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Application of energy performance contracts for rural remote areas electrification

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Abstract

The article is devoted to the application of energy performance contracts for the electrification of rural remote areas. The research presents a universal methodology for determining the main parameters of an energy performance contract. This methodology includes four main parts. The *first* part has a description of the climatic parameters on the territory under consideration and their use in mathematical modeling of isolated photovoltaic system operating modes. The *second* part has the mathematical models of an isolated photovoltaic system with battery energy storage system and diesel power plant. The *third* part consist of relevant questions and features of battery energy storage system operation in isolated energy systems. The *fourth* part is a hierarchical model of an energy performance contract. The model has the main indicators required for the client and contractor. These parameters are contract duration, contractor fee, modified levelized cost of energy and optimal composition of isolated energy system equipment. An isolated energy system located on the territory of Siberia was considered. The optimization results have the following key indicators: photovoltaic system (80 kW) with battery energy storage system (240 kW·h) reduces diesel fuel consumption by 68%. The energy performance agreement duration is 5 years and the modified levelized cost of energy is 15.53 RUB/kW·h.

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Keywords: Renewable energy sources; Energy performance contract; Hierarchical bilevel model; Battery energy storage system; Isolated energy system; Rural remote areas

1. Introduction

The modern state of energy sector development is accompanied by a rapid increase in the capacity of environmentally friendly energy sources in both centralized and isolated energy systems. This growth is the result

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of well-developed alternative energy backing policy. This promotes to the large application of renewable energy sources such as large wind farms and photovoltaic systems, elements of distributed generation and domestic micro-generation located at the consumers. The contemporary backing policy of clean energy includes different ways for example green certificates, feed-in tariff and energy performance contracts. These support mechanisms have their own specific features and areas of application.

The feed-in tariff and green certificates have proven themselves well in centralized energy systems. By their nature, the feed-in tariff and green certificates can only work in conditions of centralized energy systems with a well-defined market and algorithms of interaction between the energy generator and companies. The use of these support mechanisms for isolated energy systems is not possible due to the legal features of the functioning of such energy systems.

Under such conditions, it becomes possible to use only energy performance contracts. An energy performance contract is a special form of agreement aimed at reducing exploitation expenses (usually annual) by using new more effective technologies. An energy performance contract is concluded betwixt the client and the energy performance company. By its specifics, an energy performance contract does not depend on the type of energy system under consideration (centralized or autonomous) and can be used for any facility.

1.1. Literature review

Projects implemented under energy performance contracts have high risks [1, p. 1136]. This leads to strict financial requirements that banks or other credit organizations impose on such projects. An analysis of economic risks in the implementation of projects under energy service contracting is presented in [2]. When modeling risks, the Monte Carlo method is used. Office buildings, hotels, hospitals and supermarkets are considered as objects of study. The authors note that potential risks should not be considered separately, but together, taking into account the probability of their occurrence. The paper [3] is devoted to the investigation of markets of energy performance contracts in developing countries. The main barriers expressed in legal, financial and technical aspects are presented in detail. In addition, the authors emphasize that many developed countries with strong economies do not have a well-developed market for energy service contracts. Also, in some European countries there is a well-established policy for small and medium-sized energy service companies, while for large ones it is less developed. The authors note the important role of the state in the improvement of the system of energy performance agreements.

An analysis of the main mechanisms that contribute to the development of energy facilities is presented in [4, p. 185]. Due to the authors, the creation of new generating facilities, especially renewable energy sources, requires a detailed examination of the project. This provides a more accurate determination of the main indicators of the energy service contract, such as annual payments and the duration of the contract. The study [5] focuses on the main issues related to the perfection of energy performance contracts in various municipalities. The researchers note that there is a complex bureaucratic structure of relationships between municipalities, regional system operators and energy service companies, and this structure makes some difficulties to the expansion of the sector of energy performance contracts. Article [6] is devoted to the integration of competitive bidding when closing energy performance agreement. Energy service companies offer their technical solutions, which are evaluated by customers. The process of evaluating technical projects is carried out according to various criteria that are set by the customer. Each criterion has a certain number of points. The energy service company with the most points wins the auction and concludes an energy service contract with the customer. Ref. [7] describes in detail the market for energy service contracts in Norway. The authors note that an important role is played by municipalities acting as customers. For example, in Norway, municipalities often use financial mechanisms and programs designed specifically for the implementation of projects under energy service contracts. One of these mechanisms is financing projects through special banks that provide preferential terms for such projects. Article [8] presents an analysis of the United Kingdom energy performance sector. The paper notes the increased role of intermediaries in concluding energy performance contracts. In particular, such players can reduce transaction costs, as well as increase the chance of concluding energy performance agreements in the communal sector. Hence, the role of intermediaries will increase every year, and the market for energy performance contracts will expand, thereby creating favorable conditions for the application of new business models. The increase in standards and requirements for energy service companies will lead to a reduction in technical risks in the implementation of projects. The policy of transparency and awareness of credit institutions will increase the level of trust in energy performance agreement [9]. The paper [10] investigates the alternative energy sources application in off-grid territories. The researchers write that issues of functioning play an important role when creating isolated energy systems with clean energy production. For example, the solution of the development problems of off-grid renewable generation should be carried out in view of the functioning specifics of such systems [10, p. 340].

Game theory techniques can be used for solving problems of interaction between different parties within the framework of energy service contracts [11]. Practice shows that the customer often plays a dominant role and can choose the most effective technical solutions for himself [12]. However, the effectiveness of technical solutions in isolated photovoltaic systems depends on various aspects: the climatic situation in the area under consideration, the configuration (structure) of the energy system, equipment composition, economic indicators, the level and density of the consumer's electrical load during the year. The combination of these factors significantly affects the technical and economic indicators of the considered equipment composition.

If the installed capacity optimization task of an isolated energy system without an energy performance contract is considered, then the most effective technical solution has the minimum value of the levelized cost of energy. This is classical problem and it can be solved by various approaches and optimization methods [13].

If the construction of an isolated energy system under an energy performance agreement is considered, then, in addition to the levelized cost of energy, the contract duration also plays an important role [14–16]. This indicator depends on the return on investment and the net present value [17,18]. Net present value is determined depending on the amount of fossil fuel (diesel) saved. If an isolated energy system works with battery energy storage system, then it is needed to take into account the service life of the batteries, the quantity of replacements during the energy performance contract and after its completion, the cost of replacing the energy storage system with discounting. These moments greatly influence of the main indicators of the energy performance contract.

The goal of this paper is to propose a methodology for optimizing isolated photovoltaic system with battery energy storage system under conditions of energy performance agreement. This investigation demonstrates the importance of considering lifetime of energy accumulating units and number of its replacement for an effective contract.

2. Methodology

This part of the article presents main stages of mathematical modeling of an energy performance agreement in an isolated energy system.

2.1. Meteorological parameters

At the first stage, the preparation and analysis of the initial climate information are carried out. Climatic information is multi-year and includes various indicators necessary for calculating the energy system operation modes. These data sets are presented in the form of chronology with a discrete step of one hour [19]. The next step is to calculate total solar radiation for the territory under consideration. At this stage, various climatic parameters and indicators of the lower and middle layers of the atmosphere are taken into account [20]. At the final step, an array of a typical meteorological year is created. This array is used in calculating the main modes of an isolated energy system [21].

2.2. Isolated energy system description

In this case, the isolated energy system includes photovoltaic generation, diesel power plant and battery energy storage system. In practice, the following schemes of operation are commonly used: (a) parallel operation of diesel power plant and photovoltaic system; (b) solar generation with battery energy storage system when diesel generator works as a reserve energy source. Fig. 1 demonstrates the typical schemes of autonomous PV systems.

This study considers the combined use of these schemes.

- In late autumn and winter, the isolated energy system has the diesel generator and photovoltaic system and these generation elements work in parallel mode without storage battery system (Fig. 1(a)).
- Early autumn, spring and summer the isolated energy system works using the standard energy accumulation mode whereas the diesel generator is an emergency source (Fig. 1(b)).

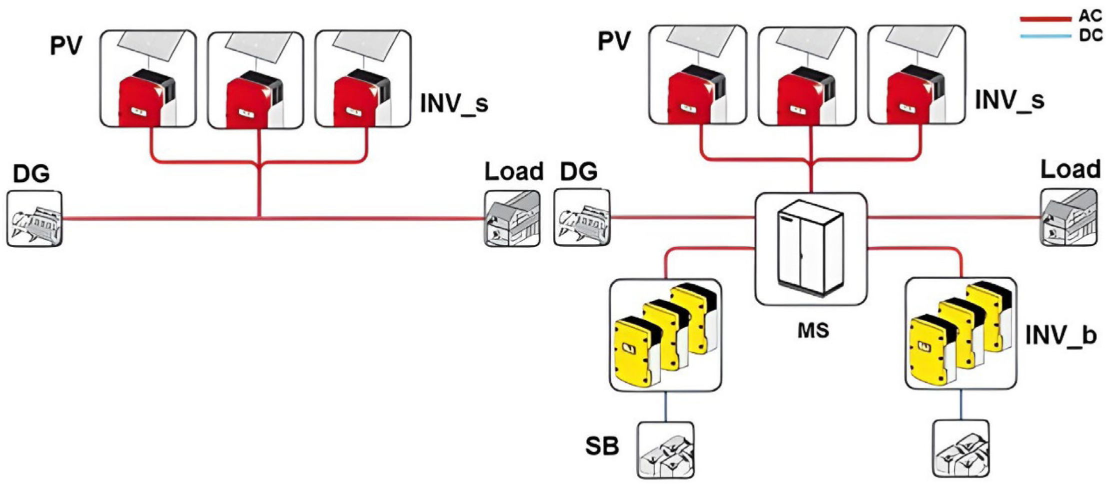

Fig. 1. Operating schemes of isolated energy systems: (a) parallel operation of diesel power plant and photovoltaic system; (b) isolated energy system with battery energy storage system, diesel generator works as an emergency energy source (www.sma.de).

Active power is a known system parameter for each moment of time. Therefore, the alternating power function in hour t has following view:

$$P_S(t) = P_{PV}(t) + P_{DG}(t) - P_L(t) - \Delta P_{\Sigma}(t),$$

$$\Delta P_{\Sigma}(t) = \Delta P_{Line}(t) + \Delta P_{INV}(t) + \Delta P_{DCB}(t),$$

where $P_S(t)$ is the alternating power function, kW; $P_{PV}(t)$, $P_{DG}(t)$ are photovoltaic and diesel power plant generations, kW; $P_L(t)$ is energy demand, kW; $\Delta P_{\sum}(t)$ is total power loss, kW; $\Delta P_{Line}(t)$ is power loss in cable and overhead lines, kW; $\Delta P_{INV}(t)$, $\Delta P_{DCB}(t)$ are power losses in the elements of power electronics (inverters, direct current combiner boxes), kW. The sign of $P_S(t)$ indicates the autonomous energy system mode: charging mode if $P_S(t) > 0$, discharging mode if $P_S(t) < 0$, and fully charged (100%) mode if $P_S(t) = 0$.

A comprehensive explanation of the math models of the main elements of an isolated energy system is presented in the following papers. A common technique for calculating of the main work modes of isolated photovoltaic power plant is described in [21–23], taking into account the dynamics of solar irradiance, frequency control and system topology. The research [24] represents a technique of power electronics installed capacity optimization in isolated energy systems. An approach to modeling the working modes of a diesel generator is described in [25].

2.3. Storage battery modeling

Modeling of battery energy storage system is carried out by the behavior of isolated energy system's operating modes. A detailed description of the exploitation parameters of battery energy storage system and the approaches for modeling are presented in [26].

Additionally, in this paper we use a technique to storage batteries categorization depending on their operating modes and external conditions [27]. Modified version of this technique was used for problems to find optimal equipment composition [28]. The technique provides variants of an energy storage system with battery types such that the degradation processes are minimized [29].

The following two battery energy storage system parameters are very important, namely local minimum state of storage devices charge and partial cycle. The next stage is to determine the service life of the battery energy storage system. The calculation is performed according to the previously described parameters. A detailed description of this model is presented in [30].

During the analysis of real photovoltaic systems (2019–2022) which are located on the territory of Siberia, many peculiarities and technical problems were identified. For example, in winter and late autumn, there is a minimum generation of electricity and at the same time, the energy demand has a maximum level. As a result, the energy storage system has a high utilization rate characterized by frequent low state of charge, high charge and discharge currents, and cyclic operation. In such conditions, an effective solution is to use storage batteries only at certain periods of the year: spring, summer and early autumn (Fig. 1(b)). In late autumn and winter, the battery energy storage system is disconnected from the isolated energy system and the solar power plant operates in parallel mode with the diesel power plant (Fig. 1(a)). At this time, the batteries are in a full charged state and are located in the battery building. Maintenance and control of the charge level of the energy storage system is carried out in accordance with regulatory documents and rules. Consequently, the generation structure and control algorithms change throughout the year for such conditions. A detailed description and integration of this approach into the installed capacity and structure optimization problem of isolated energy systems is considered in [31].

2.4. Mathematical model of energy service contract

In what follows, we describe a hierarchical bilevel model [32] for optimizing installed capacities of an isolated energy system under energy performance agreement. The parties of the contract are the client and the contractor. The client is local government, whereas the energy performance company plays the role of the contractor. One of the key hypotheses of the following model is that the regional governments have a chiefly position with regard to the energy performance company. Thus, the client is at the upper level of the hierarchical statement, whereas the contractor is at the lower one.

It is assumed that contractor pays for a new power station built and it can get profit from reducing the service expenses (for example yearly fuel saving) during the whole time of the energy performance agreement. Fuel consumption of the old power supply system before the contract is a known value for both parties. This value is fixed in the contract conditions. The client pays for the yearly fuel expenses and contractor's profit during the whole time of the agreement. When the agreement is over, the energy facilities transmitted to the client.

2.4.1. Lower level

Let x_{PV} be the number of photovoltaic panels and x_{SB} be the number of storage batteries in the system. The variables x_{PV} and x_{SB} are nonnegative integers. It is assumed that only one special kind of photovoltaic panels, as well as of storage batteries, is used. In practice, these kinds should be chosen so as to optimize objectives that one selected for the system [33]. Denote $x = (x_{PV}, x_{SB})$; n is agreement time in years; $K(x)$ is contractor investment, US\$; $M^{\tau}(x)$ are yearly service expenses in year τ, US\$.

The summary investment $K_{total}(x, n)$ includes new equipment costs and service expenses during the energy performance agreement time:

$$K_{total}(x, n) = K(x) + \sum_{\tau=1}^{n} \frac{M^{\tau}(x)}{(1+r)^{\tau-1}},$$

where r is the discount rate. If in some year τ storage devices replacement is needed, then the cost of replacement is a part of maintenance cost $M^{\tau}(x)$. Contractor's profit (net present value) is as follows, US\$:

$$NPV(x, n) = -K(x) + \sum_{\tau=1}^{n} \frac{\overline{F} - F^{\tau}(x) - M^{\tau}(x)}{(1+r)^{\tau-1}},$$

where $F^{\tau}(x)$ are yearly fuel expenses in year τ, US\$; $\overline{F}$ is a mean yearly charges of fuel before energy performance agreement, US\$. This value is stored in the terms of the agreement and it is used to determine the contractor's fee. The nonnegative value $\overline{F} - F^{\tau}(x)$ demonstrates the value of fuel saved in year τ. The contractor's fee depends on amount of fuel savings.

The parameter N is the service time of the isolated energy system, typically 20 years. Let $\overline{x} = (\overline{x}_{PV}, \overline{x}_{SB})$ be the upper bound on x. The duration n (positive integer value) of the agreement is the only decision variable of the contractor.

The goal of the contractor is to find a technical solution that has a minimum contract period while having a good profit and return on investment $ROI_{\min}$. Minimization of n follows from the fact that a large value of contract duration is undesirable for client, hence, the contract with a large n would not most likely be concluded. Therefore, for every x, $0 \le x \le \overline{x}$, the energy performance company solves the problem

$$\min n, \quad n \in \{1, 2, \dots, N\} \tag{1}$$

provided that

$$NPV(x,n) \geq (1 + ROI_{min}) K_{total}(x,n). \quad (2)$$

2.4.2. Upper level

Let $n^*(x)$ be a solution of the lower-level problem (1)–(2). The client at the upper level wants to choose the project $(x^*, n^*(x))$ that gives the optimal (minimum) value of the levelized cost of energy under energy performance agreement $LCOE_C(x, n^*(x))$, US$/kW·h. The modified levelized cost of energy $LCOE_C$ calculates the relation of the client's overall charges to the value of electricity generated during the new station exploitation. The upper level's overall charges $C(x, n^*(x))$, US$, includes two conditions: expenses got under energy performance agreement and expenses in period after its closing. After closing the contract, the client has only the costs of buying fuel and the costs of maintaining the equipment until the end of the isolated energy system service life N.

Therefore, we have the following:

$$C\left(x, n^*(x)\right) = \sum_{\tau=1}^{n^*(x)} \frac{\overline{F}}{(1+r)^{\tau-1}} + \sum_{\tau=n^*(x)+1}^{N} \frac{F^{\tau}(x) + M^{\tau}(x)}{(1+r)^{\tau-1}},$$

$$LCOE\left(x, n^*(x)\right) = \frac{C(x, n^*(x))}{\sum_{\tau=1}^{N} \frac{W^{\tau}(x)}{(1+r)^{\tau-1}}},$$

where $W^{\tau}(x)$ is the yearly energy production in year τ, kW·h. The client's variable is the vector x. The client's task has the following form:

$$\min LCOE_C\left(x, n^*(x)\right), \ 0 \leq x \leq \overline{x}.$$

In view of (1)–(2), the corresponding bilevel optimization problem is defined by

$$\min LCOE_C(x,n), \ 0 \leq x \leq \overline{x}, \quad (3)$$

$$n = \min\{n \in \{1, 2, \ldots, N\} \,|\, NPV(x,n) \geq (1+ROI_{min}) K_{total}(x,n)\}. \quad (4)$$

The formulas (3)–(4) are, to a certain extent, a balance between the expenses that the energy performance company has and the minimum expenses for the client when concluding energy performance agreement. The formulation (3)–(4) is an integer bilevel optimization problem. In general, the problems of this class are difficult and demand much time for finding solution. If x has a low dimension, the problem (3)–(4) may be solved by direct enumeration, and this is the case for the present study. Otherwise, the use of heuristic methods is reasonable.

3. The research target

In this investigation we consider the isolated energy system, which is located on the territory of Eastern Siberia. This energy system is characterized by the following main technical parameters. Consumer's load varies from 45 kW to 70 kW and has a classic character of load curve. Diesel power plant consist of three units: 100 kW, 75 kW and 50 kW. The diesel power plant consumes 87 tons of fuel every year and produces 232 thousand kW·h. The yearly carbon dioxide pollutants have about 305 tons and the levelized cost of energy is currently 43.47 RUB/kW·h.

Further, the results of the photovoltaic system and storage batteries installed capacity optimization under an energy service contract will be presented. Moreover, this investigation takes into account special issues related to the storage batteries replacement during the period of energy service contracting [26,30].

3.1. Numerical optimization results

For each variant, the necessary economic and technical parameters are determined. Fig. 2 demonstrates the area with optimal conditions for an energy performance agreement.

According to Fig. 2, there are two variants in the area of the optimal solution of the photovoltaic system equipment composition. These options are located in the optimal solution area (*red color*) and they have similar objective function values. The *Variant 1* has the following installed capacities: 80 kW (solar power plant) and 240 kW·h (storage system), while the *Variant 2* has 90 kW and 192 kW·h, respectively. The objective function values for these solutions are 15.53 RUB/kW·h (*Variant 1*) and 15.66 RUB/kW·h (*Variant 2*). Accordingly, the *Variant 1* is selected for further more detailed analysis. Detailed optimization results are presented in Table 1.

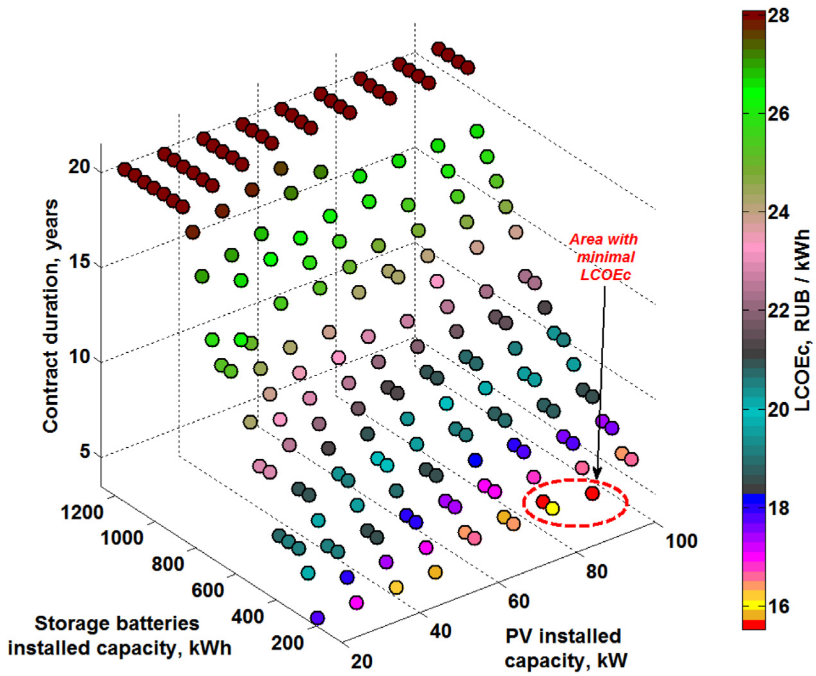

Fig. 2. Changes in LCOE under energy performance contract of the isolated photovoltaic system with batteries energy storage system.

3.2. Calculation without structure changing during the year

If the photovoltaic system always works with storage batteries during the year (Fig. 1(b)), then for the previously obtained optimal equipment composition (*Variant 1*: photovoltaic plant has 80 kW, battery energy storage system has 240 kW·h) we have the following extremely important changes. Yearly number of charge/discharge cycles is 415 and the number of cycles to failure equals to 1525. The battery energy storage system service life is 4 years and the total quantity of storage devices replacements in the isolated photovoltaic system is 4 times in 20 years. The levelized cost of energy with energy performance agreement is 20.95 RUB/kW·h, and the contract duration is 10 years. Thus, changing the structure of an isolated photovoltaic system during the year cannot reduce the quantity of storage devices replacements, but significantly accomplish the effectiveness of an energy performance agreement.

4. Conclusion

A methodology for optimizing an isolated photovoltaic system with storage batteries under energy performance contract is presented. Within framework of this investigation, the following important results were obtained.

- Energy performance contract is a very effective mechanism for investment involvement in isolated energy systems in rural remote areas (for example Siberia). Given the high cost of diesel fuel and its delivery, it is safe to say that the role for energy service contracts will only increase [9].
- Installed capacity and equipment composition optimization problem under energy performance contracting is an actual task. The correct solution of such a problem is the key to the future success of the project [33]. The solution of the optimization problem should be based on detailed mathematical models of the main elements of an isolated photovoltaic system. It allows to significantly reduce possible technical risks in the realization of the project.
- The battery energy storage system service life and quantity of replacements (during the exploitation period of an isolated energy system) are extremely important details. Considering that, storage batteries have a big share (up to 60%) of the overall investment. Therefore, the quantity of storage devices replacements with discounting makes significant changes to the optimal technical solution [26].

Table 1. The optimization results of the isolated energy system.

Equipment	
Photovoltaic system capacity, kW	80
Battery energy storage system capacity (OPzS), kW·h	240
Diesel power plant capacity, kW	100, 75, 50 kW
Number and capacity of solar inverters, pcs and kW	2 × 50 kW (100 kW)
Number and capacity of battery inverters, pcs and kW	3 × 20 kW (60 kW)
Economic indicators	
Investment, RUB mln	14.58
Yearly exploitation costs, RUB mln	0.16
Diesel fuel consumption, tons/year	27.65
Diesel fuel savings, tons/year (%)	59.35 (68%)
Generation	
Direct consumer supply from photovoltaic system, ths of kW·h	83.87
Direct consumer supply from diesel power plant, ths of kW·h	91.82
For battery charging from photovoltaic system, ths of kW·h	22.72
For battery charging from diesel power plant, ths of kW·h	34.10
Total production in a photovoltaic system, ths of kW·h	106.59
Total production in a diesel power plant, ths of kW·h	125.92
Battery energy system parameters	
Yearly charge/discharge cycles	237
Number of cycles to failure	1625
Quantity of storage devices replacements	2 (every 7 years)
Energy performance contract indicators	
Contract duration, years	5
Net present value of the energy performance company at the end of the agreement term, RUB mln	4.2
$LCOE_C$ with storage devices replacements, RUB/kW·h	15.53
LCOE_diesel (diesel generation only), RUB/kW·h	43.47

- Changing the structure of an autonomous photovoltaic system is a very effective way to increase battery lifetime, especially in winter and late autumn seasons. This fact was identified during the analysis of real photovoltaic systems which are located in the Russian Federation. This approach makes it possible to reduce the average yearly charge/discharge cycles to 237 and increase the service time of battery energy storage system up to 7 years, taking into account the operating modes and external conditions [31].
- The sample of the isolated energy system determined that the best technical solution has the following parameters: solar power plant — 80 kW; battery energy storage system (OPzS type) — 240kW·h; power electronics (battery and solar inverters) — 60 kW and 100 kW, accordingly. It allowed to save about 68% of fuel and as a result improve ecological aspects namely reduce carbon dioxide emissions. The levelized cost of energy under energy performance contract has 15.53 RUB/kW·h, compared 43.47 (only diesel generation before energy performance agreement). The contract duration is 5 years and net present value of the energy performance company at the closing of the agreement is 4.2 million RUB.
- Storage devices replacements are fulfilled every seven years, two times in total. The presented case, the best values of target function correspond to 240 kW·h capacity of battery energy storage system (OPzS type). According to this capacity and technical parameters of isolated energy system the number of cycles to failure is 1625 and the average yearly number of charge/discharge cycles is 237.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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