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OPTIMIZATION OF OPERATIONAL CONTROL OF AUTONOMOUS PHOTO-DIESEL POWER SUPPLY SYSTEM WITH DC BUS

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The relevance. *An increase in the contribution of renewable energy sources to the generation of the autonomous hybrid energy industry is important in order to reduce the environmental impact of diesel generator plants and decrease operating costs in the production of electrical energy in smart microgrids with distributed generation, including so-called «green» generation. This issue has the highest relevance for cell towers of mobile communication, rotational residential camps, meteorological stations and other remote consumers, the rated capacity of which is tens to hundreds of kW.*

Objective: *the development of computer models for optimizing the management of the operational staff and modes of an autonomous photo-diesel power supply system with a DC bus, so as to make it possible to minimize the operating time of a diesel generator plant by increasing the contribution of the photovoltaic plant at optimal technical and economic indicators. The use of a DC bus for the electricity integration from distributed energy sources is considered promising in reducing the number of hours of inefficient operation of a diesel generator plant, which will make it possible to save diesel fuel and extend the life expectancy of the diesel generator.*

Novelty. *This work expands the known options for modeling and optimizing the modes of a standalone hybrid DC power plant in terms of using an objective function with appropriate restrictions, adapting models of power equipment for the intended purposes of modeling, presenting the structure of a feasibility study based on commercially available characteristics of the elements of the power supply system.*

Methods. *The study entails the development of computer models of the intelligent control architecture of a standalone hybrid power plant including a photovoltaic plant, a diesel generator plant, an electric energy storage system, a remote consumer, as well as auxiliary converter devices. Modeling of control processes is implemented in the Stateflow library, as well as by using the language syntax of the Matlab high-level package, the capabilities of which are acceptable for the intended purposes.*

Results. *The analysis of the results shows that DC PV-diesel power supply systems can be cost-effective in all scenarios that include different types of batteries while for systems without power storage, DC distribution is often not cost-effective. The results will be of interest to specialists developing or operating standalone power supply systems and organizations planning to upgrade existing diesel power plants.*

Key words:
Solar energy, renewable energy, northern territories, photovoltaics, microgrid energy efficiency.

Introduction

The natural increase in demand for electricity, as well as the forecast depletion of fossil fuels, are causing active discussions among countries that are the leaders of the energy sector: the use of traditional hydrocarbon energy sources has led to a significant increase in the level of carbonization of the air. Today, it is the growth of the carbon footprint that is the main cause of global warming [1–3]. The concentration of carbon dioxide in the atmosphere has increased by about 40 % since the beginning of the industrial revolution [4]. Today it is feasible to improve the ecological situation by the reintroduction of renewable energy sources (RES). The contribution of RES has been increasing in recent years: by the end of 2019, 30 % of the world's electricity had been produced from RES (Fig. 1) [5]. Renewable energy sources such as solar, wind, hydropower, geothermal energy and biomass, as the name suggests, are easily renewable and relatively eco-friendly.

It has been proven that RES can be effectively and rationally used in microgrid solutions due to some technical and economic advantages. A microgrid is a localized energy system that involves distributed generation, including renewable energy sources, electric energy storage devices, loads, a power plant and energy consumption control system, communications, etc.

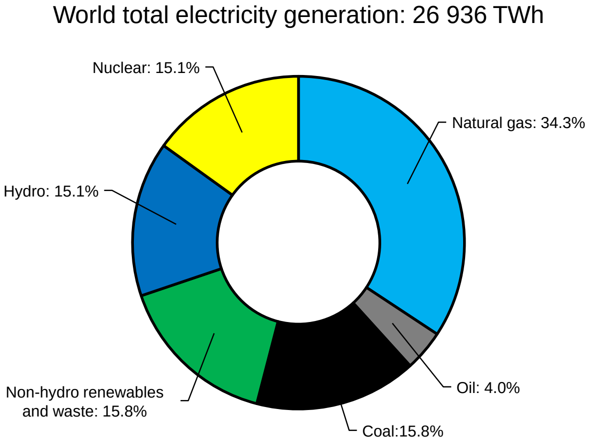

Fig. 1. *Energy balance of world electricity production, end of 2019 [5]*

Рис. 1. *Энергетический баланс мирового производства электроэнергии, конец 2019 г. [5]*

This is a small power system that can operate independently or in conjunction with centralized networks. The microgrid is capable of disconnecting from the centralized network and working autonomously in case of critical situations: lightning strikes, storms, planned and unplanned power outages, fallen trees, earthquakes, inter-

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actions with animals, earthworks, etc. It is RES technologies that are used as the most appropriate in terms of ensuring an autonomous mode of operation of microgrids that produce environmentally friendly electricity.

An urgent problem of today's research is to increase the contribution of RES, in particular photovoltaic (PV) systems, to the overall energy balance of the microgrid. Attention to photoenergy is explained by a steady trend towards improving its technical and economic characteristics. It is this trend that has shaped the relevance of this work: to optimize the microgrid with photo-diesel generation according to economic and environmental criteria.

Today, a common way to reduce the operating costs of diesel AC power supply systems is the integration of solar power plants with grid inverters, partially replacing the generation of diesel generator (DG) plants [6–8]. A disadvantage of such systems is the limitation of the generation capacity of the solar power plant relative to the power of the DG in terms of the condition of the stability of the solar power plant grid inverter in the local diesel network. It is possible to eliminate this disadvantage by building photodiesel power plants (PDPP) on direct current at optimal rated capacities of power equipment controlled by an intelligent control system. The choice of rational control algorithms is of decisive importance: it sets the direction of energy flows in the system components and determines the priority of functioning of each energy source [9].

The authors analyzed some of the literature. In particular, B.K. Das et al. [10] presented a genetic algorithm (GA) for the formation of costs of energy (COE), of CO_2 emissions and waste heat from a standalone hybrid power plant (SHPP). SHPP includes a PV system, an electric energy storage system (EES), a DG and gas turbines. In another study, I.R. Cristóbal-Monreal and R. Dufo-López [11] analyzed the impact of RES on the microgrid, which consists of an EES, DG and PV system, also using GA. Their innovation was to take into account the monthly ambient temperature, as well as the average solar radiation. W-W. Kim et al. [12] presented the optimal structure of the EES, taking into account the reliability and economy for the microgrid. Battery state of charge (SOC) was taken in the work as a parameter of the influence of the entire EES on the reliability of the power system. P. Cicilio et al. [13] presented a set of tools for microgrid performance design and planning, as well as the optimization of system size for power generation based on statistical load estimates. B. Li et al. [14] proposed a method for energy flow control and sizing for an autonomous system that includes PV, fuel cells (FC), and EES. The goal of the work was achieved using linear integer linear programming and constraint-based GA. B. Zhao et al. [15] proposed a method for determining the size of important components of an autonomous system, such as a solar power plant, a wind power plant (WPP), an EES, and a DG. The multi-objective function took into account the following key performance indicators: greenhouse gas emissions, construction costs, and renewable energy production.

Thus, the correct energy control strategy, the optimal value of the rated capacity of energy sources can increase the stability of the energy system, ensure the reliability of power supply, minimize electricity costs and increase the contribution of renewable energy. Depending on the system configuration and optimization goals, different energy management strategies are implemented based on different technical and economic criteria. These strategies can vary in complexity, requiring the use of different optimization algorithms [16].

Application options of PV DC power supply systems in the Russian Federation

In Russia, autonomous generation is a practical option for remote consumers to access to electricity. Autonomous power supply systems are the most widely used to provide electrical energy to the following groups of consumers: individual consumers of small rated capacity from units to tens of kW: cottages and country houses, weather stations, cell towers, field facilities and expeditions, farms, border, radar and navigation posts. This also concerns domestic power consumer groups of rated capacity from tens to hundreds of kW: individual large residential buildings and districts, various social facilities, villages, and low-rise settlements.

The objective, i. e. saving on maintenance, construction of power lines, roads and fuel delivery services, has long been technically and economically justified for such systems running on diesel generator plants. However, at the current exchange rates, the cost of energy generated from small-scale generation sources operating on fossil fuels is at least 0,40–0,50 $ per kWh. For this reason, increasing energy efficiency and the use of renewable energy are becoming extremely attractive. The scale of renewable energy use in Russia is still lagging behind that in Europe or Asia, but the trend towards expansion is noticeable. According to [17], more than 50 billion rubles is spent annually from the federal budget to subsidize electricity tariffs in remote regions. Taking into account the goals of the Russian energy strategy until 2035, it is necessary to create premises for an increase in the share of renewable energy: to achieve up to 3,7 % of the share of RES in the total volume of commissioned power plants, up to 2,2 % in the production of electricity from RES, and subsequently, the replacement of local diesel generation. Consideration of DC systems may contribute to the achievement of these indicators.

DC photo-diesel power plants can be used for the consumer groups described above. The experience of Alaska, Norway, and the Arctic part of Canada proves the cost-effectiveness of such solutions [18–20]. According to the authors, the implementation of such projects will significantly reduce the fuel delivery expenses of the budget. To ensure high reliability of the supply to autonomous consumers, the system contains a guaranteed power source: a diesel or gasoline generator. The authors propose a block diagram for constructing a DC photo-diesel power plant (DC PDPP), which is advisable to use for low-power power supply systems; it is shown in Fig. 2. In this design of the PDPP with a DC bus, the sources are connected through their own converters to the DC bus. The EES is connected to the same bus through a bi-directional DC/DC converter. The alternating current bus (AC bus) is used to connect the load to it. If there is a sufficient energy reserve in the EES, the load is powered by the PV plant through an autonomous voltage inverter. When the residual capacity of the EES drops below the allowable limit (the SOC indicator is monitored), the control system generates a control signal to turn on the generator, which provides electricity to consumers, and the EES switches to the charge mode.

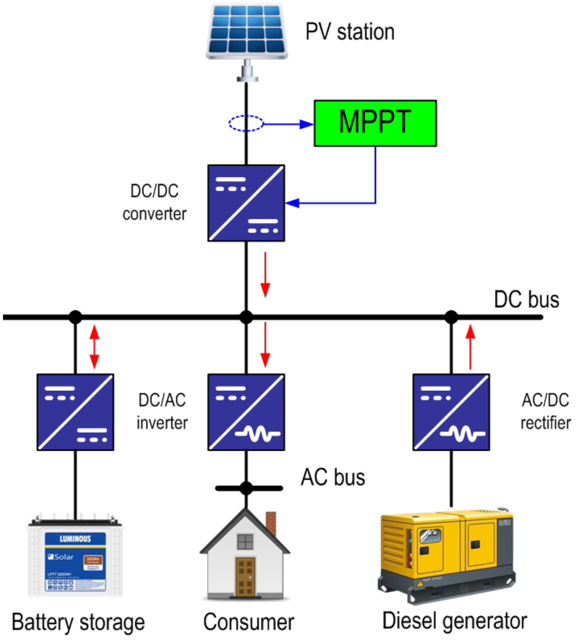

Fig. 2. *Scheme of a photodiesel power supply system of small capacity*

Рис. 2. *Схема системы питания фотодизельной системы малой мощности*

The authors propose analyzing and suggesting an upgrade of such a microgrid for a non-industrial consumer, the village of Kmovaara, the Republic of Karelia, Russia (63°39' N, 31°30' E). The consumer consists of low-rise buildings, and the village is supplied with electricity around the clock. A feature of this consumer is that the existing diesel-electric plant consists of four DGs with a total capacity of 138 kW. At the same time, only one DG [21] with a rated capacity of 32 kW is in constant operation while the rest perform the function of a reserve. It is not difficult to conclude that all the unused DGs increase the rated capacity of the DPP, which leads to a significant decrease in the rated capacity utilization factor and an increase in the cost of the equipment.

Methodology for optimizing DC PDPP in Matlab

In this article, the authors use the regular integer linear programming solver of the Matlab software package, intlinprog. The official website of MathWorks provides help on this function [22]. The unique features of the solver are the simplicity of the call syntax, relatively low computational time. This meets all the necessary requirements for solving the problem of optimizing the composition of the DC PDPP. Below are the input parameters of the solver in general form:

$$\min_x f^T x \text{ subject to} \begin{cases} x(\mathrm{int}con)\ are\ \mathrm{int}egers \\ A\cdot x \le b \\ Aeq\cdot x = beq \\ lb \le x \le ub \end{cases} \quad (1)$$

The intlinprog function (1) includes a system of constraints that contains variables that must be declared before the solver is called: *x* is the vector of the variables to be solved for, i. e. the solver is able to optimize the function in regard to several variables; *intcon* is a vector that determines which of the variables to solve for must be integers. This is followed by various kinds of restrictions: since the required variables are a vector, the parameters *A* and *Aeq* are matrices, because for each of the unknowns there may be more than one restriction; *lb*, *ub* are the lower and upper limits for the vector of the unknown variables. The main condition for the operation of the program code is the fulfillment of the power balance.

The optimization process is carried out for each average day of each season, i. e. 4 times. It is first necessary to calculate the energy generated by the photovoltaic module in each case. This process will be presented below. Further below is a code fragment of the program that calls the solver:

```
lb = [0,0];
ub = [N_pv,W_dg];
x_all = zeros(1,2);
fval_all = zeros(1,1);
for i = 1:4
 f_on_i_step=f(i,[1,2]);
 A_on_i_step=Aeq(i,[1,2]);
 b_on_i_step=beq(i);
[x,fval]=intlinprog(f_on_i_step,intcon,[],[]
,A_on_i_step,b_on_i_step,lb,ub,options);
 x_all(i,[1,2]) = x;
 fval_all(i) = fval;
end
```

The intlinprog function is used to optimize the objective function of the total cost of building and operating the system. This approach makes it possible to distribute the generated power among the components of the power system as a basis for maximizing the technical and economic advantages of DC technology. Below there is the objective minimization function (2):

$$f(x) = n_1 C_{spec}^{PV} W_{PV} + n_2 C_{spec}^{DG} W_{DG} + n_3 C_{spec}^{EES} W_{EES}, \quad (2)$$

where W_{PV}, W_{DG}, *and* W_{EES} are the actual annual electricity generation by each generating source, as well as the amount of energy stored in the EES; C_{spec}^{PV}, C_{spec}^{DG}, C_{spec}^{EES} are the specific costs for the generation of 1 kWh by each generating source; n_1, n_2, n_3 are the vectors of required variables: the optimal number of photovoltaic modules, part of the energy taken from the DG, the optimal number of EES monoblocks, respectively. The system of restrictions for the objective function (3) is presented below:

$$\begin{cases} n_1, n_2, n_3 \ge 0; \\ n_1 \le n_{\max}^{PV}; \\ n_2 \le W_{DG}; \\ n_1 W_{PV} + n_2 W_{DG} + n_3 W_{EES} = W_{load}. \end{cases} \quad (3)$$

As initial data, we use the nominal data of the equipment, insolation values in the area of the power supply facility, ambient temperature, the calculated data on the orientation of the photovoltaic module in space, as well as the proposed options for the location of the photovoltaic power station. Based on these data, the actual annual electricity generation from one photovoltaic module is determined. Next, the unit costs per unit of generated electricity are calculated for the resulting annual output. By minimizing the objective cost function (2), we determine the optimal number of reference photovoltaic modules for each season, the expected use of energy from the DG, and the number of EES monoblocks.

```
W_sum_pv_y = 0;
for i = 1:4
 W_sum_pv_s = 0;
 for j = 1:24
 W_pv = KPD_pv * S_pv * Insol(i,j);
 W_sum_pv_s = W_sum_pv_s + W_pv;
 end
 if W_sum_pv_s > P_nom_pv / 1000
 W_sum_pv_s = P_nom_pv / 1000;
 end
 W_sum_pv_s = W_sum_pv_s * 90;
 W_sum_pv_y = W_sum_pv_y + W_sum_pv_s;
end
```

In the presented fragment of the program code, the calculation is carried out according to the principle of summing the energy generated by each PV module for each hour of the average day of each season. Two nested for loops are declared. They change the season and the average day, respectively. Throughout the program code, the variable *i* means the number of the season (the first season is summer), the variable *j* means the current hour. The code provides for the limitation of electricity generation by one photovoltaic module, based on its maximum (nominal) power. In this regard, every hour we check whether the generated hourly energy exceeds the limit set in the source data (the variable *W_sum_pv_s*). If the limit is not exceeded, then the hourly energy is calculated according to a linear functional dependence; otherwise, it is limited by the maximum (nominal) power. Next, the volume of electricity for each season is calculated by evaluating daily – not hourly – energy by 90 days.

After determining the actual annual energy, it is necessary to calculate its cost and the profitability of using certain sources compared to others. The authors conclude that today the dependences of the cost of rated capacity units of PV plant equipment on their nominal rated capacities are close to linear; therefore, the optimization results are flexible and the recommended number of reference elements can be replaced by a proportional number of elements with other rated capacities. However, this statement is hardly applicable to EES; therefore, it is necessary to provide for a more accurate, hourly calculation of the energy deficit/surplus and determine the number of references EES monoblocks recommended for installation. For a PV electric system, the costs are calculated approximately, taking into account only the main components. The yearly maintenance costs of a photovoltaic module are determined and the resulting annual costs (4) are divided by each kWh of electricity generated per season.

$$C_{spec}^{PV} = \frac{Price^{PV}}{LT_{PV} \cdot W_{sum\_pv\_y}}, \qquad (4)$$

where $Price^{PV}$ is the price of one photovoltaic module; LT_{PV} is the nominal service life. Accounting for the cost of operating a DG (5) consists of two components: the cost of the apparatus and the cost of fuel. Fuel consumption is given at the average load factor (Load_factor2) of the average day of each season:

$$C_{spec}^{DG} = \frac{Fuel\_cost}{Load\_factor2 \cdot P_{nom\_DG}} + \\ + \frac{Price^{DG}}{Load\_factor2 \cdot P_{nom\_DG} \cdot 8760 \cdot LT_{DG}}, \qquad (5)$$

where *Fuel_cost* is the cost of fuel; $Price^{DG}$ is the price of a DG; LT_{DG} is its service life.

The main criterion of cost-effectiveness is the cost of 1 kWh of electricity (6). This criterion is determined based on the following expression:

$$COE = \frac{\frac{1}{T} \cdot K + C}{P_{rated}}, \qquad (6)$$

where P_{rated} is the rated capacity of the power supply facility (kW); K is the total investment in the power plant, $; T is the economic service life of the equipment, years; C is the total annual operating costs, $.

By this time, the number of photovoltaic modules has been determined, as well as the predicted use of DG power. Since weather conditions are predictable only statistically and pre-calculated RES capacities are not always available, it is impossible to specify the exact number of batteries necessary and sufficient for the uninterrupted power supply to the load. To guarantee the supply to the load during periods when it is impossible to generate sufficient energy from RES, for example, in winter, or in case of emergency situations, the following method is proposed for determining the number of batteries in the EES.

```
Nb=zeros(1,4);
Cost_b1=zeros(1,4);
Cost_b2=zeros(1,4);
for i = 1:4
 Wb=0;
 for j = 1:24
 if Del(i,j) < 0
 Wb = Wb + Del(i,j);
 end
 end
 Nb(i) = round(-Wb / P_b1);
 Cost_b1(i)=round(Nb(i) * Price_b1 / LT_b1 / 365);
 Cost_b2(i)=round(Nb(i) * Price_b2 / LT_b2 / 365);
end
```

The unbalance matrix *Del*(*i*,*j*) was preliminarily formed: the energy deficit or surplus was determined hourly for each average day of the season. Next, the available total hourly energy of all photovoltaic modules is determined (the process is similar to the annual output of photovoltaic modules that were presented above), then the energy required by the load at a given hour is subtracted from the obtained value. It is necessary to exclude any energy surplus from the resulting matrix and analyze only scarce hours. After the minimization of the cost function, the estimated use of DG power will be indicated for each average day; therefore, it is necessary to mitigate the most scarce hours with this energy. When all the estimated energy of the DG has been used, the remaining total energy deficit for the day is calculated. This amount of energy should be covered by EES monoblocks.

The authors propose considering two types of storage technologies that have become frequently used in solar power plants: lithium iron phosphate batteries ($LiFePO_4$, LFP) and armored subclass of batteries (OPzS). These technologies meet the requirements of PV power plants: high cycling (number of sustained charge/discharge cycles), low self-discharge, a wide operating temperature range, minimal maintenance, and the acceptability of deep discharge (up to 80 %). Such technologies have a significant resource for cyclic operation in summer, as well as a good potential for a predominantly buffer operation in winter. The authors compare these technologies and give their recommendations for their use as part of DC PDPP.

Results and discussion

Case A. The technical indicators of the Kimovaara power supply system without upgrading to DC PDPP are shown in Fig. 3. An autonomous power supply system based on a DG operates at extremely high consumption of diesel fuel per 1 kWh, a significant level of anthropogenic impact on the environment, as well as an unsatisfactory net capacity factor (NCF) of the DG. The generator is operated in such modes in accordance with the energy consumption schedule, with a life expectancy of more than 3000 hours. A detailed analysis of the system is presented below.

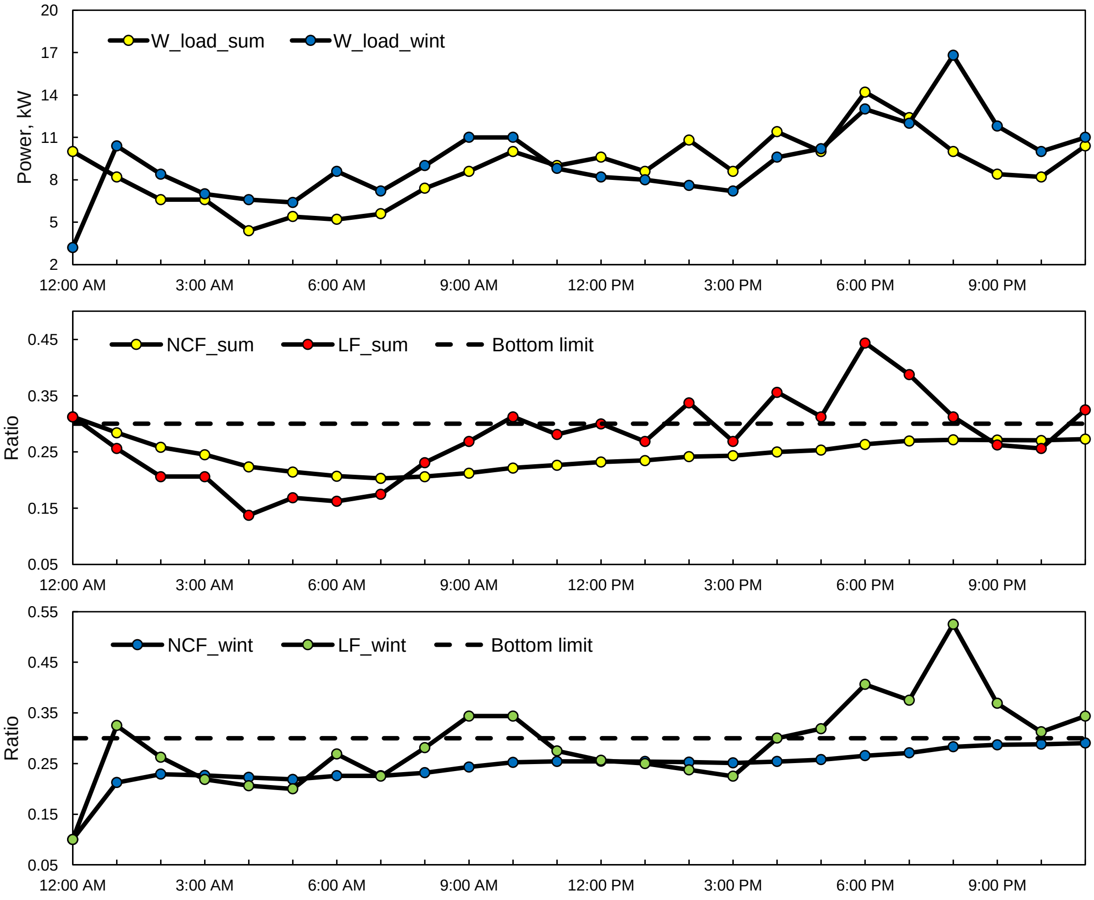

Fig. 3. *Indicators of the Kimovaara power supply system for summer and winter days (Matlab)*

Рис. 3. *Показатели системы электроснабжения п. Кимоваара для летних и зимних суток (Matlab)*

The dependence of the inefficient use of the electricity generated from the DG, as well as the indicator of electricity demand for a specific hour (W_load_sum, W_load_wint), are shown on the time scale of the average summer and winter days (NCF). The DG in operation does not provide the desired load in the range between 30 (bottom limit) and 85 % of the rated load (the LF indicator). Most of the time, both seasons are characterized by low consumption, which significantly increases the fuel consumption rate, which averages 0,42 kg/kWh. An additional negative effect is manifested in the form of a carbonization caused by the accumulation of unburned fuel fractions in the cylinders, which, in its turn, adversely affects the engine life of the diesel engine (7).

Table 1. *Emission costs and emission factors*

Таблица 1. *Стоимость и наименование выбросов*

Emission factor Наименование выброса	Costs per 1-ton emissions, $/t Стоимость выброса компонента за 1 т, $/t
CO_2	1,45
NO_x	1,87
SO_2	0,61

Table 1 shows the cost of emissions of pollutants in accordance with Russian legislation, where the Kimovaara DG produces 2,35 tons of emissions of air pollutants per year.

This number is determined based on the following expression:

$$W_{e_i} = \frac{g_{e_i} G_m}{1000}, \qquad (7)$$

$g_{в_i}$ is the specific mass emission of the *i*-th substance per 1 kg of diesel fuel; G_m is the DG fuel consumption per year.

The graphs in Fig. 3 do not show significant fluctuations between summer and winter consumption. Most of the energy is consumed by 120 local residents for electric heating. In summer, there is a clear difference between morning and evening with insignificant fluctuation. The peak of energy production is 13 kWh (6:00 PM – 7:00 PM) in summer and 18 kWh (8:00 PM – 9:00 PM) in winter. The base load on the system is 9 kW with 90 % accuracy.

Table 2. *Parameters of the diesel generator AKSA AJD 45 [21]*
Таблица 2. *Параметры дизель-генератора AKSA AJD 45 [21]*

AKSA AJD 45	Parameter Параметр	Value Значение
	Maximum power Максимальная мощность	32 kW/кВт
	Output voltage Выходное напряжение	380/400 V (AC)/В (AC)
	Fuel cons. prime with 75 % load Расход топлива при 75 % нагрузке	7,5 lt/hr/л/ч
	Price/Цена	11 700 $
	Life cycle/Срок службы	10 years/лет

The technical parameters of DG of interest are collated and presented in Table 2. The operation of one DG with a capital cost of about $18,000 also entails maintenance costs of about $2,000 per year, where most of the operating costs are the cost of diesel fuel and its delivery, which in its turn costs $21,980 per year. These economic indicators formed a high cost of electricity generated for the autonomous consumer, 0,48 $/kWh. The cost of fuel, which accounts for the largest share of total costs, can be reduced with the use of a DC PDPP. Partially, this is confirmed by the fact that the operating costs of the DG are a function of the power demand, which is clearly seen in dependence (5), because there is no other generating source that could satisfy the load requirements.

The authors emphasize that the configuration of an autonomous DG is unjustified, primarily from an environmental and economic point of view, due to its high fuel consumption, any hikes in the cost of which significantly affects the total costs. However, due to the results obtained from other studies [23, 24], in the conditions of continuous operation in the specified DG modes, it may seem worth considering alternative designs of inverter-type DGs in AC systems.

Case B. The results of the system analysis using the intlinprog solver made it possible to develop various energy management strategies for the classic seasons in terms of power consumption: summer and winter. These strategies are also applicable to the transitional seasons of the year (spring, autumn), in which pronounced fluctuations in insolation, ambient temperature, and load are observed. Of course, for the transitional seasons, alternative regimes should be provided for the priority of the operation of generating sources. Based on the solution of the program, it follows that the most economically justified season of «delay» for the design of a DC PDPP is summer. However, the use of only the PV plant–EES combination as the cheapest and most efficient is not always possible, as there are a number of limitations, for example, the inability of the municipality of the power supply facility to allocate several hundred square meters, and sometimes even kilometers, for photovoltaic modules. The code of the program takes into account this nuance, which limits the stationing area of photovoltaic modules in current case study to 210 m^2.

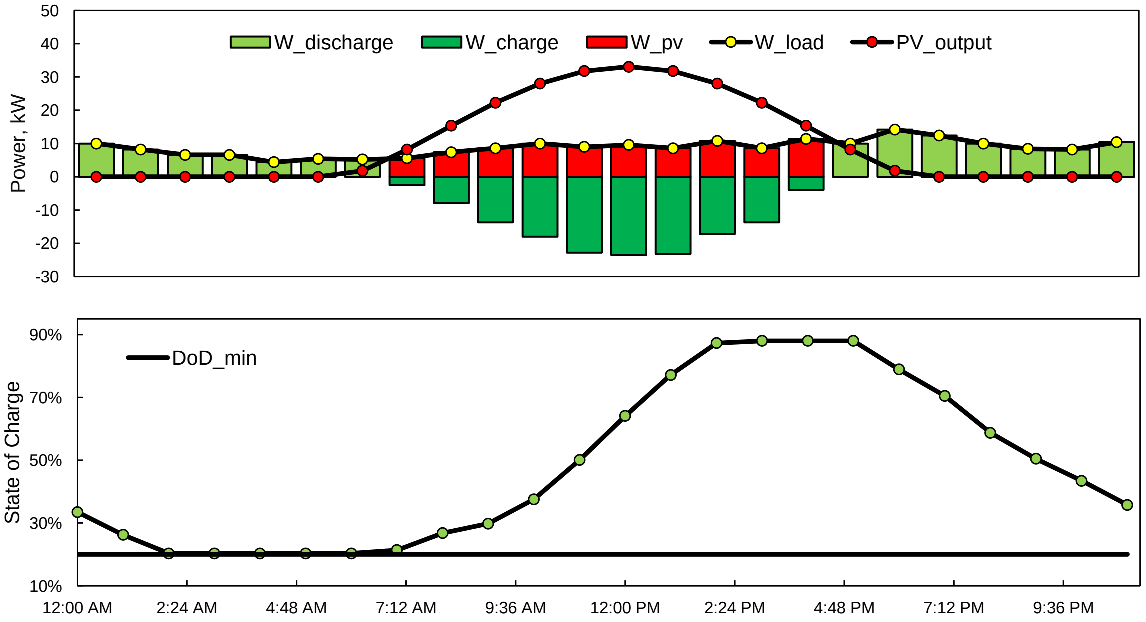

Fig. 4. *Indicators of a DC PV-diesel power supply system for a summer day in Matlab*
Рис. 4. *Показатели фотодизельной системы электроснабжения постоянного тока для летних суток в Matlab*

Technical indicators for the average summer day of the power supply system after upgrading to a PDPP on direct current are shown in Fig. 4. The PV energy varies depending on the amount of incoming solar radiation (*W_pv*). In the absence of PV energy, the exchange energy of the EES discharge follows the change in the level of power consumption (*W_discharge*). The voltage on the DC bus remains constant despite the PV plant changes during the period from 07:00 AM to 4:00 PM, the PV plant generates more power than it is required by the load. To determine the excess in the program code, the standard Matlab function *trapz* (*x*,*y*) was used, which returns in numerical form the area of the trapezoid between the *PV_output* and *W_load* functions. In doing so, based on results for the summer season, the Matlab intlinprog solver offers 165 photovoltaic modules as the minimum in terms of solving the objective cost function (2). The Matlab *trapz* (*x*,*y*) function has determined 147 kWh of electrical energy for 10 hours of excess generation for the accumulation in the EES. The number of hours of autonomous power supply from the EES is determined by the requirements of the consumer, and in most cases is between 6 and 24 hours. Fig. 4 shows that during this time the SOC indicator increases, remaining within the operating limits of the optimal operation of the cyclic mode, from 20 to 95 %.

It should be noted that the proposed SOC change graph in Fig. 4 is an iteratively tested result of supplying during three successive average summer days, starting with a fully charged EES. Thus, the capacity of the EES is enough to ensure the same operation mode for the next summer day, even with an initial charge level of 47,5 %, provided that the outcome is unfavorable in terms of the level of solar radiation, as well as the ambient temperature. The NCF indicator was calculated taking into account the joint work of the generation of the PV plant and the charge/discharge of the EES. The NCF varies from 16 to 24 % over time, taking into account the correction for the efficiency of the charge/discharge of the EES, as well as the efficiency of the DC/DC converter devices. The technical indicators of the photovoltaic module are presented in Table 3.

Table 3. *Parameters of the monocrystalline solar module SilaSolar 200W*

Таблица 3. *Параметры монокристаллического солнечного модуля SilaSolar 200W*

SilaSolar 200W	Parameter Параметр	Value Значение
	Maximum power	
	Максимальная мощность	200 W/Вт
	Optimum operating voltage	
	Оптимальное рабочее напряжение	36,7 V/B
	Efficiency of solar module	
	КПД солнечного модуля	17,2 %
	Temperature range	
	Температурный диапазон	–40…+85 ºC
	Solar module area/Площадь модуля	1,28 m^2/$м^2$
	Degradation factor per year	
	Фактор деградации за год	0,6 %
	Price/Цена	120 $
	Life cycle/Срок службы	30 years/лет

The constant and noticeable reduction in prices for renewable energy generating equipment has led to the fact that batteries are becoming the most expensive element of the energy complex. In addition, batteries, with their relatively short lifespan, are expendable in practice. It is necessary to pay special attention to the choice of batteries for the project, as well as their subsequent correct operation. Typically, in the documentation for batteries, manufacturers indicate the service life in buffer mode and under ideal operating conditions (temperature 20 °C, rare shallow discharges, constant optimal charge). Even in a system with a backup, it is difficult to provide such conditions; in an autonomous system, batteries operate in the most difficult cyclic mode, charge/discharge.

Table 4 shows the main technical and economic indicators of two types of batteries: LFP and OPzS, a comparison of which should help to make quality recommendations for EES use for various consumer groups. A wide range of batteries on the market allows choosing the right ones for a particular consumer, taking into account their territorial, temperature, and regime features.

Table 4. *Comparison of batteries for DC PV-diesel power supply system [25]*

Таблица 4. *Сравнение аккумуляторов для фотодизельной системы электроснабжения постоянного тока [25]*

Parameter/Параметр	$LiFePO_4$	OPzS
Nominal voltage		
Номинальное напряжение	3,22 V/B	2,0 V/B
Usable capacity/Рабочая ёмкость	90 %	80 %
Efficiency of battery/КПД батареи	92 %	88 %
Operating temperature range		
Диапазон рабочих температур	0…+45 °C	–20…+50 °C
Cost/Стоимость	65	34
Lifespan (stand-alone)		
Срок службы (автономный)	$/kWh/кВт·ч	$/kWh/кВт·ч
Lifespan (floating)	20 years/лет	12 years/лет
Срок службы (буферный)	30 years/лет	17 years/лет
Number of cycles (DoD=80 %)	5000	1500
Количество циклов (DoD=80 %)		
Environmental friendliness	High	Medium
Экологичность технологии	Высокая	Средняя
Cost of operating and maintenance	Not required	18
Стоимость обслуживания и ремонта	Не требуется	$/year/$/год

The test results show that the energy management strategy to minimize the operation of the DG is working correctly. It should be concluded that all components of the system work correctly, namely, the load schedule is fully supplied with energy, the EES unit switches as it discharges/charges in accordance with the developed operation logic. Let us consider the case where during the hours of shortage of energy stored in the EES and the energy of the FES, the DG should be started (autumn). In such cases, the DG is operated in such a way as to generate a power deficit if the exchange energy of the PV and EES do not meet the load requirements.

According to the results shown in Fig. 5, electricity generation from the DG is inefficient: the DG plans to cover the load demand in the morning hours from 03:00 AM to 08:00 AM, where the average 6-hour NCF is 8 %, the DG load factor (CSF_dg) will be 21 % on average. From 08:00 AM to 11:00 PM, the DG is completely disabled due to generation from the PV plant-EES combination. During this time, the power generated by the PV can satisfy the load demand, while the excess electrical energy is used to charge the EES. The charge capacity of the EES will be enough to ensure the same operation mode for the next autumn day, even with an initial charge level of 35,7 %, provided that the outcome is unfavorable in terms of the level of solar radiation, as well as the ambient temperature. Taking into account the obtained data, it is recommended that the option of installing two diesel generator units with a lower nominal value be considered. These will operate simultaneously during the seasons with maximum load consumption (winter) while using the diesel generator resource more efficiently. To model the mode of PDPP operation on a winter day, the input data were also changed. The performance of the PDPP system at a low level of PV power generation is shown in Fig. 6. The PV power generation is less than the required load from 09:00 AM to 03:00 PM. Based on the input parameters and operating conditions of the control logic of the central controller, the system responds to the implementation of the mode of using the EES to equalize the load curves of the DG, participating in peak coverage. Until 09:00 AM, the DG provides the load in full. The EES is in the state of running in the discharge mode at times of the peak voltage drop on the DC bus.

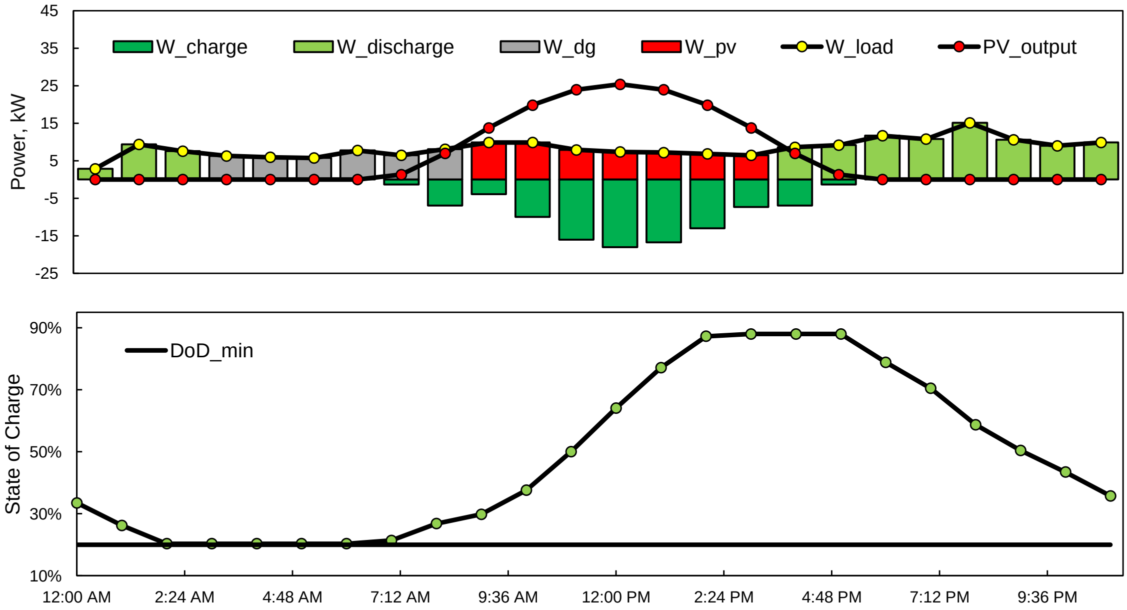

***Fig. 5.** Indicators of a DC PV-diesel power supply system for an autumn day in Matlab*

***Рис. 5.** Показатели фотодизельной системы электроснабжения постоянного тока для осенних суток в Matlab*

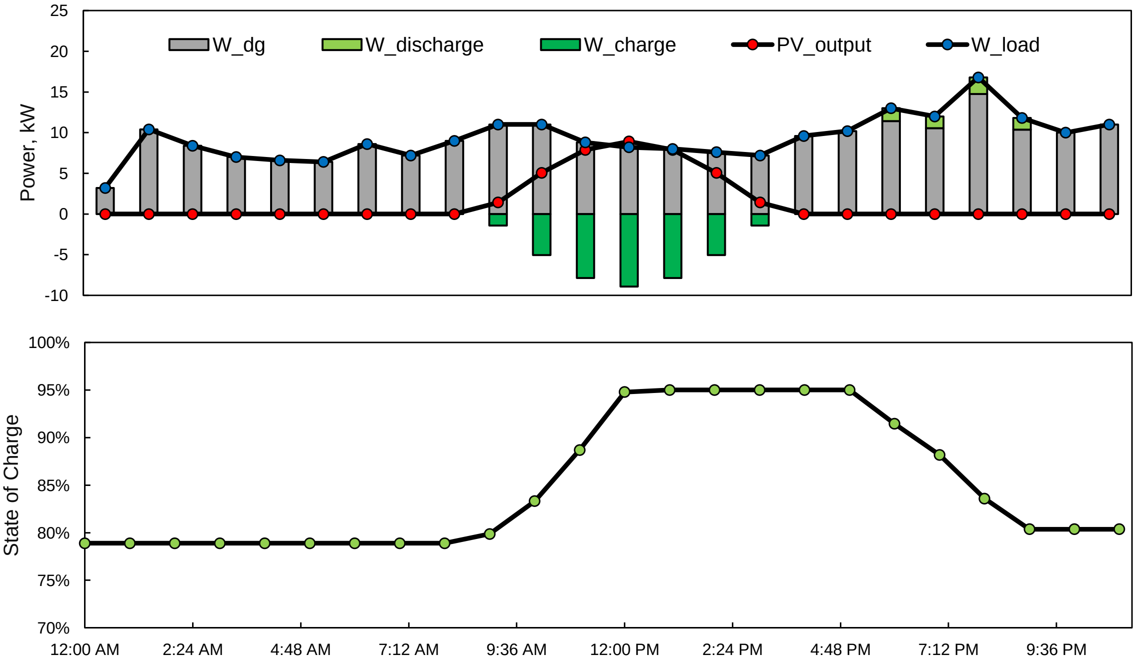

***Fig. 6.** Indicators of a DC PV-diesel power supply system for a winter day in Matlab*

***Рис. 6.** Показатели фотодизельной системы электроснабжения постоянного тока для зимних суток в Matlab*

Fig. 6 shows the EES and DG performance during their joint operation. After the morning and evening peaks, it can be seen that the EES-PV plant combination receives sufficient charging power to supply the next day (parameter SOC). However, the current command generated by the power controller performs a fast recuperation of the load power without optimizing the optimal load of the DG. This condition can be achieved by discharging the battery by supplying a proportional current according to the characteristics of the DC/DC converter. In this case, it is necessary to consider a rectifier DG with a controlled converter link.

The graphs in Fig. 6 show that the developed exchange energy management and control system is acceptably operable in the absence of sufficient electricity generation from renewable sources. A smooth transition between the charge and discharge states is also observed under different input conditions.

Conclusions

In this research paper, the authors explored the cost, technical and environmental benefits that can be gained from upgrading a standalone power system to a DC PV-diesel power supply system. The initial data of the analysis are the latitude of the area, the atmospheric transparency index, the albedo of the earth's surface, the number of the day of the year, the azimuthal and vertical angles of installation of photovoltaic panels, the average daily air temperature, the technical characteristics of the PV plant, as well as the characteristics of the EES and DG. The studies were carried out using the Matlab software package. Original code for optimizing the composition of a DC PV-diesel power supply system was developed.

The simulation results showed that the program code makes it possible to justify the choice of the optimal operating mode of the power plant, the required capacity of storage devices, rated capacity and rated voltage of the photovoltaic panels. It also helps determine effective algorithms for managing the energy complex. Various combinations of accumulators as part of a DC PDPP are considered. Thus, a decrease in the level of fuel consumption entails a decrease in the economically justified tariff for electricity from 0,48 to 0,43 $/kWh with LFP batteries, and to 0,39 $/kWh with OPzS batteries considering step-up converters. The level of carbonization of air from a DG is reduced from 2,35 to 1,9 tons per year. However, the practical implementation of a certain type of battery requires further comprehensive research on a wide range of issues, in particular, the development of hybrid intelligent systems, for example, for cell towers, which differ significantly in terms of energy consumption. Of note that the difference in the frequency of maintenance of this kind of power supply systems, where more cycles is beneficial (LFP batteries), increases the cost of the system and worsens the economic performance indicators.

Based on the foregoing, it can be concluded that the DC PDPP architecture is more economical and less hazardous to the environment, compared to other options, such as AC DGs. It is essential to highlight a piece of information that economical calculations did not include accompanying components of PV: fastening structures, connecting cables, installation and commissioning. For the EES was not included racks, battery management system etc. However, the results clearly demonstrate that environmental friendliness, technical and economic efficiency are achievable through the use of renewable energy. Although it is worth noting that the use of DGs only makes practical sense as the most economical solution at the initial stage of investment in the short term. In addition, a feature of these results is the transferability of the developed code to other packages for embedding, for example, MS Excel, Python, etc. Future research by the authors may also be combined and compared with the results of this article. Thus, in order to study the technical, economic and environmental consequences of the integration of other renewable energy sources into autonomous systems, it is deemed promising to conduct studies, according to the proposed methodology, of autonomous power supply systems from wind farm stations, fuel cells, and other energy sources.

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ОПТИМИЗАЦИЯ ОПЕРАТИВНОГО УПРАВЛЕНИЯ АВТОНОМНОЙ ФОТО-ДИЗЕЛЬНОЙ СИСТЕМОЙ ЭЛЕКТРОСНАБЖЕНИЯ С ШИНОЙ ПОСТОЯННОГО ТОКА

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Актуальность. *Увеличение вклада возобновляемых энергоносителей в генерацию автономного гибридного энергетического комплекса актуально для снижения воздействия на окружающую среду дизель-генераторных установок и уменьшения эксплуатационных издержек при производстве электрической энергии в интеллектуальных микросетях с распределённой, в том числе «зелёной», генерацией. Наиболее актуален этот вопрос для сотовых вышек мобильной связи, вахтовых жилых посёлков, метеорологических станций и других децентрализованных потребителей, установленная мощность которых составляет десятки–сотни кВт.*

Цель: *разработка компьютерных моделей оптимизации управления оперативным составом и режимами автономной фото-дизельной системы электроснабжения с шиной постоянного тока, позволяющих минимизировать время работы дизель-генераторной установки за счёт увеличения вклада фотоэлектрической станции при оптимальных технико-экономических показателях. Использование шины постоянного тока для интеграции электроэнергии от распределённых энергоисточников рассматривается как перспективный вариант уменьшения количества часов неэффективной работы дизель-генераторной установки, что позволит существенно экономить дизельное топливо и продлить моторесурс дизель-генератора.*

Новизна. *Данная работа расширяет известные варианты моделирования и оптимизации режимов автономной гибридной энергетической установки на постоянном токе в плане использования критериальной целевой функции с соответствующими ограничениями, адаптацией моделей энергетического оборудования для поставленных целей моделирования, представлением структуры технико-экономического анализа, основанной на коммерчески доступных характеристиках элементов системы электроснабжения.*

Методы. *Исследование предусматривает разработку компьютерных моделей интеллектуальной архитектуры управления автономного гибридного энергетического комплекса на базе фотоэлектрической станции, дизель-генераторной установки, системы накопления электрической энергии, децентрализованного потребителя, а также вспомогательных преобразовательных устройств. Моделирование процессов управления реализуется в библиотеке Stateflow, а также использованием синтаксиса языка пакета высокого уровня Matlab, возможности которого приемлемы для поставленных целей.*

Результаты. *Анализ результатов показывает, что фотодизельные системы электроснабжения на постоянном токе могут быть экономически эффективными во всех сценариях, которые включают в себя разные виды аккумуляторных батарей, тогда как для систем без аккумулирования электроэнергии распределение постоянного тока часто не является экономически эффективным. Результаты будут интересны специалистам, разрабатывающим или эксплуатирующим автономные системы электроснабжения, и организациям, планирующим модернизацию существующих дизель-электрических станций.*

Ключевые слова:
*Солнечная энергия, возобновляемая энергетика, северные территории,
фотоэлектричество, энергоэффективность, микросети.*

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