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# Electrification of Rural Remote Areas Using Renewable Energy Sources: Literature Review

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**Abstract:** The current stage of development of autonomous energy systems is characterized by a rapid increase in renewable energy sources' installed capacity. Such growth is observed both in centralized and isolated energy systems. Renewable energy sources show high efficiency in the electrification of rural remote settlements around the world. The power of such power complexes varies from several kilowatts to tens of megawatts. When solving the problems of rural remote settlements electrification, the main issues of optimizing the composition of equipment and the structure of the energy systems play an extremely important role. Moreover, depending on the specifications of the problem being solved, criteria for evaluating efficiency are used, which are different. For example, the following are used as objective functions: minimization of the levelized cost of energy and fossil fuel consumption; maximizing the standard of people living and reliability indicators; the payback period of the project and other indicators. Various combinations of objective functions and the solution to the multi-criteria optimization problem are possible. Moreover, an important stage in the development of renewable energy in remote rural areas is the availability of new mechanisms to support an environmentally friendly generation. These mechanisms can be used in solving problems of optimizing the structure and composition of energy equipment in remote power systems. The main purpose of this article is to demonstrate the world practices of optimal design of isolated energy systems. The review includes both the main questions that arise when solving such problems, and specific problems that require a more detailed analysis of the object of study.

**Keywords:** renewable energy source; autonomous photovoltaic system; optimization of installed capacities; storage batteries

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## 1. Introduction

The modern development of energy systems is characterized by a rapid growth in the installed capacity of renewable energy sources [1]. Currently, the total installed renewable energy capacity in the world is over 3064 GW, where the wind energy sector has 825 GW and the solar energy sector has 849 GW—Figure 1. The rest relates to hydropower and other sources of renewable energy.

This situation is the result of the following main factors: the reduced environmental impact of traditional coal/gas-fired generation; the decrease in the specific cost of installed capacity of solar panels and wind turbines; the creation of support mechanisms for the development of private environmentally free microgeneration [2].

Increasing the concentration of carbon dioxide in the atmosphere is one of the key factors for the use of renewable energy sources around the world. The historic "Kyoto Protocol" (1997) and its successor "Paris Agreement" (2015) are the main catalysts for the deep integration of renewable energy sources into centralized and autonomous energy systems. In addition, various countries are developing their own programs that promote the development of renewable generation, such as feed-in-tariff, green certificates, free connection to the energy system, guaranteed price and purchase of generated energy, tax incentives, and various other preferences. Such processes create a favorable investment climate for the development of renewable energy.

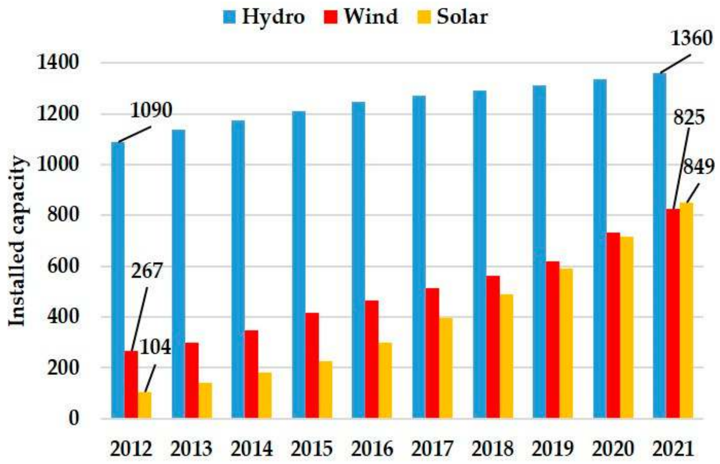


**Figure 1.** Renewable energy sources' installed capacity.

The development of the solar panels and wind turbines market has led to a decrease in the specific cost of installed capacity. Hence, this implies a decrease in the levelized cost of energy. According to official statistics, since 2010, the levelized cost of energy has decreased from USD/kW·h 0.38 to USD/kW·h 0.06 for photovoltaic systems and from USD/kW·h 0.09 to USD/kW·h 0.04 for wind farms ([3], p. 13).

Renewable energy sources have received great importance in autonomous energy systems, namely in the electrification of settlements located in rural remote areas [4]. At the same time, available energy significantly improves the standard of living of citizens, solves a number of socio-economic problems, reduces migration to big cities, and improves the ecological situation in the region [5]. Thus, renewable energy sources are an important element for the modern transformation of energy systems and the transition to distributed generation and energy storage.

The purpose of this article is to review the fundamental problems arising from the use of renewable energy sources and batteries for the electrification of rural remote areas.

## 2. Literature Review of Initial Climatic Parameters Preparation

The main task when using renewable energy sources and batteries in autonomous energy systems is optimization. Solving the optimization problem allows us to determine the following: optimal technology for the energy production and storage; optimal values of the installed capacity of renewable energy sources; economic and environmental efficiency.

### *2.1. Overview of Approaches to Determine the Potential of Renewable Energy Sources*

The potential of renewable energy sources is characterized by the amount of total solar radiation on horizontal surface and wind speed. The analysis of these indicators can be performed in various ways.

#### 2.1.1. Real Data from Meteorological Station

For example, using real measurements of solar radiation and wind speed obtained at a weather station [6–13]. The measurement period can vary from one to twenty years. This approach makes it possible to describe the behavior of parameters in the territory under consideration as accurately as possible. Article [6] describes the optimization of the installed capacity of the system: PV–Wind–Diesel and various types of batteries. The work uses real data on solar radiation and wind speed measured with a discrete step of 10 min. The study [7] demonstrates the functioning of a hybrid energy complex using solar and wind energy. When modeling operating modes, hourly values of solar radiation and wind speed from a real meteorological station are used. In [8], the optimization of an autonomous PV–Wind–Pumped storage energy system is studied. The study demonstrates that the integration of wind turbines into off-grid photovoltaic systems can reduce the levelized cost of energy. This fact is relevant in the case of a good wind speed potential. The work uses real meteorological parameters measured at the meteorological station. Article [9] is devoted to the issues of optimizing the power of the energy system and batteries. The paper also presents the optimization of control algorithms for a hybrid energy complex. The initial climate information has an hourly character. Articles [10,11] optimize the equipment composition of hybrid energy systems with renewable energy sources. The research uses weather data recorded throughout the year in the areas under consideration. The level of detail is from 15 min to an hour. Investigation [12] is devoted to the optimal size of an autonomous PV–Wind/Storage battery power system using heuristic optimization methods. The simulation runs for 8760 h in discrete one-hour increments. Various meteorological parameters from a real meteorological station are used as initial data. Article [13] describes the issue of technical and economic optimization of an autonomous hybrid energy system with hydrogen storage. When optimizing, heuristic methods are used, and the initial data are wind speed and solar radiation at the considered location.

#### 2.1.2. Using Average Daily/Monthly Data

It is possible to use the average daily solar radiation and wind speed entering the territory under consideration by months of the year. In this case, the average monthly number of sunny/cloudy days and the number of hours of sunshine are determined.

With this approach, the NASA SSE [14] and National Renewable Energy Limited—Solar and Wind Energy Resource Assessment (NREL-SWERA) [15] open databases have gained great popularity, allowing to obtain the necessary initial information for various territories. Study [16] describes a multi-criteria optimization of an integrated photovoltaic system and a hydroelectric power plant. The meteorological parameters of the NASA SSE database are used as initial meteorological data. Article [17] is devoted to the issue of optimizing a PV–Biomass–Diesel–Grid hybrid energy system using the HOMER software. Average daily values of solar radiation are used as initial climatic data. The results showed that the use of biomass gasification is cheaper than a photovoltaic system. The work [18] describes the optimization of a hybrid energy complex (Wind–PV–Battery–Diesel) for a remote village located in Sri Lanka. The simulation uses average daily data of solar radiation and wind speed. The check is performed on the balance sheet model. Article [19] demonstrates the results of the electrification of rural remote areas of Nigeria. As an example, six communities located in different regions of the country are considered. The optimization uses the following equipment: solar panels, wind turbines, batteries, diesel generators. The initial climate information is the average daily values of solar radiation and the average monthly values of wind speed. The paper [20] describes the issues of optimizing the capacity of batteries integrated into private photovoltaic systems. The simulation considered various energy demand scenarios. In modeling, average daily values of solar radiation were used. Studies [21,22] demonstrate the results of optimization of hybrid autonomous energy systems with renewable energy sources. As objective functions, the normalized cost of energy and the minimization of capital investments are used. Initial climate information is presented in the form of average daily values. Studies [23,24] describe approaches to the analysis of the potential of renewable energy sources and their application in energy systems research. The results show that daily and monthly averages of wind speed and solar radiation can be used as initial values for modeling various distributions. Moreover, such information can be initial for the formation of a typical meteorological year.

#### 2.1.3. Special Software

Special attention is paid to software that allows modeling solar radiation and wind speed. For example, the "ARENA" software package, which has a large library of distributions, such as normal, lognormal, beta, Weibull, Rayleigh, Simpson, Erlang, etc., makes it possible to obtain an array of the hourly distribution of solar radiation from already measured data. This technique can also be applied in wind speed modeling. For example, in [25–27], when modeling a hybrid energy complex, the distributions of wind speed and solar radiation are used based on average monthly values. The study [28] is devoted to increasing the efficiency of wind energy use in the northern regions of Russia. Improving the efficiency of the energy system is achieved by using electric boilers to produce thermal energy. When modeling the wind speed, the Weibull distribution is used. Scientific articles [29,30] discuss the use of solar energy and wind for hybrid energy systems. Various distributions obtained on the basis of averaged meteorological data are used as initial information. Often, when analyzing wind speed and solar radiation, the transient system simulation tool (TRNSYS) is used [31]. The article [32] provides an optimal control technique for an autonomous hybrid energy complex for power supply of a drinking water system. The simulation uses data taken from the TRNSYS software. In [33], a method for optimizing the installed power of an autonomous photovoltaic system with hydrogen storage is presented. The study used a genetic optimization algorithm, and the simulation was performed on meteorological data taken from the TRNSYS database.

#### 2.1.4. Using Classical Mathematical Models of Solar Radiation

The classical mathematical models of solar radiation are: P.I. Cooper, R.E. Schulze, M.A. Atwater, M. Iqbal, R.E. Bird, ASHRAE, and many others [34–39]. At the same time, these models make it possible to determine solar radiation for clear sky conditions (Clear sky radiation model). Therefore, the next step in modeling solar radiation is to take into account the actual cloudiness in the area. As already noted, cloudiness can be represented by the number of sunny and cloudy days by months of the year or by real long-term meteorological arrays. These indicators are used as initial parameters for determining the reducing coefficients of solar radiation. Well-known mathematical models for accounting for cloudiness are the following: B. Haurwitz, M.A. Atwater, W.A. Schertzer, F. Kasten-G. Czeplak and others [40,41]. It should be noted that various combinations of the presented models are possible [37]. These combinations primarily depend on the level of detail of initial information.

## 3. Typical Structures of Autonomous Energy Systems

In practice, the following two schemes for the functioning of autonomous energy systems with renewable energy sources are most often used: (a) parallel operation of a diesel power plant and a photovoltaic system or wind farm (Figure 2); (b) operation of a hybrid energy complex with energy storage batteries (Figure 3).

An autonomous energy system consists of a diesel power plant operating in parallel mode with a photovoltaic system, the diesel plant being the leading one and the solar plant the led one, respectively. This condition accounts for operational constraints reflected in the load factor of operating diesel generators, which should not be inferior to 30%. This condition secures the smooth and safe operation of the entire autonomous photovoltaic system [42,43].

An alternating power function can have three mutually exclusive states: positive, negative, and zero. If the alternating power function has a positive value, then there is enough energy to directly supply the consumer and charge the storage batteries.

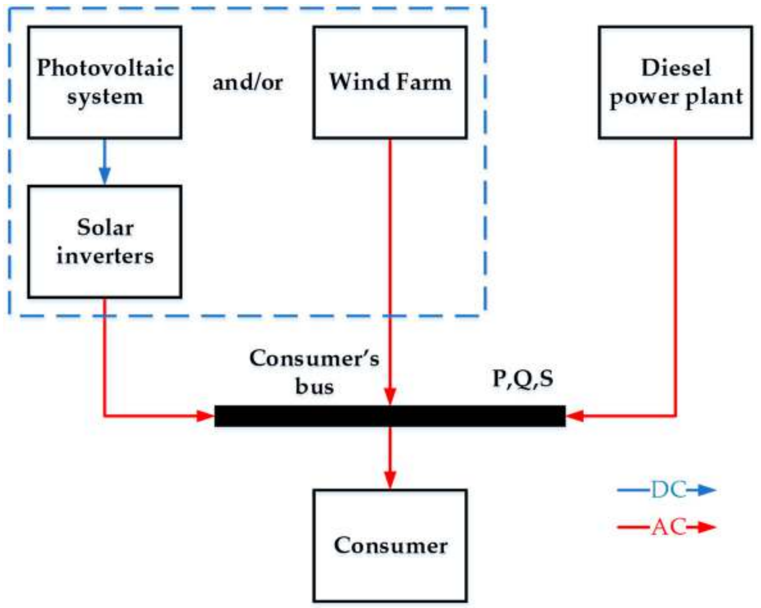


**Figure 2.** Parallel operation of photovoltaic system/wind farm and diesel power plant.

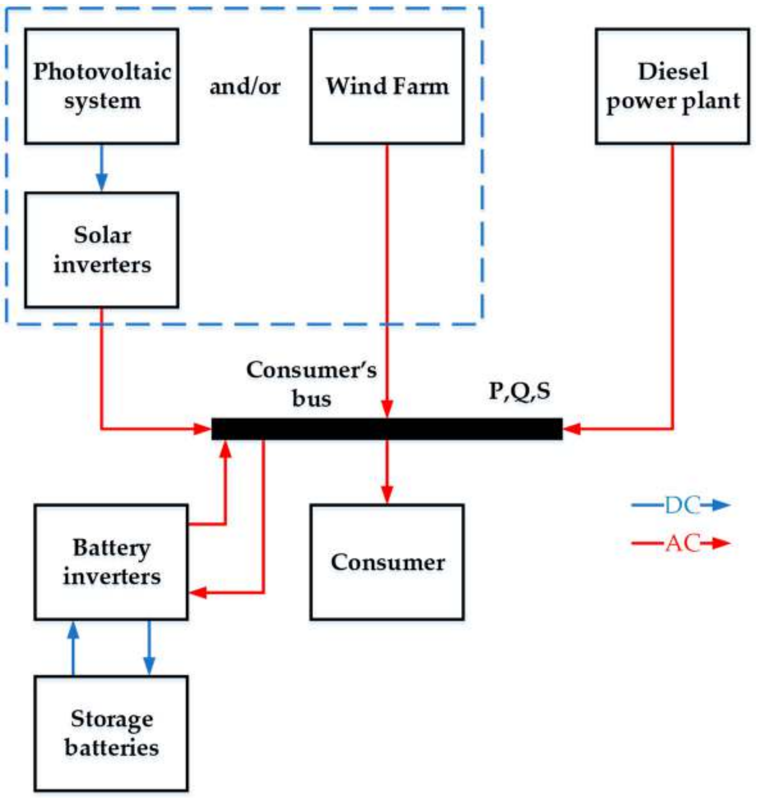


**Figure 3.** Operation of a hybrid energy system with renewable energy sources and storage batteries.

A negative value is characterized by the fact that there is not enough energy to supply the consumer from renewable energy sources, and the energy deficit is compensated from storage batteries. If the alternating power function is zero, then there is enough energy to direct supply the consumer, and the storage battery has a full 100% charge. If the storage batteries have a state of charge of less than 20–30%, then the diesel power plant is switched on. At the same time, it turns on at full power, thereby supplying the consumer and charging the storage batteries [44,45].

*Optimization Tasks of Renewable Energy Sources Installed Capacity*

The task of optimizing the equipment composition and its installed capacity is an important issue in the development of energy systems. The solution of such a task can be performed by various optimization methods (classical, heuristic, enumeration, etc.). Article [46] is devoted to the modeling and optimization of the installed capacity of the PV–Wind–Battery system. The authors used the LPSP (loss of power supply probability) method to analyze the effectiveness of various scenarios. The scenario in which the minimum cost of energy was achieved is optimal. LPSP is the probability that the loss of power supply occurs, meaning the combined (PV and energy storage) system is not able to supply the load on demand. It is a very good measure of the performance of the system for an assumed or known load distribution and other system parameters. The study [47] describes a multi-objective optimization problem for a hybrid autonomous energy system. An evolutionary algorithm was used in the optimization, and a Pareto analysis of the optimal solution was performed. The results show that in all cases, the photovoltaic system is of high importance, since the energy density of the sun in Spain has good potential. Article [48] has a similar methodological set as [47], however, human development index and job creation are used as objective functions. At the same time, the current level of the consumer's electrical load and the forecast of potential industrial loads are of great importance. Such a task is relevant for remote rural areas, where development tasks are necessary for the successful development of a settlement. Studies [49,50] are devoted to describing the software for modeling and optimizing hybrid energy complexes. Typical algorithms for optimizing the installed capacity are presented, as well as the main criteria that are objective functions. Article [51] describes the optimal composition of renewable energy sources for Ethiopian conditions. The article [52] describes the results of the optimal ratio of the power of renewable energy sources and a detailed analysis of the results obtained from the standpoint of multi-criteria analysis. The objective functions are to minimize the levelized cost of energy and carbon dioxide emissions into the atmosphere. Studies [53,54] discuss the use of autonomous hybrid complexes with renewable energy sources for water desalination. During the simulation, the amount of equipment changed discretely. The optimal composition of the equipment corresponded to the minimum value of the cost of energy in an autonomous energy system. Article [55] solves the problem of the optimal configuration of an autonomous energy system with renewable energy sources and batteries, taking into account the minimization of the cost of energy and the minimization of the total weight of the equipment. The result is such a composition of equipment that ensures the normal supply to the consumer with a minimum set of equipment. The article [56] presents a technique for optimizing the functioning of a photovoltaic system in parallel mode operating with a diesel power plant without batteries. In this case, it is necessary to take into account the technical limitations on the minimum permissible load of the diesel power plant [57]. When modeling, the composition of the equipment of a diesel power plant with one type of generators and units with different power was considered. Articles [58,59] consider the problems of increasing the efficiency and reliability of hybrid energy complexes with renewable energy sources and batteries. The results obtained show that the initial climatic parameters and the accuracy of their determination are of great importance. The article [60] provides a detailed overview of the objective functions used in solving the problem of optimizing the installed capacity and the composition of the equipment of autonomous energy systems.

Thus, the task of optimizing the composition of equipment and the installed capacity of energy sources is the main one [61]. In this case, it is possible to use various optimization methods and objective functions [62]. However, one of the main criteria for autonomous energy systems is the levelized cost of energy [63]. Moreover, this parameter is universal and can be transformed depending on the conditions of the problem. Many multi-objective optimization problems can be transformed into single-objective optimization problems by introducing penalties for the non-fulfillment of certain conditions (carbon dioxide emissions into the atmosphere, energy deficit, equipment replacement, and so on) [43,44].

## 4. Operation of Autonomous Energy Systems and Special Issues

The functioning of autonomous hybrid energy systems includes many issues related to the optimal control of the main elements.

### 4.1. Electrical Load Prediction

An important component is the correct consideration of the level of electrical load of the consumer. If the load of the consumer is predicted without taking into account development, then the effect of renewable energy sources will be minimal. The article [64] provides a universal methodology for designing a photovoltaic system, taking into account the prediction of electrical load. Noteworthy are the following research studies [65–67] providing data on the rapid electrical load increase in autonomous power supply stations fed with renewable energy sources. Specifically, it is pointed out that utility usage shows a significant increase after renewable-energy power plants are put into operation. This is a natural process related to improvements in the quality of people's lives. Consequently, the above-mentioned studies highlight the need to take into account the exponential growth in the electrical load in a context of uncertainty [68]. According to the authors, this is a crucial and complex issue involving uncertainties, the optimal development planning of autonomous power supply systems, legislative programs, acts, and more [69,70].

### 4.2. Storage Battery Operation

The operation of batteries in hybrid power systems has a number of features that affect both the technical and economic efficiency of using batteries [71]. First of all, these features reflected a greater extent in the uneven generation of photovoltaic systems and wind farms [72,73]. The stochastic component in the generation of electrical energy significantly affects the main performance indicators of batteries. For example, in photovoltaic systems, the operation of batteries is accompanied by processes with a pronounced cyclical nature during the day. The research study [74] presents a unique approach for classifying storage batteries by operational status at the level of generation equipment. This approach is based on the analysis of performance indicators of a large number of independent physical energy sources with renewable energy sources and storage batteries. It covers six key indicators of battery performance strategies over the course of a year. Each signal has its own scale numbers and corresponding rating scale from 1 to 5. Based on the given amounts, the radar model is constructed. Six main categories are also described, each with its own radar chart. Degradation processes in storage batteries and their correlation with vital signs and quantities are detailed. Each category contains only types of storage batteries and other equipment that can be used under given operating conditions. According to the author, the method described is fundamental and covers issues related to practical battery operation.

The author has perfected the above-mentioned methodology and has introduced it into energy research. The study [75] presents a pattern for the method of storage battery into the equipment optimization problem.

Therefore, in finding a solution to the problem, it is proposed to take the configuration options of the storage battery and auxiliary equipment according to the given service conditions to the extent possible. Such an approach enables the identification of storage batteries and types of auxiliary equipment that comply with performance indicators at the generating system level, thereby minimizing storage battery degradation processes. Furthermore, this approach proactively identifies types of storage batteries that do not comply with normal operating conditions and lead to rapid capacity loss

#### Storage Battery Replacement

In practice, taking into account the number of storage battery replacements throughout the operating period is of great importance [76]. Of note are studies that propose mathematical models to replace the storage battery based on the definition of performance indicators. One way to model the required number of replacement storage batteries is to identify an annual average number of charge/discharge periods [77].

Also worthy of mention is the rainflow model, based on the number of charge/discharge cycles depending on the depth of discharge [78]. This signal is divided into a certain number of intervals corresponding to a certain number of charge/discharge cycles.

In this way, the average number of battery charge/discharge cycles and the average time before battery replacements are obtained.

One of the most complex models is the Schiffer weighted Ah-throughput model [79], based on the definition of operating indicators that influence storage battery lifetime. Notably, many chemical processes affecting the battery degradation, which manifest themselves by means of electric modes, such as the charging current and the charging rate. The study [80] states that the models described in [77,78] considerably overestimate battery lifetime.

## 5. Mechanism to Support the Electrification of Rural Remote Areas

A number of complex issues are to be addressed in relation to using renewable energy sources in autonomous power supply systems. One of these issues has to do with renewable energy project funding. Such funding can be obtained through the following:

- local authorities;
- energy companies responsible for the region's energy infrastructure;
- third-party investors.

On the one hand, local authorities and regional energy companies can act as potential investors in such projects and even joint funding is possible. The use of funds of public authorities or of a local energy company is a sufficiently easy way to fund a project. This process, however, is a lengthy one: financing is not instantaneous but is delayed for a period of three to five years. Such planning is typical of all government bodies, including local energy companies which follow a specific short- and medium-term development program. At the same time, the available funding often proves insufficient.

The experience, accumulated over the past decades, of using this source of funding in Russia shows that it is not an effective way to develop renewable energy in autonomous power supply systems. First, neither regional authorities nor local energy companies can provide a clear answer to the question of how much investment is needed to use renewable energy as efficiently as possible. Secondly, it is necessary to identify the potential structure, generation type, and installed capacity of renewable energy sources. Third, a well-structured methodology is necessary for the development of an autonomous power supply systems. Regional authorities and local energy companies are to address this issue jointly in order to manage uncertainties associated with the level and nature of the future power load. Fourth, relevant energy institutes, departments, and companies have to be involved to give an exhaustive expert appraisal of projects.

Attracting investors is one of the effective ways to fund renewable energy projects in autonomous power supply systems. By their very nature, potential investors are interested in the most profitable projects, having the shortest possible payoff periods. The cost-effectiveness of projects is a safeguard for investors. Besides, a well-structured customer–investor interaction pattern comprising the peculiarities of renewable energy is also needed.

Using the main terms of energy service contracting makes it possible to draw up a list of requirements necessary for funding renewable energy projects in autonomous power supply systems. At the same time, energy service contracting terms for renewable energy sources depend on many different factors, and a careful analysis of these factors as part of a unified research study is what determines the outcome. Importantly, the conditions under which an energy service contract will be signed is a challenging task necessitating the interests of both the customer and the investor.

An energy service contract is an agreement that aims to reduce operating costs by improving energy efficiency and introducing green technologies. A distinctive feature of an energy service contract is that the investor's costs are paid for by savings that can be utilized following the introduction of energy-saving technologies. Energy service companies are increasing the overall cost. Investments can be obtained from energy service companies' own funds and through bank loans [81,82].

Article [83] reports the results of a survey among more than 1500 energy companies and establishes the main characteristics of the projects. The authors present a typical energy service contract based on these characteristics. The experience of German municipalities shows that energy contracting is a successful way to promote energy efficiency technologies in a low-income environment. A survey among 1300 municipalities found that minimum risk and lack of investment were the main reasons for entering into energy service contracts with companies [83].

Additionally, it has been noted that, in addition to common features, energy service contracts can contain a range of requirements that meet the interests of both consumers and energy suppliers [84]. Importantly, the larger the project, the greater the profit potential of the energy service company. Despite the attractiveness of energy contracts, there are several barriers to developing this approach to support energy efficiency solutions. These barriers depend on the characteristics of the region/country under study, as well as political, legal, technical, and other aspects [85,86]. However, interest in energy contracts is growing every year. The main risks associated with the conclusion of energy service contracts are presented in [87]. Of particular importance are the technological risks that are collectively identified in those technical solutions that are adopted in consideration of the relevant area's legal framework. In [88], the authors noted that a comprehensive analysis of technological solutions significantly reduces the risks involved when entering into energy service contracts. The paper also emphasizes that detailed background information is crucial as it greatly improves the accuracy of the results. A comprehensive risk assessment of the construction of centralized radiation systems operating under the terms of the energy contract is presented in [89]. According to the authors, one of the most important considerations is a careful analysis of how to calculate a solar installation's cost–efficiency ratio in the projects under consideration. This analysis is based on several factors. As an example, the authors note the importance of analyzing meteorological data (solar radiation) and take into account the nature of the study site.

## 6. Conclusions

The electrification of remote territories is a priority in the development of the energy sector. Given the significant role of renewable energy sources, it can be argued that the tasks of optimizing the composition of equipment and installed capacity will be relevant [90]. At the same time, it is important to take into account the specifics of the problem being solved, namely technical, economic, political, and other aspects, that affect the optimal composition of the equipment. For example, the integration of the task of developing autonomous energy systems, taking into account the functioning processes [91]. Mechanisms to support renewable energy sources are also important. For example, energy service contracts can be used to build wind farms and photovoltaic systems in isolated areas.

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