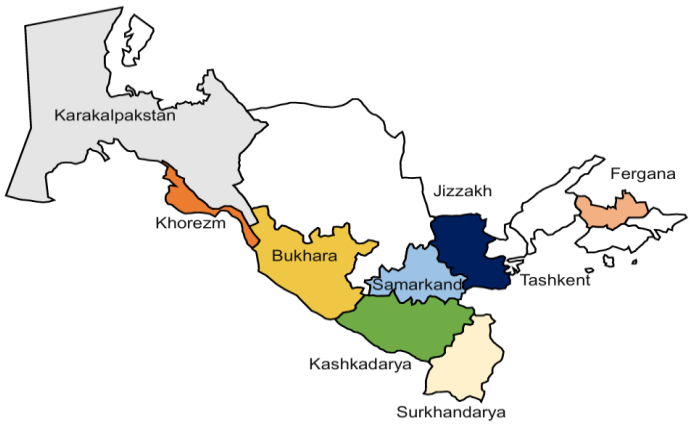


Figure 7. Promising regions of Uzbekistan for implementing AV systems in agriculture.

Table 1 presents the modeled average GHI values used in this study for selected agricultural crops. In AV design, the amount and timing of solar radiation reaching a crop under the panels should be matched to crop-specific light requirements. For example, the modeled value for cotton is 327 W/m². This value should be interpreted as a simulation input or target condition rather than as a universal agronomic threshold, because optimal irradiance depends on cultivar, growth stage, temperature, water availability, and other environmental factors (Cabinet of Ministers of the Republic of Uzbekistan, 2024; Begmatov & Aleksandrov, 2025).

Table 2

Reported Effects of Moderate Agrivoltaic Shading on Selected Crop and Soil Parameters

Parameter	Effect under moderate shading (20–30%)
Soil temperature	Decrease by approximately 3–6 °C
Water consumption	Decrease by approximately 15–20%

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Photosynthesis	Increase by approximately 10–20%
Yield	Increase by approximately 10–30%, depending on crop type

Note. Reported ranges are indicative and may vary by crop, climate, soil, irrigation regime, and AV-system configuration.



Figure 8. Cotton damage associated with a change in the GHI level.

Crop yield can depend strongly on the degree and timing of shading of both the soil surface and the crop canopy. Table 2 summarizes the reported effects of moderate shading (20–30%) on selected parameters associated with crop performance. These ranges should be treated as indicative because the magnitude and direction of the response depend on crop species, climate, soil, irrigation, panel configuration, and management.

To assess the potential for AV implementation in the regions of Uzbekistan shown in Figure 7, a methodology is proposed for estimating electrical, economic, and environmental indicators for a 1-ha plot of land.

I. Calculation of Electrical Indicators

1. Calculation of the daily electrical energy output of a single translucent PV panel:

$$P = G \cdot A \cdot \eta \quad (1)$$

where G is the daily global horizontal irradiation (approximately 5 kWh/m²/day), A is the active surface area of the PV panel (approximately 1.6 m²), and η is the panel efficiency (approximately 20%). Substituting these parameters into Equation (1) gives the daily electrical energy output.

$$P = G \cdot A \cdot \eta = 5 \cdot 1{,}6 \cdot 0{,}20 = 1{,}6\ kW/day$$

For an annual GHI of 1,700 kWh/m²/year and a panel-covered area of 8,000 m², the gross annual electrical energy before system losses is calculated before applying the average loss coefficient ($C_i = 0.8$).

$$P = G \cdot A \cdot \eta = 1700 \cdot 8000 \cdot 0{,}20 = 2\,720000\ kW/year$$

2. Calculation of annual electricity generation:

$$E = G \cdot A \cdot \eta \cdot C_I \quad (2)$$

where G is the average annual global horizontal irradiation (1,700 kWh/m²/year), A is the area covered by PV panels (8,000 m²), η is the PV-panel efficiency (approximately 20%), and C_i is the average system-loss coefficient (0.8). The estimated annual electricity generation is therefore 2,176,000 kWh/year.

$$E = 1700 \cdot 8000 \cdot 0{,}20 \cdot 0{,}8 = 2\,176000\ kWh/year$$

3. Surface energy-balance equation:

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$$Q_{abc} = G \cdot (1 - \alpha) \quad (3)$$

where Qabs is the daily solar energy absorbed by the soil (kWh/m²/day), G (GHI) is the daily global horizontal irradiation (approximately 6 kWh/m²/day), and α is the surface albedo (approximately 0.15–0.25 for soil). If α = 0.20, Equation (3) gives:

Qabs = 4.8 kWh/m²/day.

II. Calculation of Economic Indicators

4. Calculation of annual revenue from electricity generation:

$$M = p \cdot E, \quad (4)$$

where p is the average electricity price (approximately $0.05/kWh) and E is the annual electricity generation (2,176,000 kWh/year). The corresponding annual electricity revenue is approximately $108,800.

$$M = p \cdot E = 0{,}05 \cdot 2176000 = \$108800/year$$

5. Calculation of the investment payback period for an 8,000 m² panel-covered area:

$$T = \frac{C}{M} \quad (5)$$

where T is the payback period (years), C is the AV installation cost, M is annual income, and t is the assumed service life of the installation (15–20 years). The manuscript assumes an installation cost of approximately $800,000/MW and annual income of approximately $140,000/year, consisting of about $108,800/year from electricity and $31,200/year from agricultural production.

$$T = 800000 \,/\, 140000 \approx 6\ years$$

The stated payback period of approximately 4–5 years assumes government subsidies or other financial support. Because the subsidy rate and full capital-cost basis are not specified, this payback value should be treated as an estimate rather than as a directly reproducible result.

III. Calculation of Environmental Indicators

6. Estimated decrease in soil temperature under PV-panel shading:

$$\Delta T = T_{open} - T_{shadow} \approx 3 - 6℃ \quad (6)$$

The value of ΔT depends on panel density and height, soil color and moisture, wind and air circulation, and local climatic conditions.

7. Calculation of irrigation-water savings associated with moderate (20–30%) PV-panel shading:

$$\Delta W = E_0 \cdot A \cdot R \quad (7)$$

where ΔW is the volume of water saved (m³), e_0 is the baseline evaporation rate without shading, A_s is the shaded soil area (8,000 m²), and r is the relative reduction in evaporation (0.20). If e_0 = 2.5 mm/day, the dimensional conversion must use 0.0025 m/day.

$$\Delta W = 2{,}5 \cdot 8000 \cdot 0{,}2 = 4000 m^3/day$$

For a 120-day active irrigation period, an 8,000 m² shaded area, a baseline evaporation rate of 2.5 mm/day, and a 20% reduction in evaporation, the estimated water saving is approximately 480 m³. The previously stated value of 48,000 m³ is not consistent with these parameters.

$$\Delta W = 4000 \cdot 12 = 48000 m^3$$

8. Estimated reduction in the carbon footprint: approximately 500 t CO_2/year per hectare. This value requires an explicit baseline emission factor and displaced-electricity assumption to be independently reproducible.

The calculated results for one year are therefore as follows:

1. Energy performance: gross annual electrical energy before system losses — 2,720,000 kWh; estimated annual electricity generation after the assumed loss coefficient — 2,176,000 kWh.

2. Economic indicators: estimated annual electricity revenue — $108,800; stated AV-system payback period with subsidies — approximately 4–5 years.

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3. Environmental indicators: estimated water savings under the stated evaporation assumptions — approximately 480 m^3 over a 120-day active period; stated carbon-footprint reduction — approximately 500 t CO_2/year per hectare, subject to verification of the emission-factor assumptions.

These estimates indicate potential benefits of AV deployment in the regions identified in Figure 7, while also showing that the economic and environmental results depend on the assumptions used in the calculations.

Considering the electrical, economic, and environmental performance of AV systems per hectare and the climatic conditions of Uzbekistan's regions, the following AV technologies are recommended for further evaluation and implementation:

- • AV systems with automatic sun tracking can increase solar-energy capture relative to fixed-tilt systems under suitable conditions. Adjustable panel tilt can also be used to manage the degree and timing of crop shading across growth stages.
- • AV systems using semi-transparent or light-transmitting PV panels can partially transmit solar radiation, reduce direct heat load on the soil, and modify the distribution of light beneath the array. Such systems may be particularly relevant in regions where crop heat stress and water conservation are important design considerations.
- • A modular approach allows AV systems to be scaled from low-capacity mobile units (10–50 kW) for small farms, to medium-capacity systems (100–300 kW) for cooperatives, and to installations of 1 MW or more for large agribusinesses, depending on land-use conditions, grid access, and crop type.
- • Integrating AV systems with lithium-ion or sodium-ion battery storage can increase on-site use of solar electricity and improve supply reliability in remote areas. Exporting surplus electricity to centralized grids depends on applicable interconnection and market rules.
- • Remote monitoring can be used to track air and soil temperatures, irradiance, crop or soil moisture, and irrigation performance, while automated controls can adjust panel position where tracking systems are installed. Together, these functions can improve the management of water, energy, and crop microclimate.

Conclusion

1. The potential for introducing AV systems into Uzbekistan's agricultural sector is supported by the country's strong solar resource (Figure 5) and its temperature and precipitation patterns (Figure 6).

The manuscript reports that an AV system was introduced in vineyards in the Kuva District of the Fergana Region in 2025; a specific source should be cited for this project if the statement is retained.

2. AV-system performance depends on balancing electricity generation with the irradiance requirements of the crops grown beneath or between the panels.

The modeled GHI values in Table 1 can be used as design inputs, but they should not be presented as universal crop thresholds without additional agronomic validation.

3. Crop responses depend on the degree, timing, and spatial pattern of shading.

The ranges summarized in Table 2 suggest that moderate shading can influence soil temperature, water use, photosynthesis, and yield; however, the magnitude of these effects is crop- and site-specific.

4. The electrical, economic, and environmental calculations illustrate the potential value of AV systems in selected regions of Uzbekistan.

The results should be interpreted together with the assumptions stated in the methodology, particularly those concerning system losses, electricity price, subsidies, water savings, and carbon-emission factors.

5. According to the Concept for Providing the Republic of Uzbekistan with Electricity for 2020–2030,

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solar generation capacity is planned to expand substantially by 2030, creating opportunities for wider deployment of AV systems in Uzbekistan's agricultural sector (Republic of Uzbekistan, 2019).

Overall, AV systems can combine clean-electricity generation with agricultural production on the same land. Their contribution to crop yield, water conservation, and emissions reduction depends on crop selection, system design, climatic conditions, and the technical and economic assumptions applied in each project.

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