Autonomous power supply using solar energy in Russian Far East regions

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Abstract. The most useful application of PV solar power in Russia are autonomous power systems in regions with high costs of organic fuels (due to transportation problems). Effective application of PV power needs comprehensive data analysis for solar energy resources, electric and heat load graphs and fuel costs. This paper is devoted to climate and power load data analysis for Russian Far East regions (in connection with PV application) and PV-based power plant mathematical modeling for several locations.

1 Introduction

Due to the large area, complex and heterogeneous climatic and geographical conditions of Russia, as well as the extremely non-uniform distribution of fuel and energy resources (FER), a significant part of the country is characterized by high production cost for electricity and heat. Therefore, one of the most important socio-economic problem of the country is to ensure reliable electricity supply in the territory of the Russian Federation.

Autonomous power sources are also needed, especially for consumers at the dead-end power lines, in some regions of the country covered by the centralized power grid, due to restriction of joining the grid and runout of generating and transmitting equipment. In areas with a developed centralized power grid, there is also a number of local consumers with a temporary need for power supply from independent sources. Electrical equipments, temporary buildings and structures used during construction of roads and other infrastructure could become such a consumers.

In decentralized area main energy consumers are local settlements. The island settlements automatically fall into this category. Isolated consumers are receiving electricity from the local diesel gensets, or in some rare cases, using local energy resources such as wood, coal, peat, etc. Usually transport expenses share in cost of energy received from gensets is quite high

For decentralized zones the combined or hybrid power plants, which include diesel generators and systems based on renewable energy sources (solar and wind power plants) could be effective. The most important direction in the development of decentralized energy supply is photovoltaic application in these areas. Despite relatively high costs, photovoltaic is less sensible to low local renewable potential, than wind power. Also non-

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uniformity of solar energy potential throughout the region is much less, than for wind. However, in this case, due to sharp seasonal fluctuations in solar radiation, there is a problem of generated electricity storage, including the complex systems of energy storage.

It is common, that main contribution at the cost of energy generated by diesel power plants make fuel costs. Therefore, the ratio of investment in new capacity and cost of fuel displaced are the main factors, which determine the choice of an autonomous source of power generation. Selection of the optimal composition of autonomous power plants with different types of power generators and batteries due to specific geographical conditions is a difficult task and is carried out on the basis of reliable data on the load of consumers, the potentials of renewable energy resources, climatic, geological data, the cost of fuel oil, the degree of assurance of power and a variety of other factors.

2 Analysis of the typical autonomous energy consumers in the decentralized zone of Russian energy supplies

The main parameters that determine the character of electrical load of large autonomous consumers, are the type of load (in general case, municipal, social or industrial) and the number of consumers [1]. Determination of typical electrical load for decentralized consumer is a complex task due to climatic, geographic and technical characteristics of each particular region and locality. In addition, the obtaining and analysis of real load curves are complicated by the absence of detailed monitoring of energy consumption data (summer and winter days regime). Data of the magnitude of the peak power consumption of electrical energy in the region are more available.

The data, that characterize the potential consumers of photovoltaic power plants in different regions of Russia, was collected and processed, allowing to analyze the typical energy consumer in decentralized areas. Two types of these areas were identified based on their consumers specific features: a) the decentralized energy supply areas (Far East Federal District, the Arctic zone of the Russian Federation (AZRF), island territories); b) the areas of centralized power supply with the limitations of electric power supply and the presence of niche consumer (Moscow and Krasnodar region).

Data systematization and analysis allowed to identify the following groups of electricity consumers in the Russian Arctic and Far Eastern Federal District as a whole:

0.1-1 kW - autonomous lighting for road, sea and river transport, telecom repeaters, weather stations, signal units (buoys, beacons, lights airfield), including objects of ground navigation and communication of Northern Sea Route (NSR);

1-10 kW - individual settlements, isolated farms, border posts, telecommunications systems, large navigation and communication systems airfields and of NSR for year-round use;

10-100 kW – island villages, mining and gold mines, tourist camps;

100-500 kW - coastal and island sites of service of the Northern Fleet and NSR, small production and processing enterprises, settlements with a population of 100-500 people;

500-1000 kW - reloading base, fishing farms, large deer farms, shift villages and towns (up to 1000 people);

1000 kW - large settlements (more than 1000 people), port facilities; military facilities, villages, enterprises of forestry, mining and oil and gas industry.

The main types of consumers are: 1) navigation and connections facilities; 2) mobile consumers; 3) port complexes; 4) local settlements.

The data array, characterizing the indicated types of consumers, has been created on the basis of statistical data on energy consumption for isolated local settlements in Far Eastern Federal District and the Russian Arctic (Kamchatka Territory, Altai Territory, Republic of Buryatia, Irkutsk Region, Republic of Sakha (Yakutia)) and are different by the municipal districts. Currently, power supply is based on diesel generators for the most part of these

consumers.

As an example, Figure 1 shows the load curves (summer and winter regime day) for a group of villages in Kamchatka. The power consumption is normalized to the maximum power value among all settlements for each hour (for June and January).

Fig. 1. Normalized load curves (average values and dispersion) for isolated local settlements, Kamchatka region.

Because of the correlation between population and consumption of electric power the maximum power frequency consumption diagrams were built for all isolated local settlements groups (Figure 2). It can be seen from the figure, that the logical shift of the maximum power consumption varies from 0-100 kW (population up to 500 people, Republic of Sakha (Yakutia) and Irkutsk region) to 400-2000 kW (population up to 1000-5000 people, Kamchatka).

Fig. 2. Maximum power share distributions for Irkutsk region (a), Kamchatka (b) and the Republic of Sakha (Yakutia) (c).

All of the identified samples, as well as standard load curves allow to simulate the concrete load curves (summer and winter days regime) even in the absence of detailed monitoring from human settlements.

In the presence of typical load schedules for optimization of power supply in remote decentralized settlements of the Russian Federation Far Eastern region, including using

renewable energy sources, it is necessary to carry out modeling, solar-diesel or wind-diesel electrical installations with accumulation. However, due to the complexity of both the modeling itself and the conduct of feasibility studies at the first stage of research, we carried out optimization of energy supply for the first group of consumers discussed above – for navigation facilities.

3 Optimization calculation for autonomous consumer powered from photovoltaic and batteries using load graph and climate data

Optimization calculations were performed for autonomous lighting-signal unit powered from PV array (Figure 3) using mathematical model based on hour, month and year energy balance calculation.

$$W_{PV} = W_{acc} + W_{con} \tag{1}$$

W_{pv} – energy, produced by PV array, W_{acc} – stored energy, W_{con} – energy, consumed by lighting-signal unit.

Minimal cost at 100% covering of given load graph was taken as optimization criteria. Leading lighting-signal marks on Tarantseva island (42.05°N 131.08°E) to south of Vladivostok and Rechanya Matuga (61.68°N 160.23°E) in Kamchatka were selected for investigation. First location is operated during the whole year, but the second – only in summer navigation (from April to October, [2]), so load graphs and climate conditions are quite different. Such autonomous consumers can be characterized by low power (10-100 W) which doesn't allow efficiently use diesel genset, stable energy consumption during the year, absence of operative staff in the location. Last circumstance demands very high reliability.

Multi-crystalline PV module RZMP 155 (R'azan factory for metal-ceramic devices JSC) parameters with peak power of 155 W were used in both calculations. Tilt angle of latitude+15° was selected to increase winter energy output and prevent PV array snow covering.

Fig. 3. One-line electric scheme for autonomous lighting-signal unit powered from PV

Mathematical model includes calculation of hourly rows for temperature and solar radiation data based on approach described in [5] and using NASA Power data [6], calculation (for every hour) of PV array energy production, depending on solar radiation, temperature and charge controller efficiency (2)-(4):

$$T_{pv} = T + (\frac{G}{800} \times (NOCT - 20)) \tag{2}$$

$$P_{max} = P_{max}^{STC} \times \frac{G}{1000} \times (1 + \gamma \times (T_{pv} - 25)) \tag{3}$$

$$P_{op} = P \times \eta_c \tag{4}$$

Here T is environment temperature (average between maximal and minimal value from NASA Power), T_{pv} – operational temperature of PV array, G – solar radiation, obtained from NASA Power and transformed into hour data for tilted surface using approach from [5], NOCT – PV cell operation temperature at 800 W/m², 20°C, P_{max} – maximal available power output of PV module at T and G conditions, P_{max}^{STC} – at standard test conditions (1000 W/m², 25°C), γ - PV module power temperature coefficient, P – minimal power value between power consumption for battery charging and signal unit feed and P_{max} , P_{op} – operational hour power value of PV module, including charge controller efficiency dependence on input power. For most types of available charge controllers this dependence is characterized by large efficiency drop for very low input power. Approximation for this dependence was based on controller passport data and experiments and is close to

$$\eta_c \sim \frac{1}{(\frac{P}{P_{max}})^2} \tag{5}$$

Storage battery based on lithium-ion (LiC₆||LiFePO₄) accumulators was integrated into model using its efficiency (84-86%) measured experimentally for LFP200 AHA (Winston Battery Co) on lower charge-discharge currents, close to those in solar-powered power unit. Energy, indicated as W_{acc} in (2), was multiplied by 0,85 according to losses on storage battery efficiency before further usage for covering night or low-insolation days load graph. Calculation results are shown in Table 1.

Table 1. Optimal combination of PV and batteries for PV powered autonomous leading marks.

Location	Geography	PV peak power, W	Battery capacity, kWh	Capital costs, USD
Rechanya Matuga	61.68°N 160.23°E	465	10,2	9900
Tarantseva island	42.05°N 131.08°E	465	10,8	9000

It’s worth mentioning, that in two different regions the power units for leading marks have similar structure. The problem is not only in climate conditions (though heavy rains season in summer is characteristic for Tarantseva island, increasing need in batteries to run through it and PV modules to charge the batteries), but also in load graph – absence of consumption in winter allows to store energy in batteries to use it mostly in April for Rechnaya Matuga. Assuming the whole year operation of leading mark in Rechnaya Matuga one will need 930 W of peak PV power with 15,4 kWh battery and will have capital costs of 15380 USD. So load graph has the same importance as climate conditions.

4 Conclusions

The most promising consumers of energy from renewable sources in the Russian Federation are located at the Far Eastern region. On the basis of statistical information processing, the following types of consumers were identified: 1) navigation and connections facilities; 2) mobile consumers; 3) port complexes; 4) the inhabited localities. For settlements in the three regions of the Russian Far East (Kamchatka, Irkutsk region, Yakutia) we constructed typical load curves for the summer and winter regime days (average values and dispersion at each hour of the day) normalized for the maximum power consumption among the villages of each region. By the presence of maximum power consumption for each group of localities during the day and at least one data on the power consumption during the day it is possible to restore a typical load schedule for a particular village. This makes it possible for further modelling and optimization of the energy supply for these settlements, including use of renewable energy sources

The paper presents the results of optimization modeling for an autonomous lighting-signal unit, where power supply can be carried out using a solar system with accumulation. The modeling has been carried out for two points in the Primorsky Territory (the Tarantsev Island) and the Magadan Region (the River Matuga), which are characterized with very complicated climatic conditions, PV peak power - 465 W, battery capacity - 10 kWh and capital costs - near 9000\$.

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