FEATURES OF THE DETERMINATION OF THE OPTIMAL COMPOSITION OF A WIND-SOLAR POWER PLANT WITH DIESEL GENERATORS DURING MULTI-CRITERIAAL SEARCH IN CONDITIONS OF THE RUSSIAN ARCTIC

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ABSTRACT. The established trend towards decentralisation and the use of renewable energy is reflected in the choice of the composition of the generating complexes in many developed countries. It should be noted that hybrid power plants including two or more renewable sources, as a rule – photovoltaic and wind power plants, become more and more common in the world. Despite the specifics of the development of renewable energy in Russia due to the large reserves of hydrocarbons, such hybrid complexes are relevant also for our country. First of all, their use is advisable to consider in areas where the power supply is traditionally carried out by diesel power plants, working on imported fuel. For Russia, it is primarily the Arctic, the Far East and Siberia. The energy costs of these areas are huge and need to be optimised.
Thus, the issues of determining the optimal composition of autonomous hybrid complexes, consisting of wind generators, solar panels, diesel generators and batteries are an important task, which arises at the design stage of the system.
The article presents the results of a single-purpose optimisation of the composition of a hybrid complex consisting of wind-solar and diesel power plants, according to the criterion of the minimum cost of electricity (COE) for a small settlement in the Arctic. An estimation of the impact of an additional criterion for the total investment cost (TIC) limitation on a result of solving an optimisation problem is given. It is shown that the ratio of the proportions of the solar and wind power is not constant when the TIC changes and it changes when one of the renewable energy sources is excluded from the complex.

Keywords: renewable energy, photovoltaic, wind, power station, optimal composition

ОПРЕДЕЛЯНЕ НА ОПТИМАЛНАТА СТРУКТУРА НА ЕНЕРГИЕН КОМПЛЕКС, СЪСТОЯЩ СЕ ОТ ВЯТЪРНО-СЛЪНЧЕВИ И ДИЗЕЛОВИ ГЕНЕРАТОРИ ЗА УСЛОВИЯТА НА АРКТИЧЕСКИТЕ РАЙОНИ В РУСИЯ, ЧРЕЗ ИЗПОЛЗВАНЕ НА МНОГОКРИТЕРИАЛНО ТЪРСЕНЕ

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РЕЗЮМЕ. Установената тенденция към децентрализация и използването на възобновяема енергия се отразява при избора на състава на енергийните комплекси в много развити страни. Трябва да се отбележи, че хибридните централи, включващи два или повече възобновяеми източника, като правило - фотоволтаични и вятърни електроцентрали, се срещат все по-често в света. Въпреки спецификата на развитие на възобновяема енергия в Русия поради големите запаси от въглеводороди, такива хибридни комплекси са от значение и за страната ни. На първо място, тяхното използване е препоръчително да се обмисли в райони, в които електроснабдяването традиционно се извършва от дизелови електроцентрали, работещи на вносно гориво. За Русия това са предимно Арктика, Далечният изток и Сибир. Енергийните разходи в тези райони са огромни и трябва да бъдат оптимизирани.
По този начин, въпросите за определяне на оптималния състав на автономни хибридни комплекси, състоящи се от вятърни генератори, слънчеви панели, дизелови генератори и акумулаторни батерии, са актуална и важна задача, която възниква още на етапа на проектиране на системата.
Статията представя резултатите от едноцелева оптимизация на хибриден комплек, състоящ се отвятърно-слънчеви и дизелови електроцентрали, според критерия за минимални разходи за електроенергия за малко населено място в Арктика. Дадена е оценка на въздействието на допълнителен критерий за ограничението на общите инвестиционни разходи върху резултата от решаването на проблем с оптимизацията. Показано е, че съотношението на пропорциите на слънчевата и вятърната енергия не е постоянно, когато критеритерят за ограничение на общите инвестиционни разходи се променя, а той се променя при изключване на един от възобновяемите енергийни източници от комплекса.

Ключови думи: възобновяема енергия, вятър, електроцентрала, оптимален състав

Introduction

The sustainable development of the Arctic, rich in natural, biological and recreational resources, is impossible without creating the appropriate infrastructure, including a reliable and cost-effective power supply system for oil and gas extraction complexes, equipment of main oil and gas pipelines, polar stations, rotation camps, localities. For the Russian Arctic, a relatively new area is the use of renewable energy sources (RES), such as solar and wind energy.

The relevance of the development of renewable energy in the Russian Arctic is due both to the enough potential for solar and wind energy and to the significant material costs and environmental losses when using traditional fuels. And, if it is inappropriate to equip drilling platforms with an installed electrical power up to tens of MW with expensive wind (W) or photovoltaic (PV) power plants, then in the Arctic zone there are quite a few low-power facilities that are currently powered by diesel power plants (DP): particularly, these are small localities, research stations, and rotation camps.

Delivery of essential supplies to the Arctic territories (primarily, food, medicines and petroleum products) is currently carried out through the Northern Supply Haul. Cargo delivery is implemented by rail, air, sea, river and road transport. This, coupled with travel distances and the lack of developed infrastructure, greatly multiplies the cost of goods, placing pressure on the federal budget.

In some cases, such as in the rural locality Lamutskoye in Anadyrsky District of the Chukotka Autonomous Region, the economically feasible cost of 1 kWh is 200 RUB. In 2016, the government allocated about 7 billion dollars at the rate in mid-2016 for the Northern Supply Haul, which amounted to around 2.8% of the expenditure budget for that year.

One of the solutions to reduce economic costs is the use of RES in the Arctic and other energy autonomous regions. At the same time, hybrid wind-solar power plants are becoming increasingly common. Many studies are devoted to study of the optimal composition of autonomous hybrid complexes (Bernal-Agustin at al., 2006; Abdel-Karim at al., 2011; Ayodele and Ogunjuyigbe, 2015), some are carried out by Russian scientists (Marchenko and Solomin, 2016; Popel, 2017; Turovin et al., 2017; Suslov et al., 2018). In the paper (Popel, 2017) the author came to the conclusion that there is a large potential for different kinds of RES in the Arctic.

However, in these and other works, the authors used composition optimisation for plants located in the southern regions of the Earth. At the same time, the use of renewable energy in northern latitudes has its own characteristics that were not noted in the works.

In addition, multi-criteria search seems to be the final decision among the best options for people. It is important to understand how the solution to the optimisation problem changes when additional criteria are taken into account. Thus, the article considers how the optimal composition of a hybrid plant changes when in addition to the cost of generated electricity, an additional limiting criterion is taken into account: initial capital costs.

Characteristics of the Use of PV and W Power Plants in the Arctic

Use of Photovoltaic Plants in the Arctic

Contrary to common belief, the level of solar radiation allows to consider the region as an appropriate place for PV-plants. The map of allocation of average daily values of the direct solar radiation above the Russian Arctic Circle shows, that on average, the regions of the Arctic zone are characterised by a value of direct solar radiation within the range of 2.5-4.5 kWh/m^2/day. In this case, the common criterion for the applicability of PV is the value of annual insolation of 1000 kWh/m2 (Lukutin et al., 2015), corresponding to 2.7 kWh/m^2/day.

It is well known that the duration of light periods throughout the year is identical and it equals the total duration of nights (Popel et al., 2015). In the Arctic, the allocation of these periods has certain peculiarities - if in the equatorial zone the day and night intervals are approximately equal, in the Arctic region most of the light periods occur in the summer when there is full sunlight all day long above the Arctic Circle. It's necessary to consider this natural phenomenon with the geographical location and intended purpose of the complex: for example, the SPS can be very effective when using the complex during the operational season (at meteorological and exploration stations, etc.), even above the Arctic Circle, when the sun does not set below the horizon.

The low temperature, that's typical for the Arctic region, has a positive impact on the efficiency factor of the modules. And the efficiency turns out higher than nominal. The results from the experiment of Serbian researchers show that, in general, the modules work with a higher efficiency in December than in other months (Pantic, 2016).

Essential increase of manufacture of PV-modules is promoted also by radiation reflected by the snow. But it is important to take into account the reduction in production from PV due to snow on the surface of the panels. If necessary, organisational (mechanical snow removal) or technical (for example, the use of special frameless modules[1] shown in Fig. 1,) measures may be applied.

Fig. 1. Experimental PV-panels of the Regional Test Centre in Williston (Vermont, USA) with frameless (foreground) and traditional (in the background) modules for studying the effect of snow on electricity generation and the bearing structure of PV-panels

From a technical point of view, the use of PV-plants in the Arctic is the simplest solution. The key here is the opportunity to construct a plant without moving parts, which greatly simplifies the low-temperature service. The integration of a solar tracking system significantly increases the efficiency of the PV-plant, however, due to large capital costs, such technical solution is not always used in a milder climate, not to mention the Arctic - where this system requires the development of special design solutions, making the construction even more expensive.

In addition, the PV-plant can be located close enough to consumers, because the magnitude of solar insolation does not change abruptly on the ground, in contrast to the wind speed in the case of W-plant.

Use of Wind Plants in the Arctic

In the conditions of the Arctic, the potential of W-plants is noticeably bigger compared to the potential of PV-plants. In most of the Russian Arctic, the average annual wind speed exceeds 5 m/s[2], which is considered to be favourable for the use of wind generation (Lukutin et al., 2015).

The use of W-plants in the Arctic is characterised by the following factors.

[1] How solar panels can thrive in winter weather. [Electronic resource]. Available at: URL: http://poweroverenergy.org/renewables/solar-panels-can-thrive-winter-weather/

[2] Natsionalnyiy atlas Rossii: vetrovoy rejim. [Electronic resource]. URL: национальныйатлас.рф/cd2/172/172.html

Firstly, maximum localisation of W-plant elements is required. A serious problem that has led to the suspending of several promising wind farm projects is the difficult delivery of parts to Russia and their onward transport to the Arctic and the Far East. To some extent, the problem of transport infrastructure is related to this problem. Distance barriers, underdeveloped infrastructure, the absence of specialised equipment in far-flat regions create difficulties in delivery and installation of WPS equipment.

Of course, there are special requirements for W-plants in the Arctic. Lubricants and bearing structures of WPS should be made of low-temperature materials. A reliable and effective system of protection against the action of hurricane winds is necessary in the Arctic and the coastal regions of the Far East. Construction in earthquake-prone areas which have more than 8 points on the MSK-64 scale (the bulk of the coastal areas of the Far East) requires strengthening of bearing structures of WPS, their foundations and power lines. Construction of W-plants of medium and high power (more than 300 kW) is possible only on a pile foundation.

Another problem is the lack of qualified personnel to repair W-plants in far-flat regions.

In addition, in some cases, a refined analysis of the wind potential of a locality may indicate that the W-plants should be located in a place removed from the autonomous consumer, that makes construction irrational due to increasing capital (transmission lines to the consumer, transport infrastructure to the plant) and operational (voltage loss in power lines) costs.

Methods for Optimising the Composition of Hybrid Wind-Solar Power Plants

Existing optimisation methods

Currently, there is a large number of methods for determining the optimal composition of hybrid complexes (Al-Falahi Monaaf at al., 2017): classic (iterative, analytical, graphic, linear), modern (artificial, hybrid), computer (genetic algorithms), etc. Some of them use averaged statistics on the level of insolation, wind speed, daily load, etc.

Some methods, for example, computers, allow to increase the detail of calculations. They involve the use of retrospective data on insolation and wind speed at short intervals (up to every hour of the year), and a set of averaged daily load schedules (Sosnina et al., 2018). Technical and economic parameters are calculated for each period of time throughout the entire period of operation of the hybrid power plant [A1]. The disadvantages of this approach include the need for a large, detailed database of meteorological data for previous years, and the advantages include the possibility of modelling the operation of the complex at any stage of operation, which makes it possible to optimise its modes of operation. Refusal to use a large number of averages can be assessed differently: on one hand, there is a deviation from a statistically verified typical description of weather conditions, on the other, climate change can be taken into account and the probability of using outdated and irrelevant statistical information is generally reduced.

Most of the classical methods use single-purpose optimisation, while more modern methods allow us to determine the optimal composition of the complex based on several criteria.

Method of research

In (Ayodele and Ogunjuyigbe, 2015), the genetic algorithm was used to determine the optimal structure of an autonomous hybrid complex of a PV-W system with DP backup and batteries, and optimisation was carried out according to the criteria of COE, reliability and carbon emissions. On the basis of the mathematical description presented in (Ayodele and Ogunjuyigbe, 2015), the optimal composition of the hybrid system was determined for the selected locality.

The initial data were taken from 12 typical graphs of the electrical load, as well as the hourly values of insolation and wind speed over the last year. In order to simplify the calculations, the values of the array of meteorological data were extended to the entire estimated life of the station according to, the passport of the PV plant - 25 years. The calculation programme was implemented in the MO Excel program and its VBA application. The search for a solution was initially carried out according to the criterion of the lowest COE, which made it possible to use the selection method instead of the more complicated genetic algorithm.

Determination of the Optimal Composition of Wind-Solar Power Plant

Characteristics of the object of study

In the case-study we considered the settlement Nizhneyans in the Yakutia region with a population of about 250 people. The optimal composition of the PV-W power plant with DP was calculated for the urban-type locality of Nizhneyansk.

During the calculation, data about the hourly, monthly averaged, load values in Nizhneyansk in 2016 were used. Thus, 12 typical electrical load curves were taken as a basis. The diagrams of averaged daily loading are characterised by the absence of salient peaks and valleys in electric energy consumption and, in general, correspond to a small settlement with a poorly developed industrial sector. The lowest average value of load per hour is 176 kW (July), the highest is 376 kW (December), the average value of the load per hour during the year was 288 kW. Fig. 2 shows a typical daily load curve for January and July.

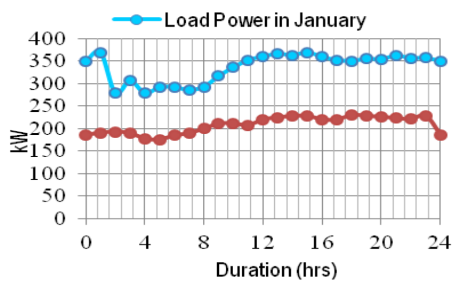

Fig. 2. Typical daily load curve for January and July

Mathematical description of system elements

Solar power plant

Data on hourly wind speeds and solar insolation are taken from the database[3]. For a more detailed analysis, the

[3] Data base Renewables.ninja. [Electronic resource]. Free access: https://www.renewables.ninja, (Date of access 3 June 2019)

meteorological data for all available years should be used, however, in this study, the calculation was made for the life cycle of the HC of PV-W system within 25 years based on data for 2017. The PV modules Quantum KSM 200 were selected as photovoltaic cells for the PV-W system.

The power from the PV module was calculated as

$$P_{pv\_output} = P_{pv\_r} \times H_t \cdot \eta_{pv}, \quad (1)$$

where P_{PV_r} – is the nominal rated power of the module, H_t – is the total solar radiation on a fixed inclined surface, η_{PV} – is the efficiency of the module.

The economic calculation also considers the cost of DC/AC converters required for operation in the PV-W system.

In the course of the calculation, some assumptions were made – for example, the effect of temperature on the power generation of the PV module wasn't taken into account. However, the air temperature averaged over the hourly zone exceeded 20°C only once, reaching 20.4°C. Thus, the decrease in electrical generation by the module due to temperature is negligibly small, since technical parameters of the module are specified by manufacturers of PV modules for air temperature of 20°C.

Fig. 3 shows a diagram of the output power of the PV module for 10 days in the period from 1st to 10th August.

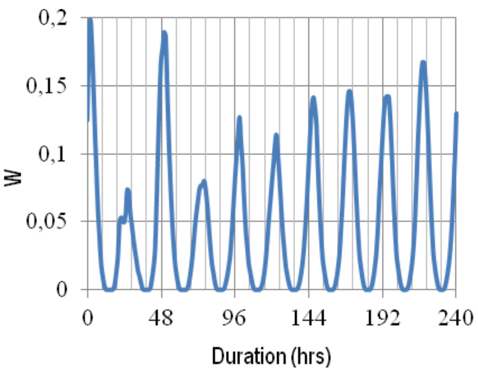

Fig. 3. The output power of the PV module for a 10-days period in August, Kw

Wind power plant

Wind turbine Condor Air WES 380 / 50-50 was chosen as a wind power plant. Fig. 4 shows a diagram of the output power of a wind turbine for 10 days in the period from 1st to 10th August.

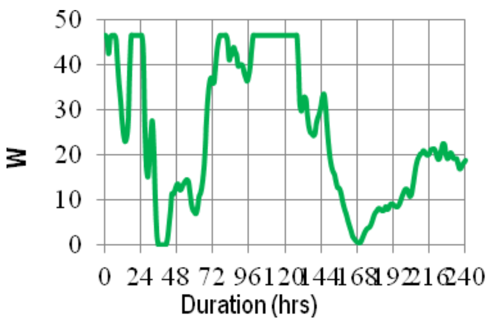

Fig. 4. The output power of the wind turbine for a 10-days interval in August

The power of the wind turbine was calculated using the equation

$$P_w = \begin{cases} 0 & V < V_{ci} \\ P_r \cdot \left(\dfrac{V^3 - V_{ci}^3}{V_r^{\ 3} - V_{ci}^3} \right) \cdot \eta_w & V_{ci} < V < V_r \\ P_r \cdot \eta_w & V_r < V < V_{co} \\ 0 & V > V_{co} \end{cases} \quad (2)$$

where V – is the actual wind speed at the height of the tower, V_{ci} – is the initial wind speed (wind turbine switching on), V_{co} – is the limit wind speed (wind turbine switching off), V_r – is the nominal wind speed, P_r – is the nominal wind turbine power; η_{pw} – the electrical efficiency of the wind turbine.

Diesel power plant

In order to ensure reliable power supply to consumers, the total power of a diesel power station was chosen equal to 450 kW, which is almost 20% more than the maximum averaged over the hourly zone power during the year. This margin is required for stable operation of the system.

Usage of several diesel generator sets instead of the big one allows to provide the required level of reliability, and an optimal choice of the nominal rated capacities of the generators - to obtain effective operational factors, as demonstrated in the work [Ogunjuyigbe et al., 2016].

The fuel consumption of DP for a given hour *t* was calculated by the formula:

$$F(t) = (0.246 \times E_d(t)) + \left(0.08415 \times \frac{P_r}{1\,h} \right), \quad (3)$$

where P_r – is the nominal power of diesel set, kW; *0.246* and *0.08415* – empirical values, taking from (Ayodele and Ogunjuyigbe, 2015), l/kWh; $E_d(t)$ – energy deficit calculated as $E_d(t) = E_{RES}(t) - E_L(t)$, where $E_{RES}(t)$ – electric power from RES at a given hour, $E_L(t)$ – electric power required by consumers and numerically equal load power at a given hour.

Results

The main factors that were used for optimisation during the implementation of the algorithm were certain economic criteria: the cost of electricity (COE) and the related parameter – the life cycle cost (LCC). However, in the process of calculations, other parameters of the complex were also determined - the total investment cost (TIC), carbon dioxide emissions (E_{CO_2}), annual system cost (ASC), dump energy (D).

As a baseline, an optimal configuration without PV-W system was found. Three diesel generator sets have a rated power of 250 kW, 150 kW and 50 kW. Two more types of optimal configurations were determined: DP+W plant and DP+PV plant. Finally, another configuration corresponds to a fully optimal composition and includes DP and PV-W plant. Figure 5 shows the installed capacity in the four options.

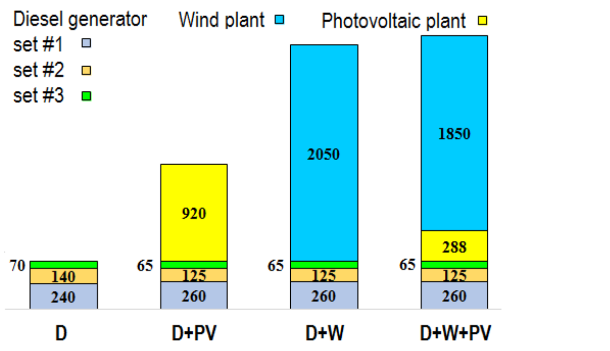

Fig. 5. The installed capacity of four considered configurations

Table 1 shows the cost of electricity (COE).

Table 1. *COE of considered configurations*

	Configurations			
	DP	D+PV plant	D+W plant	D+W+PV plant
COE, rub.	16.58	14.36	7.70	7.51

The main technical and economic parameters of the power plant operation under various configurations are presented in the radar diagram in Fig. 6

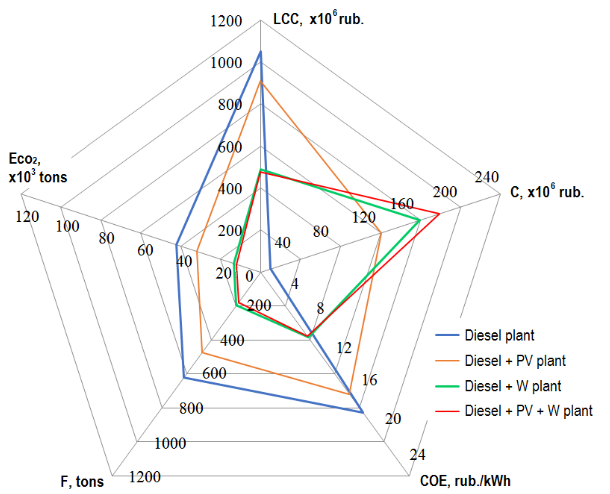

Fig. 6. The main technical and economic parameters of the system operation under considered configurations

The amount of generated electricity in the option #1 is 2533 kWh and it is equal to the demand for electricity. In variants 2-4, energy of dump appears – waste unused energy. In option #4, dump D is large and it is about 55%. However, despite this, the LCC is the smallest in the presence of such a dump value.

On the other hand, a large amount of dump energy can be used for water supplies. According to approximate estimates, the dump energy of about 3.1 million kWh/year is enough to heat 39,400 tons of water from a temperature of 5°C to 70°C. Based on empirical data on the average person's consumption of about 85 litres of hot water per day, this would be enough for hot water supply of more than 1300 people. The population of Nizhneyansk is about 250 people, therefore, dump energy can be used to heat the locality.

Fig. 7 shows the PV-W system behaviour with DPS for 24 hours in May.

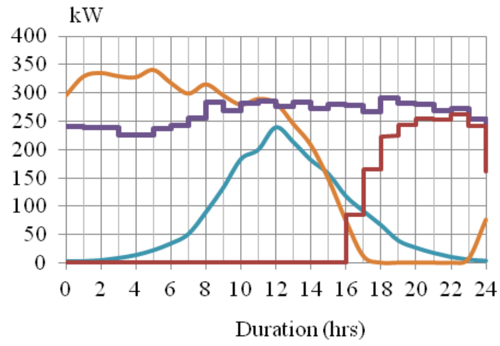

Fig. 7. Demonstration of the work of elements of the HC for 24 hours in May
Curves of generated/consumed power: blue – PV plant, green – W plant, Yellow – load, red – diesel plant

The study also found that the construction of a SPS for a given area is not justified up to a certain level of investment. Fig. 8 shows the dependence of the rate of change of LCC on the level of investment. As indicated in Figure 7, every 1 million rubles invested in W-plant reduce the LCC by approximately 19 million rubles.

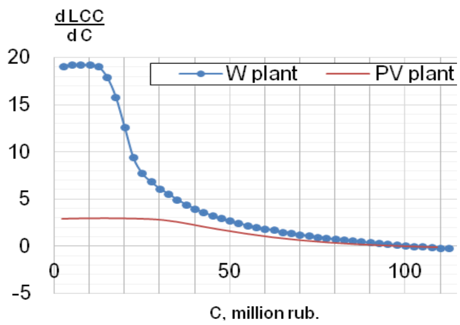

Fig. 8. The dependence of the rate of change of LCC on the level of investment TIC

With the increase in investment, the effect decreases, however, the construction of wind turbines is still preferable to the PV-panels up to a level of investment of about 50 million rubles, which corresponds to 25 wind turbines of the selected capacity. If the investment in the project is 50 million rubles or more, then in order to reduce LCC and COE, it is advisable to include PV-generation in the system. However, beyond the optimal investment point with the optimal configuration found above, LCC and COE begin to grow.

Conclusion

The widespread distribution of wind and solar energy in the Arctic, despite its great potential, is currently constrained by a number of factors. The main problem of using W plants in harsh climatic conditions is reliability – the equipment must be protected from the action of hurricane winds, sudden changes in temperature should be withstood and work should be carried out in conditions of extremely low temperatures. The use of PV plants is limited mainly to the geographical features of the region – with a sufficient level of insolation, on average, there are significant periods of the polar night during the year (up to half a year at the North Pole); However, it is worth noting that the potential of solar energy is still noticeably inferior to the wind one.

At the same time, most of the power supply facilities are located in areas with a milder climate. However, the development of technologies cannot be ignored and as a result of this an increasing number of facilities based on RES appear in the Arctic region.

The construction of the PV-W systems should be carried out based on the latest global trends in the design of such objects. The need for deep reconstruction of many power supply systems of remote low-power consumers in the Russian Arctic due to their low efficiency establishes excellent conditions for creating “from scratch” high-tech and efficient systems with intellectualisation elements.

In the work, the optimal structure and parameters of the D-PV-W plant for the settlement Nizhneyansk of the Yakutia region are determined. An estimation of the impact of an additional criterion for the total investment cost (TIC) limitation on a result of solving an optimisation problem is given. It is shown that the ratio of the proportions of the solar and wind power is not constant when the TIC changes and it changes when one of the renewable energy sources is excluded from the complex.

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