Validation of the efficiency of using solar energy resources for autonomous power supply of the trans-border area between Russia and Mongolia

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Abstract. The study provides an analysis of the state of the electric power supply in the trans-border area of Baikal-Khövsgöl. We identified the problems of power supply and the presence of decentralized consumers. The analysis of indicators of solar energy resources of the area from both Mongolia and Russia sides was based on various data sources. The NASA data of solar radiation incident on the different surfaces was selected for further calculations and zoning of the area. We evaluated the economic feasibility of the construction of the solar power plant (SPP) serving tourism infrastructure facilities with a capacity of 10 to 100 persons located on the northern coast of Lake Khövsgöl, which are provided with electricity from diesel power plants (DPP). The research used an iterative express method for determining the optimal power of a SPP for autonomous power supply, developed by the authors. The criterion for optimality is the minimum ratio of capital investment in a SPP and the cost of substituted fuel at a DPP. The research findings attest to the fact that the introduction of the SPP for stand-alone electric power supply seems to be economically viable for both stationary and mobile facilities. Undiscounted payback periods resulted from the diesel fuel substitution range from 2.5 to 6 years.

1. Introduction
The central part of the trans-border area between Russia and Mongolia is occupied by a unique natural formation, a basin of lakes Baikal and Khövsgöl, within which two unique national parks are located, belonging to sites for the special use of natural resources, namely, the Tunkinsky national park (its area of more than 1183 hectares covers the entire Tunka area of the Buryat Republic) and Khövsgöl national park (its area of more than 1106 hectares occupies almost 27% of the Khövsgöl aimak of Mongolia) [1-3]. Power is supplied to consumers in the Russian part of the territory of Tunka area of the Buryat Republic via an extended single-loop 110 kV transmission line (TL), Kultuk – Kyren – Zun-Murino – Mondy, of “Buryatenergo”, a branch of PAO MRSK of Siberia, which is further extended to the Okinsk district of the Republic to the Samarta substation. Consumers located within the area of Khövsgöl national park are powered from this TL via an interstate 35 km 10 kV TL, Mondy-Khanh, by PAO Inter RAO, a Russian operator of electric power export/import. There are also distant islanded consumers, mainly tourism infrastructure facilities and cattle-breeder encampments powered by DPP.

Consumers located within the areas adjacent to Lake Khövsgöl from the east, west and south are powered from the central energy system of Mongolia via 298 km 110/35 kV TL, Bulgan – Muren –
Khatgal, and further via 6, 10 and 15 kV distribution networks. Power demand in this area exceeds the transmission capacity of the power grid. Furthermore, the capacity of the Bulgan-Muren TL connecting the aimak with the central part of Mongolia cannot currently be increased either technically or technologically [4].

At the same time, the territory of the Tunkinsky and Khövsgöl national parks in the strategy and program documents of the Republic of Buryatia is considered as promising for the development of tourism and recreation [5-7].

Taking into account the challenges in ensuring electric power supply to consumers and the special status of the area, it seems reasonable to assess the efficiency of renewable energy use both in the zone of centralized and autonomous power supply. Similar studies are carried out in scientific organizations of different countries [8, 9].

This assessment requires reliable data on energy potential indicators and their changes during the year. This study deals with this very issue.

2. Heliopotential analysis
The area has sufficient heliopotential. Previous studies indicated that its use compares favourably with wind potential in terms of power supply [10].

The paper considers the main heliopotential indicators (multi-year data on exposure of different surfaces to solar radiation under medium cloud cover) based on three data sources: Reference books on climate for 1966 and 1991 (50-year observations) in the territory of Russia and NASA databases (from 1983 to 2005) [11-13]. Some of the annual heliopotential indicators available in all the three data sources for the Ilchir settlement (the Republic of Buryatia, 51°57’ N, 100°57’ E) are given in Table 1.

Table 1. Average annual heliopotential indicators for the Ilchir settlement (the Republic of Buryatia).

| Source                                      | Total solar radiation incident on the horizontal surface, kWh/m² | Direct solar radiation incident on the perpendicular surface, kWh/m² |
|---------------------------------------------|------------------------------------------------------------------|---------------------------------------------------------------------|
| Reference Book on the USSR Climate, 1966    | 1382                                                             | 1537                                                                |
| Scientific and Applied Reference Book on the USSR Climate, 1991 | 1388                                                             | 1552                                                                |
| NASA Data                                   | 1224                                                             | 1378                                                                |

The indicators of heliopotential presented in the table vary significantly among themselves. All values of NASA data are significantly lower, especially the total solar radiation incident on the horizontal surface.

In the area of Lake Khövsgöl, the annual direct solar radiation incident on the perpendicular surface, given the average cloud cover, is 1450-1480 kWh/m² according to some estimates [14].

Figures 1-2 below show the change during the year for the values of solar radiation incident on horizontal and perpendicular surfaces for the Ilchir settlement as based on the three data sources.

As is evidenced from Figure 1, data in different sources are almost identical, except for the summer period. The NASA data, on the whole, follow the data in the reference book, but they are lower by 12% predominantly in the spring-summer period.

Analysis of the data in Figure 2 shows that the nature of changes in the solar radiation incident on the perpendicular surface within a year according to the reference books data has pronounced peaks in the spring (high peaks) and fall (lower peaks) periods. In the NASA data, the fall peak is not very pronounced.
Figure 1. Total solar radiation incident on the horizontal surface according to different data sources.

In practice, most often, solar collectors used for power supply purposes are installed at an angle equal to the latitude of the area in the given location point. To calculate the values of solar radiation incident on the tilted surface, data on radiation incident on horizontal and perpendicular surfaces are used.

Figure 2. Direct solar radiation incident on the perpendicular surface according to different data sources.
Figure 3 shows the change of estimated values based on the data from three sources of information on solar radiation incident on the tilted surface placed at an angle equal to the latitude of the Ilchir settlement.

![Figure 3. Estimated values of the total solar radiation incident on the tilted surface based on different data sources.](image)

In Figure 3, the nature of changes in the calculated solar radiation incident on the surface tilted at an angle of the site’s altitude within a year, according to the reference books, is identical to two obvious spring and fall peaks. Differences in the nature of the changes based on the NASA data values are significant: the maximum is observed in the spring period only.

However, the total estimated values of solar radiation incidence on the tilted surface vary slightly (by about 3%) across data sources (table 2).

### Table 2. Estimated values of heliopotential for the Ilchir settlement (the Republic of Buryatia).

| Source                                               | Total solar radiation incident on the tilted surface, kWh/m² |
|------------------------------------------------------|-------------------------------------------------------------|
| Reference Book on Climate of the USSR, 1966           | 1647                                                        |
| Scientific and Applied Reference Book on Climate of the USSR, 1991 | 1652                                                        |
| NASA Data                                            | 1610                                                        |

The only comprehensive source of data for the entire Baikal – Khövsgöl area is the data provided by NASA, which cover just over 20 years. Reference handbooks offer a longer but more remote time period, whereas the NASA data extend almost to the most recent state. Therefore, the data provided by NASA were selected as a data source for the cartographic representation of heliopotential, as it would allow uniform coverage of the entire study area (figure 4).
Analysis of the data shows that the trans-border area is favourable for using solar energy. Total solar radiation incident on the horizontal surface ranges from 1200 to 1300 kWh/m$^2$ and more.

Even though southern coastal areas of Lake Khövsgöl and the Transbaikal region show the best values of heliopotential, in the northern areas of Lake Khövsgöl, there are favourable conditions for solar energy development.

3. Assessment of solar-based power supply efficiency

To substantiate the efficiency of the use of solar energy resources for autonomous power supply, we provide a case study analysis of tourist bases located on the shore of Lake Khövsgöl, which are supplied with power coming from DPP. Indicators of heliopotential are based on the NASA data for the point with coordinates 51°63' N, 100°55' E (north of Lake Khövsgöl). In addition to DPP, we took into account three options of consuming power from SPP. Hereinafter, the options will be numbered as Option 1, Option 2, and Option 3. The studied tourist bases differ in the volume of power consumption, load and the number of persons and are the most typical for the given area. The number of persons ranges from 10 to 100. Fuel cost is assumed to be 58 thousand rubles per ton. Input data used for the calculation are given in Table 3.

| Option number | Maximum load, kW | Specific fuel consumption at DPP, gce/kWh | Capital investment in SPP, thousand rubles/kW |
|---------------|-----------------|------------------------------------------|---------------------------------------------|
| Option 1      | 5               | 450                                      | With storage batteries – 160,             |
| Option 2      | 20              | 410                                      | without storage batteries – 76            |
| Option 3      | 50              | 380                                      |                                             |

Table 4 shows the technical specification of the photovoltaic converters (PV) adopted for the equipping the SPP.
Table 4. Specification of AST-240 Multi PV.

| Parameter          | Value      |
|--------------------|------------|
| Maximum capacity   | 240        |
| Efficiency, %      | 14.8       |
| Dimensions (L/W/H), mm | 1640x992x40 |

A technical and economic evaluation of the above options was performed based on fuel saving and the payback period. Optimal capacity of SPP is determined using the express method described in [15]. The express method correlates rather well with other more detailed methods of calculating heliopotential indicators.

The express method for determining the optimal capacity of a renewable energy source (RES) for a consumer isolated from the power system is universal and can be applied to any type of RES, including solar power plants. The methodology is based on the ratio of cost indicators (capital investment in RES and the cost of substituted fossil fuel in the existing energy source).

The studies are performed at several stages. At the initial stage, the method provides for the recalculation of the heliopotential indicators given in the reference handbooks and atlases [16] to bring them in line with the location of the investigated point. Then, based on the annual distribution of the obtained values of the energy resource and equipment specification, the possible power generation of the photovoltaic converter of unit capacity is calculated.

Next, the technical and economic performance indicators of the options of SPP application with successive capacity additions are determined; the energy capacity and net generation of electric power are calculated based on a comparison against the demand profile by months of the year. For the obtained values of net power generation and economic performance indicators that are descriptive of the consumer, the amount and cost of the substituted fossil fuel are calculated, and the capital investment in SPP of the corresponding capacity range is estimated. The criterion of capacity optimality is the minimum ratio of capital investment in the SPP to the cost of substituted fuel at the DPP.

The output information is the optimal design capacity of the SPP, as well as its corresponding net power generation, the required capital investment in the SPP, and the amount of the fuel to substituted during the operation of the plant. Based on these indicators, the commercial feasibility of the SPP construction project for a particular customer is assessed.

The calculated value of possible power generation by a single PV converter, taking into account the efficiency of the module and inverter, in the considered options is 0.41 thousand kWh/year.

Table 5. Calculated technical and economic indicators of different options of power supply from a solar power plant.

| Option number | The number of panels, pcs | Solar plant capacity, kW | Annual output, thousand kWh | Volume of substituted fuel, t | Payback period, years\(^a\) |
|---------------|--------------------------|--------------------------|-----------------------------|-----------------------------|-----------------------------|
| Option 1      | 30                       | 7.2                      | 12                          | 3.8                         | 2.5-5.2                     |
| Option 2      | 100                      | 24                       | 41                          | 11.6                        | 2.7-5.7                     |
| Option 3      | 250                      | 60                       | 102                         | 26.9                        | 2.9-6.2                     |

\(^a\) Note: Without storage batteries – with storage batteries.

The results of the research obtained using the computational model available to the authors, which takes into account the natural indicators of the heliopotential and the technical specification of the PV, are summarized in Table 5. Optimal capacity of SPP is from 7 to 60 kW, depending on the load of the
consumer. The number of hours of the utilization of the installed SPP capacity will be approximately 1700 hours/year. The share of substituted fuel resulted from SPP operation is estimated at 35-40%.

Calculations have shown that the payback period for all the options ranges from 2.5 to 6.2 years depending on the SPP configuration. Notably, the higher value corresponds to the option of equipping the plant with battery storage, whereas the lower value corresponds to the option of parallel operation of the DPP and SPP without storage battery.

4. Conclusion
As evidenced from the calculations, efficiency of SPP construction for independent power supply of both stationary (tourist camps and settlements) and mobile facilities (encampments of cattle-breeders) owing to substitution of diesel fuel is substantiated and worth pursuing. Based on our estimates, it is necessary to introduce solar power plants with the total capacity of 250-300 kW for the power supply of the tourism infrastructure facilities remote from the power grids. At the same time, to substantiate the use of heliopotential for each specific facility, it is advisable to conduct corresponding studies on a case-by-case basis.

In conclusion, it should be noted that there are some gaps in the input data on heliopotential, which may have led to some inaccuracies in the technical and economic calculations. In the future, we plan to develop and study this problem with a more accurate consideration of individual indicators.

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