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ECONOMICS AND ECOLOGY OF SOLAR ENGINEERING

Reducing the Costs of Paying for Consumed Electric Energy by Utilizing Solar Energy

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Abstract—The use of a low-power solar network and standalone power plants is the most promising for the needs of the housing and utilities sector, small industrial enterprises, social and public health facilities, recreation areas, remote objects, and agricultural industries; this will make it possible to reduce the load on the energy system at peak moments, as well as to decrease losses when transporting electric energy in its elements. It is assumed that the minimum value of the unit cost of generated electric energy is used as the criterion for configuring and selecting the parameters of solar power equipment, which will make it possible to set up an economically feasible additional power supply to the consumer, since it excludes the use of storage devices and rearrangement of the power supply system.

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INTRODUCTION

Among the various power plants operating on renewable energy, those that utilize solar energy are the most intensively developed at present.

Solar photovoltaic energetics is characterized by intense and accelerated development, which has especially appeared in the last six years despite the relatively low cost of hydrocarbon material and fuel based on it. Such a dynamic is also related to reduction in the cost of projects and equipment for solar power plants (SPPs). This is mainly due to a decrease in capital costs per unit and an increase in the operational efficiency of photovoltaic panels.

ANALYSIS OF RESEARCH

In reports based on enlarged indicators of operation of the energy sector, so-called "utility-scale" SPPs are most often represented an connected to the Unified Energy System of the Russian Federation and generating electric energy on a commercial scale [1]. However, many studies state that the most promising at present are low-power plants, both networks and standalone, used for the needs of the housing and utilities sector, small enterprises, social and public health facilities, recreation areas remote from centralized power supply systems of farms and households producing agricultural products. Distributed generation facilities also pertain to the mentioned categories. The introduction of such small solar generation facilities makes it possible to decrease the load on the energy system, as well as losses in its elements when transporting energy to consumers [2, 3].

The use of low-power plants is most widely covered in special literature, where two aspects of their operation are presented: the first is SPPs whose photovoltaic panels are installed at a selected angle to the horizon on a flat-plate roof of a building; the second involves photovoltaic panels integrated into the building structure.

However, the use of such power supply systems is limited by the structural features of the roofs. It is necessary to consider mutual shadowing of the lines of photovoltaic panels and structural elements in the first approach to forming the SPP structure and parameters [4–6]. This leads to limited power of the plant and the use of the engineering potential of solar energy in the places where they are installed. When integrating photovoltaic panels into a building's structure, the decrease in the volumes of generated electric energy is related to deviation of this special orientation from optimal [7], which leads to a decrease in the coefficient of the installed power of the electrical equipment, i.e., low-efficient conversion of solar energy into electric.

In addition to selecting the method for equipping of SPPs with the photovoltaic panels, one of the main problems in their design is coordination of electric energy generation and consumption diagrams. The electric energy generation diagram is completely governed by the patterns of the arrival of solar radiation to the collecting surface of the panels. This is, first, a diagram that has one maximum, at midday. The diagrams of the loads of electric energy consumers that fall on the morning and evening hours, when the intensity of solar radiation is low, most often have two to three consumption peaks. Two methods of compensating for the difference in electric energy generation and consumption diagrams are described in the literature: the first method is to use accumulating equipment to store excess energy in periods of high insolation and in the period of low solar activity or the absence thereof; the second is to join consumer groups into microgrids. The first approach is related to the high costs of purchasing accumulating equipment, which are commensurable with the cost of photovoltaic panels and therefore with an increased unit cost for electric energy generation [8, 9].

The connection of several consumers and their integration into one microgrid contributes to the achievement of higher technical solar potential in the region, but it requires remote computer control of all sectors; therefore, a decrease in the total system reliability is possible in terms of redundant reliance on computational resources and communication channels [8, 10].

The implementation of generation systems based on renewable energy sources is related to their installation and commissioning costs, which requires analysis of each variant of arrangement from the viewpoint of economic efficiency. In the practice of power supply, the selection of economically efficient projects is based on preliminary technical and economic assessments, i.e., determination of the capital (primary) investments and current (annual) costs [1].

It is convenient to use such a concept as the unit cost of the generated electric energy to rapidly assess the economic efficiency of the introduction of SPPs [1]. When compared with the applicable price of electric energy, such a solution can demonstrate the profitability or unprofitability of an SPP project.

The aim of the investigation is to study the arrangement and general parameters of SPP equipment for additional power supply to consumers taking into consideration the solar radiation intensity within a year, the structural features of roofs, and the characteristics of the load diagram to reduce electric energy costs.

MATERIALS AND METHODS

The proposed approach to searching for the SPP parameters ensuring economically efficient electric energy generation yields a preliminary solution to the problem of determining the amount of photovoltaic panels takin into account their spatial orientation, the regional solar energy potential, and the dimensions of the field where the photovoltaic panels are to be located. Here, the criterion is the minimum unit cost of generated electric energy:

$$\sum_{i=1}^{L}\left(\frac{K}{T_{\text{o}}}\right)\Bigg/\sum_{n=1}^{365}\sum_{t=t_1}^{t_2}[\text{Rsum}_{\beta\gamma}(t,n)NS_{\text{pvp}}\eta_{\text{pvp}}] \to \min, \quad (1)$$

where $\text{Rsum}_{\beta\gamma}(t, n)$ is the hourly sums of the total solar radiation for the geographic point with the coordinates (φ, N, λ, W) for the time moment t of the day n, kW h/m^2; N, S_{pvp}, η_{pvp} is the number (pc.), surface area (m^2), and efficiency factor (p. u.) of the photovoltaic panel; t_1 and t_2 are the start and end times of daylight; L is number of the i-type elements (photovoltaic panels, inverters, charge controllers, storage batteries); K, T_{o} are the cost ($) and term of operation (y) of the i-type element of the SPP.

The limits in the course of solving this optimization problem are as follows:

(1) The angle of inclination of the collecting surface β to the horizon is within 0–90°.

(2) The value of the angle of orientation of the collecting surface for the cardinal directions γ is within −90° to 90°.

(3) The dimensions of the location area determined by its length and width is $a \times b$, m^2.

The solar energy potential for the city of Zernograd of Rostov oblast was determined by a rapid method of assessing the solar energy potential at a certain point; the territory of southern Russia [11] is realized in the form of a computer program where the geographical coordinates and spatial orientation of the collection area are entered as the basic data [12]. The search for the optimum angle of inclination of the collection area to the horizon in a given point of the Southern Federal District is also carried out with the developed computer program [13].

The estimated time of operation of the solar batteries was assumed to be from 08:00 to 17:00.

RESULTS AND DISCUSSION

Four variants of the arrangement of SPPs were analyzed to reduce costs of paying for electric energy consumed by an intrashop lighting system in the processing plant areas:

1V is maximum achievement of the solar potential taking into account shadowing and when using accumulating devices [5, 8];

2V is maximum achievement of the solar potential by the photovoltaic panels integrated in a roof structure [7, 8];

3V is joint use of both approaches 1V and 2V [5, 7, 8];

4V is an SPP whose parameters and arrangement are selected based on proposed criterion (1).

Table 1 presents the results of the technical and economic assessment.

Table 1. Results of technical and economic assessment for different variants of SPP arrangement

No.	Total capital costs, \$	Annual costs, \$	Annual electric energy generation, kW h	Difference of total generation from load, kW h	Unit cost of electric energy generated by SPP, RUR/kW h	Capital costs per unit, \$/kW	Payback period, years
1V	33846	6133	6807	2383	51.8	5641.0	34
2V	44042	6714	14699	10274	26.3	3238.4	21
3V	40433	6530	12086	7662	31.1	3814.4	23
4V	3116	200	1588	–2836	7.3	1558.0	14

The capital costs for variants 1–3 are one order of magnitude higher that the proposed arrangement, which is, first, determined by the use of the storage batteries in the SPPs, the share of costs for which is 59–77% of the total. The capital costs per unit for the construction of the SPP are the lowest for its proposed arrangement. However, the use of storage batteries makes it possible to more fully achieve the available solar energy potential of the plant's location area , especially when photovoltaic panels are integrated into the roof structure of the building (2V); however, the annual volume of generated electric energy is the largest: 14699 kW h. The technical potential of insolation is 44.3% less than when the flat-plate part of the building's roof is used (1V), which is determined by the mutual shadowing of lines within the morning and evening hours. The SPP generates the least energy in arrangement variant 4: 1588 kW h, with the share of load being 36.9%, which makes it possible to additionally exclude accumulating equipment.

The shortest payback period is variant 4: 14 years. The minimum value of the unit cost is 7.3 RUR/kW h, which is 11% lower than the applicable price for electric energy for the processing plants of Rostov oblast, 72.2% less than for arrangement variant 2, and seven times less than for variant 1.

Figure 1 shows the daily electric energy generation curves for the different SPP arrangement variants and the curve of electric load of the lighting system of the milling workshop areas for June 22 (the day with the maximum insolation level) and December 21 (the day with the lowest solar radiation intensity).

It is clear from Fig. 1a that for arrangement variants 1–3, the SPP during a summer day (with a high level of solar radiation intensity) of generation exceeds the loads for nearly the entire day (from 08:30 to 19:00), which exactly requires the use of storage batteries in the plant structure. An SPP structured according to these arrangements completely ensures the power supply of the lighting system of the areas also nearly within the total daylight in winter, but requires accumulation or utilization of the excess electric energy. The proposed SPP arrangement in variant 4, substantiated by criterion (1), which ensures the minimum level of electric energy generation, only partially covers the load; however, despite the small value of the achieved technical potential, the plant structure uses the minimum amount of equipment, which is characterized by low capital costs.

Figure 2 shows the share of power supply to the considered consumer from the network and SPP on June 22 and December 21, respectively.

Figure 2 shows that the load is completely provided only within the summer period during the highest intensity of solar radiation at 14:00; only half of the lighting system is ensured by the SPP during the same period in winter.

Figure 3 shows the daily curve of payment for consumed electric energy for summer and winter days

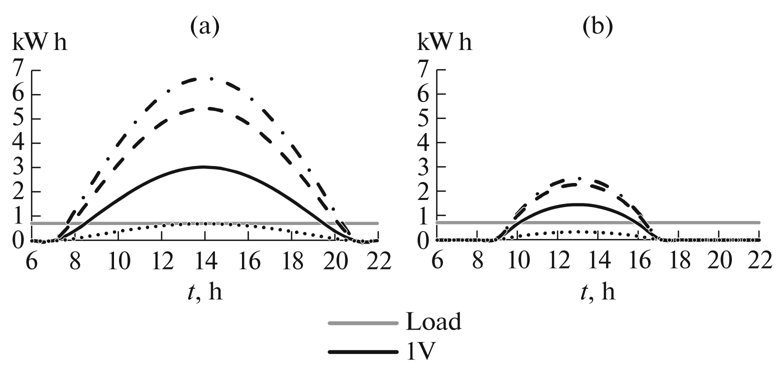

Fig. 1. Daily curves of load and electric energy generation from SPPs of different arrangements as of June 22 (a) and December 21 (b).

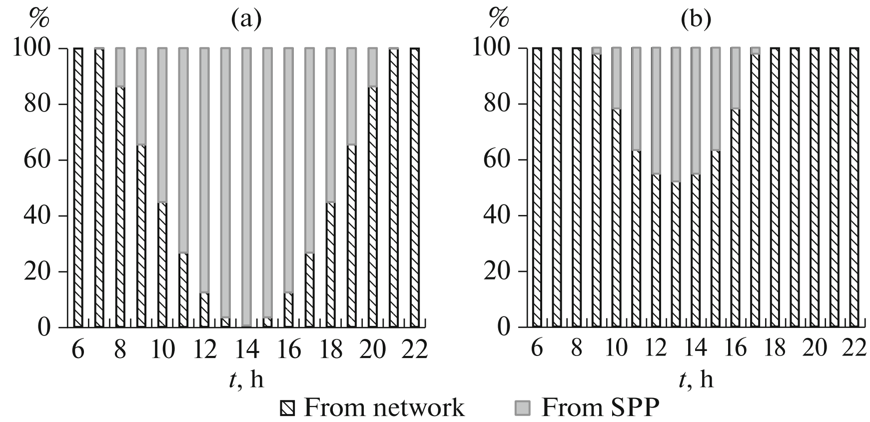

Fig. 2. Share of power supply to considered consumer from network and SPP on June 22 (a) and December 21 (b).

when additional power supply from the SPP is arranged according to variant 4 and only from the network.

Let us analyze the value of payment for consumed electric energy within a day to ensure power supply of the lighting system of the milling sectors of the processing plant. The largest payment when purchasing electric energy from the electrical network at 8.15 RUR/kW h (the price applicable to the processing plant of Rostov oblast as of April 2017) is 5.85 RUR/h. In case of additional power supply from the SPP within the solar activity period (from 07:00 to 09:00), its value decreases to 4.4 RUR/kW h, which is 24.7% less than the payment for utility-scale electric energy. A smooth decrease is observed, and it reaches a minimum at 13:00, which corresponds to the insolation peak and is specified by the character of solar radiation arrival to uniformly located south-oriented collecting surfaces. The cost of electric energy decreases by 6.0–13.5% during the morning hours, and by 17.9–24.7% at moments of high solar activity within the operating period of the SPP.

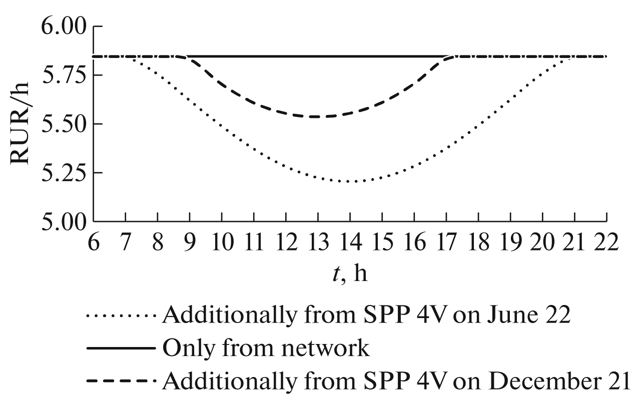

Fig. 3. Payment for consumed electric energy on June 22 and December 21.

During the winter period, when low solar activity is observed, the payment decreases by 10.9–11.6%, when the Sun is at its zenith, and by 5.3–8.9% during the morning and evening hours.

CONCLUSIONS

The total solar energy potential for Zernogradskii district in Rostov oblast can be partially achieved at the considered plant owing to the technical constraints of the characteristics of the roof structure (the flat part of the roof with small dimensions is used for the design), conditions of its shadowing, and a fixed angle of inclination of its pitch part.

Some SPP arrangement variants are analyzed. The maximum achievement of the available technical potential of solar energy leads to significant growth, sometimes by 2–2.5 times, and capital costs due to the necessity of accumulating devices to utilize the excess generated electric energy. The difference in the form of electric energy generation and consumption curves can also be compensated by integration of some consumers into a microgrid. However, this can be done only for industrial zones and isolated production areas located in the rural territory or for certain small settlements.

The use of the minimum unit cost of generated electric energy as a criterion when arranging and selecting the SPP equipment parameters makes it possible to organize economically efficient additional power supply to the lighting system of the milling area of a processing plant, since the use of accumulating devices is excluded and does not require reorganization of the power supply system. Such an approach makes it possible to decrease the cost of paying for consumed electric energy by approximately by 13000 RUR due to a reduction in the cost of each consumed kW h of electric energy from 8.15 to 7.3 RUR/kW h within the period of active solar activity.

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