Analysis of options for small solar power plants for the Republic of Khakassia of the Russian Federation

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Abstract. The analysis of electricity tariffs for consumers of the Republic of Khakassia of the Russian Federation has been performed. Tariffs for the population are quite low. The use of small solar power plants for private residential buildings is inexpedient due to the long payback period. Tariffs for legal entities and organizations are much higher than for the population and have a steady upward trend. The main consumption of electricity by such consumers occurs during daylight hours. That is much in line with the energy generation by solar panels. It is concluded that calculations are necessary to determine the expedience of using small solar power plants for this group of consumers. The classification of the types of low-power solar power plants is given, their advantages and disadvantages are highlighted, and the area of application is shown. The results of the comparative analysis of three types of small solar power plants for a state facility of the Republic of Khakassia are presented. The expediency of using small network solar power plants without electric storage batteries with a limitation of the power supplied to the network was substantiated.

1. Introduction
The interest in the possibility of using solar energy for electricity production is growing every year, since solar energy is free, inexhaustible, and the cost of electricity from renewable sources decreases every year.

Environmental problems of a planetary scale and the foreseeable prospect of depletion of the Earth’s fuel and energy resources cause the growth of new energetics throughout the world based on the large-scale use of renewable energy resources of the planet: solar radiation, wind, water flows, geothermal energy and biomass energy [1].

Depending on the capacity, solar power plants can be divided into three groups [2]:

- Low power (less than 100 kW).
- Medium power (from 100 kW to 5 MW).
- High power (5 MW and more).

High power solar plants in the Russian Federation operate as part of the electric power system. As of September 2020, the total installed power of such solar power plants in the Russian Federation was 1,252 MW [3].

The use of solar power plants of low and medium power is limited to objects remote from electrical networks. At the same time, an autonomous system with electric storage batteries and reserving by
gasoline or diesel generator is used [4]. Small solar power plants operating in parallel with the electrical network have not become widespread. At the end of 2019, a law on the development of microgeneration was adopted [5]. The law allows to sell surplus generated electricity to the network at wholesale prices.

2. Analysis of electricity tariffs

Electricity tariffs have a steady upward trend. The average annual growth of tariffs for consumers of the first price category in the Republic of Khakassia is 9.6% for a voltage of 0.4 kV and 8.7% for a voltage of 10 kV. These tariffs are applied for organizations, enterprises and legal entities connected at a voltage of 0.4 kV or 10 kV [6].

For the first seven months of 2020, the average tariffs, including VAT, for consumers of the first price category for a voltage of 0.4 kV, in the Republic of Khakassia, are 7.4 rubles / kWh, for a voltage of 10 kV - 6 rubles / kWh.

Regulated tariffs for individuals living in houses with electric stoves and electric heating are significantly lower than unregulated tariffs. The graph shows a steady upward trend in tariffs. The average growth over the period under review is 6.3%, which is significantly lower than that of unregulated tariffs.

Estimation of the payback period of low-power solar power plants for private residential buildings in the Republic of Khakassia showed the inexpediency of their use due to low electricity tariffs [7].

The analysis of electricity tariffs in the Republic of Khakassia showed that the highest tariff is for legal entities and organizations connected to low voltage (0.4 kV). This is a fairly large group of consumers, represented by various state and private institutions, firms, shops, small businesses. These consumers work mainly during the day shift, which is an advantage for their use of solar power plants (figure 1).

![Figure 1](image1.png)

**Figure 1.** Daily schedule of the power of the organization working in the day shift, combined with the schedule of the generated power by solar panels.

The daily power schedule of these consumers is in much in line with the solar panel generation schedule. This allows you to consume energy from solar panels directly without directing it to batteries. Thus, the efficiency of the use of electricity from solar panels is increased.

3. Types of solar power plants of low power

Modern solar power plants of low power can be divided into two groups: autonomous (figure 2, (a) and network (figure 2, (b) - (d). Network solar power plants) can be divided into three types: without batteries and power limiter (figure 2, (b); without batteries and with a power limiter (figure 2, (c); with batteries and with a power limiter (figure 2, (d).
3.1. Low power autonomous solar power plants

Such a power plant can supply consumers who do not have a connection to a centralized network, or at a high cost of such a connection. For example, peasant farms located far from power transmission lines and substations. The considered scheme can also be used in case of power shortage and refusal to connect to the centralized power system.

Modern charge controllers have the function of tracking the maximum power point - MPPT (Maximum Power Point Tracking). The capacity of the electric storage battery (ESB) should be sufficient to compensate for failures in the generation of electricity from solar panels in the presence of cloudiness and at night. Depending on the composition and power of alternating current consumers, the one- or three-phase inverter is selected. When using a solar power plant as the main source of electricity, the inverter must form a completely sinusoidal voltage at the output. The presence of a gasoline (diesel, gas) generator in the scheme is necessary to back up the power plant in the event of repairs, in case of failures, as well as to provide the missing power in case of insufficient production of solar panels in winter and on cloudy days. For consumers of the III category of reliability on power supply [8], a break of up to 24 hours is allowed. This time may not be enough for prompt repair in case of power plant equipment failure. In winter, in the conditions of central Russia, as well as in the long cloudy weather, the generation of panels is significantly reduced, which can lead to interruptions in the power supply.

As the experience of using such systems in Russia shows, the share of electricity from solar panels is usually about 50% of the total generation [1]. The remaining electricity is generated by the fuel generator. Increasing the share of "solar" energy in the mid-latitudes of Russia is inexpedient. This requires an increase in the power of solar panels and the capacity of the ESB, respectively, increasing capital investment in solar power plants. Some of the increased costs are offset by the generator's fuel economy, but in summer there will be an underutilization of the increased installed power of solar panels. At the same time, the payback period will increase. Thus, it is expedient to choose the power of the panels and the ESB capacity on days with the greatest solar insolation. Then, in summer, the electrical load is covered by solar energy, and in other periods - together with the fuel generator. At the same time, the use of the installed power of solar panels will be maximum for the considered geographical latitude of the area.

There is a large selection of fuel generators with different power and types of fuels used on the modern power equipment market. Diesel generators are more economical than gasoline generators, have a longer resource and a higher cost. Gas generators are available for operation with liquefied petroleum
gas (LPG) or natural gas. Their cost is higher than that of gasoline, but expenses on fuel are lower due to the lower cost of gas.

The possibility of parallel operation of solar panels and a fuel generator for the total load should be noted. This is achieved by using a self-synchronizing inverter. Parallel operation mode allows you to increase the rated power of an autonomous solar power station to cover the peak part of the electrical load graph. There are inverter gasoline (diesel) generators on the market, which have lower fuel consumption at low loads.

3.2. Network solar power plants without batteries and without power limiter
Such a scheme can only be used if the consumer has a connection to a centralized electrical network. The scheme under consideration is distinguished by a simple design, the lack of batteries and a charge controller, a long service life, and a moderate cost. The inverter is automatically synchronized with the electrical network. In the event of a power failure, the inverter shuts down.

The electricity generated by solar panels is converted into alternating voltage by an inverter and supply consumers. If the consumption is less than the power generated by the power plant or is absent, then the electricity enters the network. In case of insufficient generation of solar panels, the rest of the power is taken from the electrical network.

In the Russian Federation, large power plants are currently built according to the specified scheme and sell electricity to the wholesale electricity market. This requires appropriate documentation. Wholesale market prices are currently in the range of 1–2 rubles / kWh [9]. Such a price level makes it inexpedient to operate low-power network solar power plants [7]. To enter the wholesale market, a power plant must have power of at least 5 MW.

In 2018, the Russian government submitted to the State Duma a bill on microgeneration. The law was adopted at the end of 2019 [5]. It assumes that individuals who own power plants, including those operating on renewable energy sources with a capacity of up to 15 kW inclusive, will be able to sell the generated electricity according to the rules of the retail electricity markets. To sell electricity, it is necessary to technically connect a micro-generation facility to local networks, as well as conclude a purchase and sale agreement with a guaranteeing supplier, whose coverage area has a mini-station based on renewable energy sources [5]. Electricity is purchased at the prices of the wholesale electricity and power market. Due to low purchase prices, it is not profitable for the owners of such power plants to sell electricity to a guaranteeing supplier.

Thus, at present in Russia, the use of low-power network-type solar power plants is expedient to reduce consumption without supplying power to the electrical network. On the equipment market, there are network type inverters for solar power plants without limitation and with limited power output to the network type. Inverters without power limitation are cheaper, but it is necessary to ensure full consumption of the generated power.

It can be noted that network-connected solar power plants, without limiting the power supplied to the network are the simplest and have lowest cost of the considered types of power plants. Their use is advisable if it is allowed to supply power to the electrical network or when working in the base part of the electrical load schedule, when the power consumption always exceeds the generated power of the power plant.

3.3 Solar power plants without batteries with power limiter
The scheme can only be used if the consumer has a connection to the centralized electrical network. The unique feature of this power plant scheme is the use of an inverter with the power output limitation function. This requires a current sensor installed on the power input cable from the electrical network. Depending on the number of phases of the inverter and the mains supply, the sensor is connected in one or three phases. The sensor is connected to the inverter with a measuring cable and can be removed up to 100 m from the inverter. The cost of such an inverter and current sensor is 20-30% higher than the cost of an inverter without power limitation. It should be noted that in many network inverters with power of 1 kW or more, this function is built-in by the manufacturer.
The use of the scheme under consideration makes it possible to completely exclude the transfer of power from the power plant to the electric network, to use the generated electricity only for own consumption. Thus, in Russia, with the help of the solar power plant under consideration, it is expedient to replace the most expensive electricity at the retail tariff of consumers of the first price category.

The disadvantage of the scheme is the presence of periods of time when, in the presence of solar insolation, the generated electricity is not in demand. This leads to a decrease in the use of the installed power of the solar panels and increases the payback period of the power plant. This problem can be solved at the design stage of a power plant when calculating its power. At the same time, the schedule of SPP generation on the days of the greatest solar insolation should be overlapped by the schedule of electricity consumption (see figure 1). In many cases, this limits the percentage of electricity replaced by the power plant from the centralized network. The degree of substitution of network energy, depending on the load schedule of the consumer, can be 10-70%. A further increase in the level of network energy substitution is possible by adding storage batteries to the considered scheme or by designing a solar power plant as a generating facility with energy delivery to the network. In this case, the sale of the generated energy will be carried out at the weighted average prices of the wholesale electricity market, which are much lower than retail prices and are in the range of 1–2 rubles / kWh [9]. At such prices, the payback period significantly increases. Thus, work on distribution to the network is expedient in the presence of higher ("green") tariffs for the electricity sold from renewable sources or other incentives from the state (tax incentives, compensation for equipment costs) and energy companies.

3.4 Network solar power plants with batteries and power limiter
The scheme can be used if the consumer has a connection to a centralized electrical network, and can also act as a backup power source. The scheme under consideration uses a hybrid inverter with a power output limiting function.

The hybrid inverter includes an ESB charge controller and a network inverter with the function of limiting the power output to the centralized network.

The scheme under consideration combines the advantages of autonomous and network solar power plants: full use of the power of solar panels, the ability to operate in the absence of voltage in the centralized electrical network (backup power source), a high percentage of substitution of network electricity, the possibility of parallel operation with the network with an increase in power consumption, lack of power output to the network. The main drawback of the considered scheme is the high cost due to the presence of ESB and an expensive hybrid inverter. It should be noted that the capacity of ESB in this scheme should be minimal. The battery is required only to exclude periods of downtime of solar panels in the presence of solar insolation. In this case, the unclaimed solar energy is stored in ESB. Thus, the increased cost in comparison with the scheme without ESB is partly offset by an accelerated payback. Some of the increased cost is offset by an increase in the percentage of replacement of expensive network electricity with solar power.

4. Comparison of options of small solar power plants
We will calculate the required equipment power, generation and payback periods for various types of solar power plants. As an object, we will consider a state institution of the Republic of Khakassia. Figure 3 shows a graph of the electrical load of the object in question over two weeks. The organization works in the daytime from 8-00 to 17-00. Saturday is a shorter working day. The graph shows the power consumption during the daytime from Monday to Friday and the power reduction on Saturday. The organization is closed on Sunday. The organization has a server, a canteen, office equipment, electric lighting, a computer network, video surveillance, security and fire alarms. Consumption at night and in weekends is associated with the operation of the server room, lighting, video surveillance systems and fire and security alarms. In the organization, the security service is constantly on duty.
Figure 3. The graph of the electrical load of the object in question.

The calculation results are presented in table 1. The option of a network power plant without a limiter was not considered, since for a capacity of more than 1 kW, network inverters without a limiter for the output power are not produced. The network solar power plant without batteries with the power limiter is the preferred for application (table 1). It has a short payback period, does not require maintenance, and consists of two main parts: solar panels and the inverter. The generation of such a power plant is about 10% of the electricity consumption of the facility in question. Further increases in power and generation will lead to underutilization of the installed solar panel power during the summer weekend. This will increase the payback period.

The power of solar panels can be significantly increased using electric storage batteries (the third option in table 1).

Table 1. Calculation results for various types of power plants.

| Option No. | 1 | 2 | 3 |
|------------|---|---|---|
| Type of solar power plant | Autonomous | Network without batteries with power limiter | Network, with batteries and power limiter |
| Power, kWt | 100 | 20 | 81 |
| Electricity generation per year, kWt*h | 277629 | 27571 | 108940 |
| Cost, thousand, rubles |
| Solar panels | 2784 | 679 | 2784 |
| Inverter | 1008 | 171 | 1008 |
| Electric storage battery | 3675 | – | 3675 |
| Diesel generator | 527 | – | – |
| Capital investments, thousand, rubles | 10392 | 1105 | 9707 |
| Annual economic effect, thousand, rubles | –404194 | 190677 | 752018 |
| Discounted payback period, years | – | 5.2 | 10.1 |

In this case, the surplus generated electricity on summer weekends accumulate in ESB. The capacity of the battery is selected taking into account the coverage of the night part of the current weekend. The
The cost of ESB is quite high and is approximately equal to the cost of solar panels with an inverter. In this version, the electricity generation is four times higher than in the second version and reaches 40% of the total consumption of the facility. The investment in the third option is 9 times more, and the payback period is twice as long as in the second option. A further increase in the power of solar panels and ESB capacity will increase power generation, but will lead to a noticeable increase in the payback period. The equipment of the third variant is maintenance-free during its operation.

Option No. 1 of a fully autonomous power plant with reservation using a diesel generator has shown economic in inexpediency. The annual economic effect is negative and significant in size. This is due to the high cost of electricity from a diesel generator due to the high cost of fuel. The disadvantage of this option is the cost of periodic maintenance of the diesel generator. Pollutant emissions are formed during the operation of a diesel generator. It is not desirable within the city.

Thus, in the Republic of Khakassia of the Russian Federation, it is expedient to use low-power network-type solar power plants without electric storage batteries, with limited power output for consumers of the first price category of an unregulated tariff.

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