Energetic and ecological justification of RE-hybrid systems for vulnerable ecosystems

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Abstract. About two-thirds of the territory of Russia, which covers 11 million km², lies in a region with severe climatic conditions. These northern ecosystems have a unique climate and are supplied with supplies by outdated diesel generation. Therefore, an urgent need has arisen to modernize the power supply systems in question using modern energy-efficient technologies, including power plants based on Arctic renewable energy sources that convert the high natural potential of renewable energy on these territories. For example, the coastal territories of the Russian North are situated in the zone of high wind power potential. In the article a method of modernization through the use of modular hybrid energy complexes are proposed. In total, about 4,700 such stations can be installed in Russia, and the total environmental effect from them will be about $1 million. Moreover, these power plants have a high science intensity. The problem of correct optimization of the parameters and architecture of wind-diesel power plants is also investigated in the article.

1. Introduction
In accordance with the “Energy Development Strategy of Russia-2030”, the development of the energy infrastructure of the Arctic and Far Eastern regions of Russia is one of the important priorities. These territories make up geographically about 65% of the country's territory and are located in zones of decentralized energy supply. The total installed capacity of diesel generation in the northern regions is more than 500 thousand kW. Diesel power plants produce about 2.5 billion kWh. Fuel consumption in isolated and hard-to-reach territories of the Russian Federation are shown in Figure 1 [1].

![Figure 1. Fuel consumption in Russian regions.](image-url)
Total consumption fuel is about 340 thousand tons per year. The regions with the highest fuel consumption are Resp. Yakutia (Sakha), Krasnoyarsk Krai, Yamalo-Nenets Autonomous Okrug, Kamchatka Krai, Magadan Oblast and Sakhalin Oblast. Delivery of diesel fuel to these regions is carried out within the framework of the expensive "northern delivery".

The cost of imported diesel fuel in isolated areas reaches $1 thousand per ton (30-80% is delivery component [2]). In this regard, 50 billion rubles were allocated by Government to subsidize energy tariffs in these zones for year. 77% from that volume of subsidies falls on four regions: the Republic of Yakutia (Sakha) – 42.5%, Kamchatka Krai – 17.7%, Yamalo-Nenets Autonomous Okrug – 9.5%, Krasnoyarsk Krai – 7.1% [2].

Thus, due to the remoteness of consumers and the high cost of fuel delivery, the electricity tariff for consumers in these territories ranges from $0.4 to $2 per 1 kWh [3], which is much more expensive than in centralized energy supply zones (for comparison tariff is $0.05 per 1 kWh in the Leningrad Oblast). Due to expensive logistics, barrels of diesel fuel from some settlements are not removed, but are mostly randomly stored near the premises of diesel stations (Figure 2). The residues of harmful substances accumulated in barrels lead to general pollution and deterioration of the ecological state of the vulnerable Arctic nature, and in some cases - to man-made disasters (Figure 3 [3]).

In August 2019, the Federal Law to modernize inefficient diesel (fuel oil, coal) generation in isolated and hard-to-reach areas was adopted [4]. The [4] includes measures for the selection of investment projects for the modernization of inefficient generation, updating schemes and programs for the prospective development of these regions, analyzing the feasibility of amending the legislation of the Russian Federation, etc. In world and domestic practice, one of the most effective solutions for supplying electricity to decentralized consumers abroad are autonomous hybrid systems based on installations of renewable energy and traditional (diesel) generation: wind-diesel, solar-diesel, wind-solar, hydro-wind and other power complexes. In view of the high renewable potential (basically, wind) of the northern territories of Russia, hybrid systems based on renewable energy sources can be effectively used in these territories.

2. Environmental effects of hybrid systems
The introduction of renewable energy sources in the decentralized regions of Russia has the following systemic effects:

- increasing energy security by increasing "local" fuel and renewable resources;
- diversification of energy facilities and reduction of energy losses for energy transportation and distribution (till 20%);
- increasing the reliability of power supply and reducing the cost of energy for the consumer;
- a decrease in the volume of fuel supply within the framework of the "northern" delivery;
• improving the environmental safety of the energy sector by reducing harmful emissions into the environment and reducing the pollution of the vulnerable northern territory by ejected diesel barrels.

The main consumers of the remote northern regions are low-power facilities (up to 300 kW). For power supply to these consumers, the most effective solution is the creation of modular hybrid systems with a capacity of 150 – 300 kW with wind power plants with a capacity of 50–100 kW.

The authors have conducted a study and have determined the total number of modules calculated for areas with Vann ave > 4.5 m/s at a height of 10 m and the cost of electricity > 0.2–0.26 $/kWh. It’s about 4700 modules (wind-diesel hybrid systems) with capacity including:
• Yamalo-Nenets Autonomous Okrug – up to 1350 modules.
• Kamchatka Krai – up to 1090 modules.
• Republic of Yakutia (Sakha) – up to 926 modules.
• Nenets Autonomous Okrug – up to 442 modules.
• Chukotka Autonomous Okrug – up to 422 modules.
• Other subjects – up to 470 modules.

Table 1 shows data on emissions of power plants operating on fossil fuel and renewable energy sources, including diesel power plants [5].

|          | Coal | Oil | Gas | Diesel | Wind | Solar |
|----------|------|-----|-----|--------|------|-------|
| CO₂      | 955  | 818 | 430 | 772    | 7–9  | 98–167|
| SO₂      | 11.8 | 14.2| –   | 1.6    | 0.02–0.09 | 0.2–0.34|
| NOₓ      | 4.3  | 4.0 | 0.5 | 12.3   | 0.02–0.06 | 0.18–0.30|

The ecological effect from reducing emissions into the atmosphere [6] is determined taking into account the emissions cost. Firstly, the emissions cost can be formed in the form of the so-called carbon tax, i.e., in the form of a payment rate for a certain volume of carbon dioxide emissions [7]. Secondly, the cost will be determined on the basis of market mechanisms by trading in quotas. In the world in 2018, the average price for 1 ton of CO₂ was $25 [8]. Taking into account the Paris Agreements, the price per ton of CO₂ in the world will grow. By 2030, growth is expected to reach $100. The article considers three options for price growth: slow, probable and fast. Based on three economic models, the price effect of 4700 modules with an average diesel fuel replacement rate of 50% is calculated (Table 2).

|          | CO₂ | SO₂ | NOₓ | Sum  |
|----------|-----|-----|-----|------|
| slow option | 445 | 190 | 83  | 718  |
| probable option | 595 | 249 | 143 | 987  |
| fast option | 743 | 369 | 202 | 1314 |

It is important to note that all options take into account the average values from Table 1, take into account the mandatory introduction of a tax on greenhouse gases in Russia, and are calculated for the operation of all power plants from 2020 to 2030. However, the total value of $1 million confirms the ecological significance of such systems.
3. The architecture of the energy complex adapted to Russian conditions

The general structural diagram of the power redistribution in wind-diesel power plant (WDPP) is shown in Figure 4. A distinctive element of the circuit is software and hardware module of intelligent system of transformation, control, distribution of energy (SHM ISTCDE), the function of which is to ensure high-quality and reliable AC power supply to the consumer in modes with a completely disconnected diesel power plant (leading mode). The SHM ISTCDE hardware consists of two power devices for dynamic power balance control: bidirectional current transducer (BDCT) and controlled ballast load (CBL); the main controller of SHM ISTCDE, performing high level control [9].

**Figure 4.** The general structural functioning diagram of an autonomous power complex based on renewable energy sources managing by SHM ISTCDE:

- high speed communication interface;  
- control connections to remote devices; 
- WT – wind turbine; PVM – photovoltaic module; DGS – diesel generator set; BDCT – bidirectional current transducer; Battery – accumulator battery; CBL – controlled ballast load; S1 – section of the AC circuit with unstabilized frequency and voltage; S2 – section of the DC circuit with unstabilized voltage with voltage limit at the upper boundary; S3 – section of the DC circuit with unstabilized voltage; S4 – section of the DC circuit with voltage stabilization within the battery parameters; S5 – section of an AC circuit with stabilized voltage and frequency (S5 is an autonomous chain).

BDCT is a bi-directional converter connected to the battery, which allows you to work in two directions simultaneously: to maintain quality indicators in the internal network and to ensure its uninterrupted operation due to power from the network. In this case, the accumulating system is used only for balancing.

BDCT operates in the following modes:

- the slave mode, as an inverter driven by the network (or other source). BDCT is consuming or recuperating power on the AC side for maintaining the voltage on the load in a given range. In case of a voltage drop, BDCT pumps up power (battery discharge), when the network voltage is exceeded, BDCT consumes power (battery charge). 
- the master mode, as a main source or network (there are no other sources in the network or are slaves) and generates a stabilized voltage sinusoid.
The process of designing the WDPP with high penetration level and low capital costs is a complex multidimensional optimization problem. The main algorithm for optimization is shown in Figure 5.

For determination of hybrid system parameters, it is necessary to take into account a number of criteria, such as climatic and energy resources, technical, economic and environmental conditions, transport and logistics features of equipment delivery, parameters and characteristics of the equipment. The main goal of the project implementation of the power supply system should be a variant selection and optimization of the composition, parameters and operating modes of the WDPP equipment to maximize the saving of diesel fuel and minimize costs. For this, a multicriteria problem is solved, consisting in optimization according to several criteria:

- specific discounted costs of electricity production → min (main criterion);
- ecological effect of atmospheric emission in an equivalent value → max (additional criterion);
- autonomy time (autonomous operation without maintenance): \( T_a > T_{\text{min}} \) (limitation);
- maximum useful generation of renewable energy: \( W_{\text{res}} \) → max (additional criterion).

The authors have prepared a number of articles according to the scheme proposed in Figure 4. The methodology for assessing the losses of equipment operating in severe climatic conditions is described in the article [10]. Analysis and processing of wind resource data and some algorithms for the operation of diesel power plants are given in the article [11]. Optimization and simulation model of WDPP is described in articles [12–15]. Section 4 will provide some refinements for the algorithm.
4. Necessary additions to the methodology
The modular architecture of the power complex allows you to choose the required combination of power equipment, which will cover the needs of any energy consumers. GIS-spaces multilayer scheme is being developed to simplify the selection process [16, 17].

One of the ways to increase energy efficiency is the division of diesel power plants into diesel generators of lower power, which leads to additional savings in diesel fuel without the use of power storage systems. The articles [11, 12] describe algorithms for power distribution between diesel generators. In addition to these articles, the savings in diesel fuel for the same period of time are determined (Table 3).

| Table 3. Number of switching (on/off) DGS of different power. |
|---------------------------------------------------------------|
| Lagrange multipliers | 20 kW | 50 kW | 50 kW | 80 kW | DPP | Reduced fuel consumption,% |
|----------------------|-------|-------|-------|-------|-----|---------------------------|
| Lagrange multipliers |       |       |       |       |     | 60 | 58 | 63 | 42 | 223 | 13 |
| Lagrange + “greedy” algorithm |     |       |       |       |     | 32 | 56 | 48 | 30 | 166 | 10 |

Fuel consumption due to the use of the “greedy” algorithm with respect to the Lagrange multipliers method increases fuel consumption by a third, that is, a reduction in fuel consumption per year is about 10%, while the number on/off cycles of DGSs decreases by a quarter, and the mean timelife of individual DGS rises by 3–4 years.

The parameters determined from the previous blocks go to the block for calculating of the parameters required for optimization (Table 4).

| Table 4. Parameters calculation block. |
|---------------------------------------|
| Initial data | Technical | Economical | Ecological | Parametric | Social |
|--------------|-----------|------------|------------|------------|--------|
| Penetration level | Power, capacity, etc | CAPEX, OPEX, income | noise level, CO₂ price | Parameters of facilities | Staff |
| LCOE | Eco-friendly | Ecological effects |
| Efficiency | Economical efficiency | Legal restrictions | Local restrictions | Autonomy time |

The sufficiency condition is formed from the main parameters on the basis of which the optimization takes place. If the parameters are insufficient, additional simulation calculations are performed. Using the hierarchy analysis method [18], matrices of paired comparisons of parameters are compiled and weight coefficients are determined for each parameter. Parameters related to a certain criterion are assigned conditional priority weights. In the last block, there is a multi-criteria ranking of all options in a table, on the basis of which the optimal composition of WDPP is selected for certain criteria.

5. Conclusion
The high value of electricity tariffs in autonomous and decentralized energy supply zones and high potential for renewable energy sources create good prerequisites for the design of modular hybrid systems with a high penetration level.

The implementation of the principles of a multipurpose integrated approach to the creation and assessment of the effectiveness of projects of hybrid systems, including taking into account the environmental effects, provides an increase in the economic efficiency and investment attractiveness of projects based on renewable energy sources for harsh natural and climatic conditions. On average, the economic effect of reducing emissions is estimated at $1 million over 10 years of using the WDPPs (4700 modules with 50%-penetration level).
The proposed and implemented principles for creating SHM ISTCDE of an intelligent systems allow optimizing the modes of electricity production and consumption and creating WDPP. BDCT provides autonomy and allows generating equipment to operate in modes with a high penetration level.

Practical recommendations were developed and algorithms for reducing diesel fuel were worked out due to the economical operation of the diesel part of the power plant. The total savings of diesel fuel per year is about 10%, while the lifetime of diesel generator set is increased by 3-4 years.

Optimization will be carried out on the basis of the hierarchy analysis method, the results of which will be presented in subsequent works of the authors.

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