Application of Climatic Characteristics Statistical Assessments and GIS Technologies for Solar Energy Systems Development

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Abstract. The problems of optimising the placement of photovoltaic panels to ensure the most stable power generation are considered. Method for assessing the risks of solar power plants operation instability in the based on taking into account the climatic characteristics of the variability of the insolation and snow cover using GIS technologies is presented. This approach is especially important for Russia, a country with a wide variety of natural and climatic conditions. To test this technique, we calculated the intra-annual and year-to-year variation of the statistical characteristics of the total insolation incident for regions of Russia. The use of GIS technologies made it possible to assess the distribution of the features of the variability of solar radiation over the area. This paper presents the results of calculations and constructed maps for the Republic of Altai, the region of Russia with heterogeneous insolation conditions, where solar energy has been actively developing recent years. In these territories, zones with the lowest indicators of variability in the input of solar radiation have been identified where a high level of stability of electricity generation on photovoltaic power plants can be predicted.

1. Introduction
Over the past five years, Russia is intensifying the process of renewable energy sources developing thanks to measures taken by the Government to support renewable energy grid facilities: the annual tenders for the construction of renewable energy facilities up to 2024, state obligations for the return of investments in 15 years, the conclusion of contracts for the supply of power and others. By August 2020 RES power plants operated in various regions of Russia: Photovoltaic power Stations (PVPS) - 1132,8 MW, Windfarms – 538,7 MW. The target volume of commissioning under the Russia RES program is 5,4 GW until 2024, of which wind power capacity – 3,4 GW, PV power capacities – 1,9 GW.

On a vast territory of Russia with a great variety of natural and climatic conditions, resource risks are of particular importance, since the used solar, wind, and hydropower resources are subject to climate variability and significant time fluctuations [1]. A feature of the modern development of solar energy in Russia is that new large PV Power Stations are network-based and it is necessary to make forecasts of guaranteed supply promptly. Data show high temporal variability of solar resources in different types of climates due to the high diversity of climatic conditions and insolation
across the territory of Russia. This variability study also causes significant fluctuations in the power output of plants, which increase the risks of a stable supply of energy efficiency to the grid and lead to the dangers of higher project costs if it is necessary to install energy storage devices. Snow cover data are important characteristics for risk assessments during the construction and operation of PV solar stations in the regions of Russia. For engineering structures, snow creates an additional load on the supporting structures. This is especially important for mountainous and poorly studied areas. The Altai Republic is just such an area. In the calculations, it is necessary to consider schemes of uniformly distributed and unevenly distributed snow loads on the pavement in their most unfavorable design combinations. For the efficiency of the photovoltaic panels, the height of the snow layer and the duration of the snow cover are important characteristics. Covering the working surface with snow leads to a significant decrease in the calculated values of the instantaneous efficiency of the modules (over 35-40%) [2-5].

In many studies, a GIS-based Multi-Criteria Decision Analysis (GIS-MCDA) technique are used to generate maps that represent potential areas for solar power plants in countries with different climate conditions [6–9]. Nowadays, geoinformatics methods are actively used in studies of the solar energy potential and risk assessment for different territories. [10-13]. Geoinformatical systems (GIS) allow solving the following tasks:

- visualization of resources for calculating derived quantities (technical, economic potential of energy);
- analysis of territories by the level of resources and the possibility of placing solar energy facilities on them as applied to various scales of territorial studies.

The result of such studies is usually presented as interactive maps, GIS and atlases, displaying both initial and derived quantities, as well as factors limiting the placement of solar energy facilities. Methodology is increasingly based on sequential multicriteria analysis. Moreover, in different countries such methods have been developed as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and Elimination and Choice Expressing Reality (ELECTRE) [14], Ordered Weighted Averaging (OWA) [12, 15] improving the analysis process and eliminating subjectivity in considering certain factors. The objective of this study is to provide an approach for assessing the influence of climatic factors on predictability of solar plants power generation.

2. The data and methodology

We have carried out the research on the possibilities of using statistical methods and GIS technologies to determine the degree of risk of photovoltaic solar energy in Russia and to choose the areas for PV Power stations construction.

The authors estimated the spatiotemporal variability of the total solar radiation (Sr) input to the horizontal surface for a number of Russian regions. The basis for these estimates was the calculation of the statistical characteristics of the incident solar radiation, according to the NASA SSE database for a ten-year period (2009-2018) [16]. The data arrays for the calculations were formed from the specified initial materials with a space interval of 0.5°. Analyses of the coefficient of variation (Cv) were used to numerically estimate the variability of the direct solar radiation input to the horizontal surface. The variability of monthly and daily mean values was assessed.

$$C_v^i = \frac{\left[ \frac{1}{N} \sum_{j=1}^{N} (x_{ij} - \bar{x}_j)^2 \right]^{\frac{1}{2}}}{\bar{x}_j},$$

where: $x_{ij}$ - all Sky daily Insolation Incident on a Horizontal Surface \( \left( \frac{kWh}{m^2\text{day}} \right) \).

$N$ – number of years in the calculation period, $j = 1,\ldots,12$.

Then the annual average $C_v$ for every month and the mean coefficient of variation for the whole year were calculated.
The values of the coefficient of variation of monthly or average monthly daily amounts of radiation characterize the intra-monthly variations, \( C_v \) daily - year to year variability of solar radiation input. Based on the obtained long-term data with the use of GIS technologies, map-schemes were created for the distribution of annual average monthly values of \( C_v \) months over ten years (2009-2018), as well as data on intra-monthly variability by calculating \( C_v \) days for the same period by months for a series regions of Russia with different natural and climatic conditions.

To assess the danger of the construction of a solar power plant in Russia, we propose to use the data on the height of the snow cover. Our estimates showed that the most reliable are snow cover observations data at meteorological stations of the Roshydromet [17]. Such an information layer was included in the GIS developed by the authors and is shown in Figure 3.

3. The Results and discussion

This article presents the results of calculations and risk assessments for the territory of the Republic of Altai, one of the country's mountainous areas, promising for the development of tourism. The climate is humid continental, with short hot summers and long frosty winters. In the Republic of Altai, with vast natural and recreational opportunities for the development of multi-species tourism, the urgent problem is the need to ensure the accelerated development of energy, engineering, transport and roadside infrastructure, waste management. Until 2014, the Republic did not produce electricity, except for three small hydropower plants and diesel generators in remote villages. Up to 50% of the population had limited access to electricity. Dispersed resettlement, poorly developed infrastructure, vulnerable natural ecosystems, and the border character of the region require ensuring social, economic, and environmental safety [18]. These factors, the recreational potential of the area and the high availability of renewable energy resources (sun, wind, small rivers) provided the basis for the first territorial cluster of renewable energy in Russia. To date, there are seven Hevel PV power stations operating in the Republic of Altai with a total capacity of 120 MW (Figure 1.). Their estimated annual electricity generation is about 154 million kWh. The first PVPS in Altai were built in the most energy-deficient Kosh-Agachsky area, where previously all electricity generation was provided by the operation of diesel generators. Due to the SPPs, it was possible to reduce the transmission of electricity from neighboring regions and increase the reliability of electricity supply.

![Figure 1](image_url)

**Figure 1.** Schematic maps of the distribution of the coefficient of variation (\%) of the total insolation input to the horizontal surface according to the NASA SSE database in the Republic of Altai (Russia) for ten years (2009-2018): (a) annual average monthly values of \( C_v \), (b) annual average year to year variations of daily Sr.
Based on the results of the calculations performed using the NASA SSE database, schematic maps of the distribution of the coefficient of variation of total solar radiation of monthly mean values and daily values over the territory of the Altai Republic were created (Figure 1.). Analysis of the combined maps made it possible to identify the zone with the lowest risks of using solar resources in the Altai Republic - Chomsky and Turochaksky regions north of latitude 51°30'. As well as territories lying to the east of the Ust-Kan settlement. The area near the village of Kosh-Agach and to the south are characterized by very high daily variability, which may be due to the high-mountainous position (more than 2000 m above sea level) of this region. Due to the very significant seasonal climatic differences on the territory of Russia, it is also essential to analyse the intra-annual variability of the statistical characteristics of solar radiation. The intra-annual variation of the solar radiation input to the western region of the Altai Republic (near the village of Ust-Kokska), and, accordingly, changes in the risks of obtaining stable electricity generation at photovoltaic stations are presented in the graphs. As can be seen from Figure 2, from March to September, the average daily input of total insolation is more than 4.0 kW · h/m² per day. The coefficient of variation of monthly average Sr values in this period is less than 12%. In the autumn-winter period, the coefficient of variation is much higher - up to 19%. The intra-annual instability of direct solar radiation in May was revealed village of Ust-Kokska district, the risks of using photovoltaic (PV) panels increase during this period. The daily Cv S values are characterised by very high variability in the summer period when the generation of electricity from the operation of solar panels is increased (Figure 2.). The coefficient of variation of daily Sr values is more than 40% in summer, and in May-June - more than 70%. It proves the very low reliability of the forecasts of the guaranteed power output from photovoltaic panels in a territory, and due to the high natural resource risks of PV panels, it shows the need for the mandatory availability of duplicate power generation capacities.

The analysis of electricity production at the solar power plants commissioned in the Altai Republic by calculating the average capacity factor for a certain period showed large differences both in time and depending on the location of the PVPS (Table 1.). Average annual capacity factor values var from 17.00% at Kosh-Agachskaya PVPS to 11.6% at Mayminskaya PVPP, for the autumn-winter period (X-XII) this figure is even lower - 10.36% and 4.90%, respectively. For three PV Power Stations: Ininskay 25 MW, Ust-Koksinskaya 40 MW and Chemal 10 MW – commissioned in 2019-2020 – due to short operation period there is no possibility to calculate the average value of capacity factor at the moment. As can be seen from the map (Figure 3) the northeastern and southwest regions are the most unfavorable regions for the operation of PVPS in the Republic of Altai due to the significant impact of snow in winter. The Average annual snow layer is over 40 cm. And favorable - the central regions and

**Figure 2.** Intra-annual changes of annual average monthly total total insolation (Sr) values (kW · h/m² per day) and Cv values (%) of monthly average data of insolation for a long-term period in the area of the village, near Ust-Koksinsky PV PS.

**Figure 3.** Schematic maps of the distribution of snow cover (cm) according to measurements at Roshydromet observation stations in the Republic of Altai (Russia) for ten years (2009-2018).
the southeast in the area with Kosh Agach. The snow cover is less than 10 cm (Figure 3). PVPS-s are already operating here with the most high installed capacity utilization rates 17.0% in the region (Table 1).

Table 1. Electricity generation at Photovoltaic power stations in the Republic of Altai in 2017-2018. Source: authors’ calculations based on data [19, 20].

| PVPS name & Installed capacity | PVPS commissioning | Electricity output X-XII 2017 (MWh) | Capacity factor IX-XII (%) | Output of PV Power Plant | Capacity factor 2018 (%) |
|-------------------------------|-------------------|----------------------------------|--------------------------|-------------------------|-------------------------|
| Kosh-Agach 10MW               | 2015-16           | 2291                             | 10.36                    | 14888                   | 17.00%                  |
| Mayminsk 20 MW                | 2017-19           | 2 167                            | 4.90                     | 20 316                  | 11.60%                  |
| Ust-Kansk 5 MW                | 2016              | 688                              | 6.23                     | 6 329                   | 14.45%                  |
| Ongudaisk 5MW                 | 2017              | 716                              | 6.48                     | 5 350                   | 12.21%                  |

Comparison of the capacity factor data for the operating PV PS's in Altai region and the schematic maps compiled with the use of GIS technologies showed a better correspondence for the diagrams compiled according to the calculations of the daily year-to-year variability of the insolation incident than for the monthly characteristics. So the estimates of day-to-day variability for multiyear period are more promising to use as one of the components by choosing a location for the construction of solar power plants.

4. Conclusion

The verification of assessing the variability of insolation and data on the efficiency of operating PVPSs in the Republic of Altai was carried out. The insolation variability was evaluated using the method of calculating the coefficients of variation of average monthly and daily values of total insolation input. The efficiency of PVPSs operating in the Republic of Altai - by calculating the capacity factor of the installed PV systems. The verification showed good convergence of the selected areas for the PV solar stations locations using GIS technologies and locations of the operating PV PS with higher capacity factor values. The performed researches have shown the possibility and prospects of using this methodology for assessing the natural resource risks of using solar energy resources. The research showed, that due to the large spatially irregularity of snowfalls this factor must be also taken into account for the location of PV PS. The development of energy storage systems will significantly increase the efficiency of the RES electric power industry, ensure reliable and uninterrupted power supply to consumers. For example, generation can optimise equipment operation modes, distribution networks can maximise the load of power centres, and consumers can optimise power consumption while saving it for future use. It is planned to carry out further developments to refine the methodology and conduct assessments in other regions of Russia with a high potential for solar resources.

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