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SOLAR RADIATION

Assessment of Solar Energy Resources in Central Asia

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Abstract—The solar energy resources in Central Asia are assessed. Sources of actinometric information—the results of long-term ground-based measurements and mathematical simulation—are analyzed. Actinometric data of the publicly accessible NASA SSE global climate information database for this region is verified and its correspondence to the task was proved. The methods used to assess the gross and technical potential of solar energy are described briefly, and the results of calculations for Uzbekistan and Kyrgyzstan are provided.

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INTRODUCTION

Central Asia, in its physical–geographical and socioeconomic conditions, is one of the most promising areas for the effective use of solar energy. The structures of energy balances of Central Asian countries differ. Thus, in Kyrgyzstan and Tajikistan, over 80% of power generation is produced by hydroelectric power plants [1]; the basis of the fuel and energy complex of Uzbekistan, Turkmenistan and Kazakhstan is hydrocarbon fossil fuels [2]. Development and modernization of the electrical systems in these countries requires the construction of transmission and distribution networks, which is associated with large investments in this sector. In these circumstances, it seems urgent to analyze alternative energy supply option, including enhanced integration of local renewable energy resources. The problem of adequately assess the solar energy resources of Central Asia is considered, taking into account the available spaces to accommodate power supply systems and installations.

ACTINOMETRIC DATA SOURCES FOR CENTRAL ASIA

In order to assess the solar energy resources in a given territory, it is possible to use the following methods of obtaining primary data:

1. Analytical methods when the necessary values for a particular geographic point are determined by calculation.

2. Long-term instrumental observations on actinometric stations and their statistical generalization.

3. Mathematical simulation using remote satellite sensing of the Earth's atmosphere and surface.

4. Short-term monitoring of the actinometric characteristics in places for proposed construction of solar installations.

Analytical methods are based on solar geometry equations and require well-substantiated parameterization of a number of characteristics (diffusion indicatrix, surface albedo, etc.). Furthermore, this parameterization is significantly nonuniform in space and time, resulting in low accuracy of results.

A more reliable source of long-term data is ground-based measurements accumulated and generalized in climate reference books. Climate reference books contain quite a wide range of data: mean monthly, daily, and hourly totals of solar radiation reaching horizontal and vertical surfaces, as well as the amount of direct solar radiation on a surface normal to the beam under different cloudiness conditions. The problem in this case is the lack of territorial coverage of actinometric stations and the need to extrapolate (or interpolate) data from observation points, which significantly increases the inaccuracy of estimates.

Direct measurements of solar radiation at the site of proposed supposed construction of installations require the purchase of expensive equipment and software for automation of measurements. In addition, the short monitoring duration of determines the high inaccuracy of the results.

Up to now, to assess solar energy resources over large territories, databases based on mathematical simulation and the results of remote satellite sensing of the Earth's atmosphere and surface have become more accessible. Among the global and regional databases, a detailed analysis of which was done earlier in [3, 4], the NASA SSE database (NASA SSE DB) [5] can be considered the most productive. The results of simulation in this database are, in particular, values of monthly average daily amounts of solar radiation components incident on receiving surfaces of different orientation. The calculations take into account peculiarities of different climatic zones, including surface albedo, cloud state, and distribution of aerosols and

Results of verifying monthly average NASA SSE data on 25 actinometric stations of Central Asian region and Russian Federation; 1—characteristics of daily amounts of total solar radiation on horizontal surface; 2—the same for daily amounts of direct solar radiation on surface normal to beam, kWh/m^2

Region of verification	Number of points N	Average value, METEO		Average value, NASA		BIAS		Correlation coefficient		RMS	
	1, 2	1	2	1	2	1	2	1	2	1	2
All stations (Russian Federation and Central Asian region)	300	4.41	4.45	4.23	5.21	–0.17	0.76	0.96	0.89	0.57	1.16
All stations of Central Asian region	204	4.75	4.93	4.46	5.61	–0.29	0.67	0.97	0.89	0.58	1.13
Stations of Central Asian region with pronounced mountainous relief	108	4.75	4.73	4.41	5.47	–0.35	0.75	0.96	0.89	0.65	1.10
All stations (Russian Federation and Central Asian region) with pronounced mountainous relief	204	4.24	4.11	4.10	4.95	–0.15	0.83	0.95	0.88	0.60	1.16

Notation: Measurements data of the following actinometric stations was used: in the Russian Federation—Makhachkala, Kizlyar, Sulak, Bermamyt, Shatzhatmaz, Krasnodar, Sochi, and Pyatigorsk; in Central Asia—Frunze, Cholpon-Ata, Tien Shan, Susamyr (Kyrgyzstan), Kairakkum, Haramkul, Dushanbe, Kurgan Tyure, ac. N.P. Gorbunov (Tajikistan), Karakalpakstan, Takhiatash, Tamdy, Tashkent, Kyzylcha, Ferghana, Samarkand, and Termez (Uzbekistan).

other components in the atmosphere. Model actinometric and meteorological data in the NASA SSE DB cover the entire surface of the globe with a resolution of 1° × 1°.

VERIFICATION OF NASA SSE DATA FOR THE CENTRAL ASIAN REGION

Like any simulation results, the data in the NASA SSE DB require verification (comparison) with ground-based actinometric measurements. Earlier [3, 4, 6], it was shown that data errors in the database for the monthly average daily amounts of total solar radiation on a horizontal surface for the plain territory of Russia does not exceed 10–15%. A peculiarity of the territory of Central Asia is the presence of mountains, for which simulation of solar radiation inflow on the receiving surface of different orientation causes some difficulty. This is an additional basis for verifying NASA SSE data on ground-based actinometric measurements of the region. For comparative analysis, we selected 25 operating solar radiation stations in Central Asia and Russia, of which 17 are located in mountainous areas (see list in notation to Table 1). As the main characteristics of the deviation of amounts of NASA data SSE from ground-based measurements, we selected the relative error δ of average daily amounts of total solar radiation inflowing on a horizontal surface $\delta = \frac{(S_{\mathrm{NASA}} - S_{\mathrm{METEO}})}{S_{\mathrm{NASA}}}$. There, S_{NASA} and S_{METEO} are the long-term average daily amounts in NASA SSE DB and on ground-based measurements, respectively. Errors in the average monthly, average annual, and average seasonal daily amounts for each actinometric station are analyzed.

It was found that relative errors (δ) of the average annual values of daily amounts do not exceed 12%, except for two stations in the sample: the Tien Shan (Kyrgyzstan, 2700 masl, where δ = –20%) and ac. N.P. Gorbunov station (Tajikistan, 4169 masl, δ = –21%). For the values of the daily amounts, the average for winter period deviation is generally higher, but for most stations it does not exceed 15–20%. Deviations of means for the summer period are in the range of 12–15% for all compared stations, and deviations of the NASA SSE data from ground-based measurements were equally both positive and negative.

In verifying the monthly average values of daily amounts of total radiation on a horizontal surface and direct radiation to the surface normal to the beam, the complex of variables listed in Table 1 was calculated: BIAS, the average difference between the used parameter values of the NASA SSE DB (NASA_i) and actinometric stations (METEO_i) $\mathrm{BIAS} = \frac{1}{N}\sum_{i=1}^{N} \mathrm{NASA}_i - \frac{1}{N}\sum_{i=1}^{N} \mathrm{METEO}_i$; RMS, root-mean-square deviation of the compared indices ($N = 12n$, where n is the amount of actinometric stations under consideration, 12 is the number of months in a year). The verification results are shown in table and Fig. 1.

As can be seen from table and Fig. 1, the data of the NASA SSE DB show understated values for the monthly average daily amounts of total solar radiation and an excess for direct radiation. The correlation

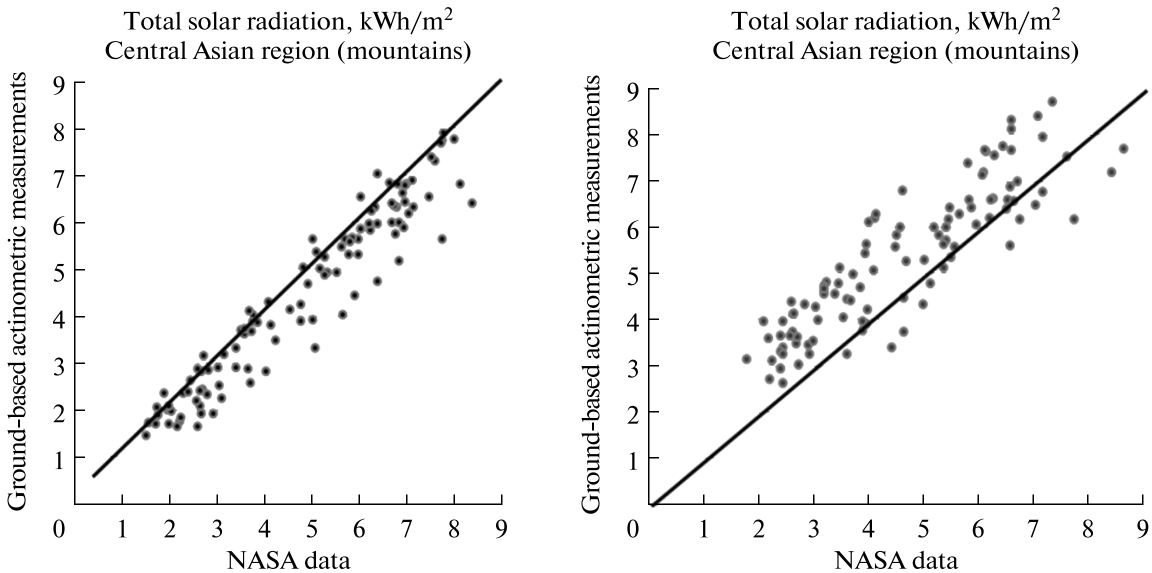

Fig. 1. Results of verifying NASA SSE data on actinometric stations of Central Asian region located in mountainous regions: monthly average daily amounts of total solar radiation on horizontal surface (left) and direct radiation to surface normal to beam (right).

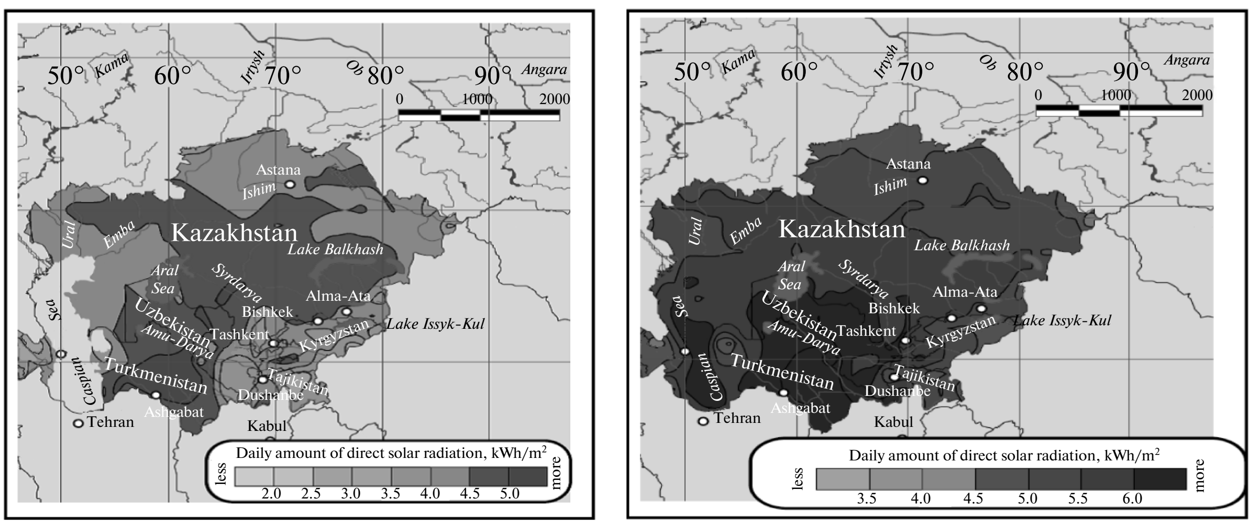

Fig. 2. Distribution of average daily amounts of solar radiation: left, direct radiation to receiving surface normal to beam, annual average values; right, total on horizontal surface, average values for summer.

coefficients of the data sets for both cases are close to 1. The average differences of values range from 7 to 17% for total and direct radiation, respectively. RMS deviations of the data sets are between 13–23%. Thus, for the monthly average daily amounts, the data of the NASA SSE DB adequately characterize the total radiation values. Convergence of the results can be considered quite acceptable for resource estimates and engineering calculations.

ESTIMATION OF GROSS AND TECHNICAL POTENTIAL OF SOLAR ENERGY FOR THE TERRITORY OF KYRGYZSTAN AND UZBEKISTAN

Estimation of the gross and technical potential of solar energy for Kyrgyzstan and Fig. 2 shows maps of the distribution of the annual average daily amounts of direct and total solar radiation for the territory of Central Asian countries, constructed according to the NASA SSE DB. It can be seen that the values of the daily amounts of total radiation average for the summer period, even on a horizontal surface which is not optimally oriented, in a number of regions (Uzbekistan, Turkmenistan) reach 6 kWh/m^2. Direct average daily radiation on a normal surface on average for a year in the same territories reaches 4.5–5 kWh/m^2. These figures correspond to the regions of the world's most favorable for the use of solar energy and exceed the indices of many European countries where solar installations have found wide practical application.

According to [7], the gross potential of renewable energy sources is the average annual amount of energy contained in this form of a renewable source for its total conversion into efficiently used energy. The gross potential of solar energy P_{GROSS} in the regions of the Central Asia was estimated from NASA SSE data and was the annual amount of total solar radiation inflowing to the area of this region S:

$$P_{GROSS} = \frac{I}{8140} S(\text{tons of conditional fuel}), \quad (1)$$

where I is amount of total solar radiation inflowing to a horizontal surface per year (kWh/m^2). The inflow of solar radiation is spatially nonuniform, so to assess the gross potential, the following calculation algorithm was developed:

1. Since the NASA database value characterizing solar radiation is assigned to a cell with a size of $1° \times 1°$ of geographical latitude and longitude, the territory of the region (country) under consideration is divided into such cells.

2. The area of each cell is calculated taking into account changes in latitude.

3. On the basis of NASA SSE data, annual inflow of total solar radiation in the given cell is determined. In cells not fully “occupied,” the magnitude of the inflowing total radiation per year is calculated taking into account the area of the territory that falls into it.

4. The obtained values of the annual inflow of solar radiation are summed over all cells, taking into account the territorial boundaries of the regions (countries).

Using this provided algorithm, gross solar energy potential for the territory of Uzbekistan and Kyrgyzstan is determined, which is about 86 and 35 bln t of conditional fuel per year, respectively.

The technical potential of a renewable energy source is the part of the gross potential the conversion of which into efficiently used energy is possible at this technical level and in compliance with environmental protection requirements. To determine this, it is necessary to identify the factors that limit the use of solar energy in the given area. The most significant factors were as follows:

1. *The territory on which it is possible to install solar energy converters.* Because different standards of construction are applicable to each land category, we have introduced land coefficients. They define the proportion of the area of each land category (and main subcategories) that can be used for solar power installations. On the basis of the distribution of lands by categories [8, 9], we estimated the proportion of land available for solar installations in Uzbekistan and Kyrgyzstan as 0.02 and 0.016 from the territory of each country, respectively.

2. *Technical improvement of solar energy converters.* The main characteristics of this factor were the average efficiency of solar energy conversion into electric (14%) and thermal (40%) energy. As a result, the technical potential of solar energy for the territory of Uzbekistan and Kyrgyzstan has been determined taking into account the gross potential of solar energy and the above-described limiting factors:

$$P_{TECH} = P_{GROSS} \times f(S, K_{land}) \times \text{COP}(\text{electricity}, \text{heat}), \quad (2)$$

where P_{TECH} is the technical potential and $f(S, K_{land})$ is a function that reflects the share of available territories. Taking into account the possible mutual shading of solar energy receivers, to calculate the technical capacity as the base value (total potential), the annual amounts of total solar radiation inflowing to a horizontally oriented surface were used.

Calculated according to the above algorithm, the technical potential of solar energy of Kyrgyzstan is about 700 bln kWh/year for the generation of electricity, and about 2 bln Gcal/year for the generation of heat; for Uzbekistan, about 2000 bln kWh/year for the generation of electricity and about 5 bln Gcal/year for the generation of heat.

Note that, currently, the production of electricity in Kyrgyzstan is about 13 bln kWh/year, and in Uzbekistan, about 50 bln kWh/year (1.9 and 2.5% of the technical potential of solar energy, respectively). Also, in the Kyrgyz Republic, there is a deficit of electricity. Uzbekistan covers its own needs, but more than 85% of power is generated from fossil fuels. The above estimates of the technical potential indicate huge resource opportunities for solar energy; however, these results require further work to assess the profitability of energy production using solar systems and identify the sustainable economic potential of solar energy use. One approach to assess the economic efficiency of solar installations is described in [10], which demonstrates the engineering method and estimates the possible monthly average performance of a PES (PES) based on multicrystalline photoelectric modules (PEMs) near the cities of Bishkek and Osh are made. The expected cost of the generated electricity in the conditions of Kyrgyzstan, excluding maintenance costs of borrowed funds for the construction of a PES from estimates can be about 10 euro cents/kWh. Such estimates can be extended to the territory of Central Asian countries, given that the largest contribution to the cost of a power plant and, therefore, to the cost of the electricity produced are from the cost of PEMs. Prices for PEMs are largely determined by the degree of localization, the volumes and the level of automation, and the choice of raw material suppliers.

The authors assessed the efficiency of solar water heaters in [11].

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