ISSN 2618-9992

Energy Systems Research

Volume 7, Number 4, 2024

International scientific peer-reviewed journal since 2018

Available online: http://esrj.ru

About the journal

Energy Systems Research is an international peer-reviewed journal addressing all the aspects of energy systems, including their sustainable development and effective use, smart and reliable operation, control and management, integration and interaction in a complex physical, technical, economic and social environment.

Within this broad multi-disciplinary scope, topics of particular interest include strategic energy systems development at the international, regional, national and local levels; energy supply reliability and security; energy markets, regulations and policy; technological innovations with their impacts and future-oriented transformations of energy systems. The journal welcomes papers on advances in heat and electric power industries, energy efficiency and energy saving, renewable energy and clean fossil fuel generation, and other energy technologies.

Energy Systems Research is also concerned with energy systems challenges related to the applications of information and communication technologies, including intelligent control and cyber security, modern approaches of systems analysis, modeling, forecasting, numerical computations and optimization.

The journal is published by Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences. The journal's ISSN is 2618-9992. There are 4 issues per year (special issues are available). All articles are available online on English as Open access articles.

From December 19, 2023, the journal is included in the list of peer-reviewed scientific publications (VAK) in which the main scientific results of dissertations should be published in scientific specialties:

1.2.2. Mathematical modeling, numerical methods and software packages (technical sciences),

2.4.3. Electrical power engineering (technical sciences),

2.4.5. Energy systems and complexes (technical sciences).

Indexed by: RSCI, CyberLeninka, Google Scholar, Crossref.

The journal is registered with Roskomnadzor. Certificate Эл № ФС77-84526 January 16, 2023

Topics

- Energy production, conversion, transport and distribution systems
- Integrated energy systems
- Energy complexes
- National, regional, international and global energy systems
- Energy system protection, control and management
- Smart energy systems, smart grids
- Energy systems reliability and energy security
- Electric, gas, oil and heat supply systems
- Energy system development and operation
- System problems of energy consumers
- Energy economics and policy
- Renewable energy and clean fossil fuel based systems
- Distributed energy systems
- Sustainable energy transitions
- System problems of power and thermal engineering
- Artificial intelligence in energy systems
- Information and communication technologies in energy systems
- Energy system analysis and modelling
- Computational methods and optimization in energy systems

Contacts

Scientific secretary: Alexey Mikheev, Dr. of Eng.
E-mail: info@esrj.ru
Tel: +7 (9148) 950980 (English, Russian)
Fax: +7 (3952) 426796
Address: 130, Lermontov str., Irkutsk, 664033, Russia

CONTENTS

Impacts of Institutional Transformations in Energy Markets: The Baikal Region of Russia

O.V. Dyomina[1,*], S.N. Naiden[1]

[1] Economic Research Institute of the Far Eastern Branch of the Russian Academy of Sciences, Khabarovsk, Russia

***Abstract* — The paper examines the evolution of institutional conditions in the electricity markets of the Baikal region from 2018 to 2023. The fundamental market conditions remained unchanged, however, the key changes followed the inclusion of the Republic of Buryatia and the Transbaikal Territory into the Far Eastern Federal District (FEFD), which has a set of unique institutional frameworks designed to invigorate the economy. These include targeted measures aimed at improving economic accessibility of electricity by averaging tariffs on electricity and subsidizing expansion of networks through investment support and leveraging the infrastructure available in the advanced development areas. Features of regional energy system of the Baikal region are analyzed comparatively. The regional power systems of the Transbaikal Territory and Buryatia are technologically inferior to those of their neighbors (the Irkutsk Region in the Siberian Federal District and southern regions of the Far Eastern Federal District). This technological disparity can be attributed to several key factors: a heavy reliance on thermal power plants, extensive wear and tear on infrastructure, and inadequate development of low-voltage networks. The study also explores the scale, structure, and dynamics of electricity consumption in the Baikal region and estimates economic accessibility of electricity for local population. Although the Republic of Buryatia and the Transbaikal Territory have comparable income levels and higher tariffs than Irkutsk Region, they experience the lowest electricity accessibility among all subjects of the Far Eastern Federal District. These data indicate that Buryatia and the Transbaikal Territory lack any significant competitive advantages in energy accessibility when compared to their neighboring areas.**

***Index Terms* — Electricity market, economic accessibility, physical availability, Baikal region, Republic of Buryatia, the Transbaikal Territory, income groups.**

I. INTRODUCTION

The Baikal region is situated in the south of Eastern Siberia and includes three subjects of the Russian Federation: the Irkutsk Region, the Republic of Buryatia (Buryatia), and the Transbaikal Territory. The 1.6 million km^2 region produces 2.4% of the total gross regional product (GRP) of the country and is home to 2.9% of the country’s total population [1-2].

Local regional energy systems are integral components of the Interconnected Power System of Siberia (IPS Siberia), which, in turn, is a part of the Unified Energy System of Russia (UES Russia). The Baikal region is part of the 2nd pricing zone of the national wholesale electricity market. The institutional frameworks of the aforementioned subjects differ. The Irkutsk Region is a part of the Siberian Federal District (SFD), whereas Buryatia and the Transbaikal Territory joined the Far

* Corresponding author.
E-mail: demina@ecrin.ru

http://dx.doi.org/10.25729/esr.2024.04.0001

Received September 18, 2024. Accepted November 22, 2024.
Available online December 28, 2024.

Eastern Federal District (FEFD) in 2018 [3]. This transition enables these two regions to benefit from the preferential regimes for economic activity and state support of producers and consumers, provided by the Government of Russia to promote development in the Far East [4].

This paper aims to compare the accessibility of energy supply among the consumers in Buryatia and the Transbaikal Territory during 2018-2023, following their integration into the FEFD. The estimates cover both electricity supply (physical availability) and electricity demand (economic accessibility).

This research evaluates physical availability through several factors: network topology, regional power system capacities, structure of installed capacities, technical condition of generating capacities, reliability of fuel supply, energy exports-imports, risks of supply shortages, and risks of capacity shortages. Economic accessibility is estimated by examining the following factors: dynamics and structure of consumption, electricity-to GRP ratio, the breakdown of material costs, average income, electricity tariffs, and purchasing power.

II. Changes in the Institutional Conditions in the Electricity Market

The Baikal region exhibits notable differentiation in electricity market conditions although there are standardized fundamental rules governing the 2nd price zone of the wholesale market. In 2017, Buryatia was put on the list of territories with a special operational framework for wholesale and retail markets. This involves specific payments for the power of generating facilities that supply power to the wholesale market and usage of indicative electricity prices for all consumers, except for residential customers [5].

In 2018, despite Buryatia and the Transbaikal Territory joining the FEFD, the fundamental conditions of markets did not change. However, this integration enhanced the existing support measures for the economic agents in these regions. Buryatia has been implementing these measures since 2022, while the Transbaikal Territory has yet to fulfill the established requirements [6-8]. Nevertheless, both regions are eligible for state support to enhance network development through the available infrastructure funded by the budget, as well as investment project assistance, and subsidies for the costs associated with connecting equipment to electrical and gas networks [9].

The energy systems in the Baikal region are advancing steadily. The anticipated support measures in the Far East were designed to enhance the conditions for the electricity consumers in Buryatia and the Transbaikal Territory. A thorough analysis and evaluation of the implications of the institutional transformations in the Baikal region (which includes Irkutsk Region that does not benefit from these preferential measures) would help compare the trends and the changes in the economies and energy systems of separate subjects. This information could be used to justify decisions on adjusting the regional energy policy regarding newly added territories of the FEFD.

The Baikal region is a strategically significant area to consider when evaluating the potential inclusion of other subjects from the FEFD into the second price zone.

III. Physical Availability of Electricity in the Electricity Market in the Baikal Region

From 2018 to 2023, the institutional framework governing the electricity market supply remained unchanged. The Baikal region belongs to the second price zone of the wholesale electricity market, while the development of regional power systems and pricing obey the general rules (with the exception of Buryatia).

Regional power systems of the Baikal region are part of the IPS Siberia and UES Russia. External energy ties allow for energy exchange between neighboring regions. Power system of Buryatia includes two unconnected load centers: Southern and North-Baikal. Southern load center is connected to the power systems of the Irkutsk Region, the Transbaikal Territory, and the Central Mongolia. North-Baikal load center is connected to the power systems of the Irkutsk Region and the Transbaikal Territory. The power system in the Transbaikal Territory has ties to power systems of Buryatia and Amur Region (Table 1).

The power systems of Buryatia and the Transbaikal Territory are not comparable in scale to the Irkutsk Region's power system recognized as one of the largest in Russia [10]. This expansive network encompasses large and small energy facilities, along with private and state-owned companies involved in the extraction and processing of energy resources.

Various conditions shape distinct levels of physical and economic availability and accessibility of electrical supply for consumers in the regions.

TABLE 1. Regional power systems, Baikal region

Indicators	Irkutsk Region	Buryatia	Transbaikal Territory
Installed capacity, MW	13 090.5	1 523.8	1 693.8
Installed capacity breakdown, %	Thermal – 30.2 Hydropower – 69.8	Thermal – 92.5 Solar power – 7.5	Thermal – 94.1 Solar power – 5.9
Power reserve volume, % of the maximum consumption*	28.7	33.3	15.6
Power growth 2018-2023, %	-0.5	10.0	6.1
Volume of electricity production, billion kWh	71.1	6.3	7.9
Volume of power exchange, million kWh	4 262.0	-312.2	-933.3
Production growth, 2018-2023, %	+36.2	+6.9	+9.1
External power connections with	– Krasnoyarsk Territory and Tuva Republic: 500 kV high voltage power line – 4; 110 kV high voltage power line – 4; – Buryatia: 220 kV high voltage power line – 7; 110 kV high voltage power line – 1; – Sakha Republic: 220 kV high voltage power line – 4.	– Irkutsk Region: 220 kV high voltage power line – 7; 110 kV high voltage power line – 1; – Transbaikal: 220 kV high voltage power line – 5; 110 kV high voltage power line – 2; –Central Mongolia: 220 kV high voltage power line – 2.	– Buryatia: 220 kV high voltage power line – 5; 110 kV high voltage power line – 2; – Amur Oblast: 220 kV high voltage power line – 2; – Sakha Republic: 220 kV high voltage power line – 2.
Load centers at risk of emergency power outages	Transit 110 kV Taishet – Tulun, 500 kV Taishet substation, Eastern electric network, Transit 110 kV Shelekhovo – Slyudyanka, Transit 220 kV Kirenga – Severobaikalsk	none	none

* Standard reserve rate for IPS Siberia is 12%.

Demand and supply in the electricity markets in Buryatia and the Transbaikal Territory are shaped by external factors as the regional power systems are excessive in capacities but deficient in power. The primary generating capacities in Buryatia and the Transbaikal Territory are represented by thermal power plants constructed in the Soviet time. The average age of the plants in Transbaikal Territory is 36 years (the age of individual blocks varies from 12 to 61 years) and that in Buryatia is 39 years (the age of some blocks is 5 to 53 years). As a result, there is a need for modernization of existing generating capacities and construction of new facilities.

Nevertheless, between 2024 and 2029, there will be no introduction of new capacities or any modernization efforts [11-12]. As of 2024, new power plants have been solely solar power plants constructed under the renewable energy contracts. A large portion of Buryatia is part of Baikal natural territory, where any activity incurring negative effect on the environment is prohibited. This increases the importance of renewable energy in the region [13]. Between 2017 and 2020, six new solar power plants were constructed in Buryatia, with the total capacity of 115 MW, and four new solar power plants with the total capacity of 100 MW were constructed in the Transbaikal Territory between 2019 and 2022. The share of solar power in total power generation of the region, however, is still small and their inconsistent power generation makes no difference.

Thermal power plants use coal mined in excessive volumes inside the regions, which ensures reliable fuel supply. This, however, imposes significant environmental burden [14-15].

The balance of supply and demand in the new regions of the FEFD shows that the demand for electricity is covered by both domestic capacities and capacities of the neighboring power systems. Technically, domestic

TABLE 2. Consumption in power systems of the Baikal region

Indicators	Irkutsk Region	Buryatia	Transbaikal Territory
Maximum power consumption, 2023, MW	10 168	1 143	1 465
Annual growth rate of power consumption, 2018-2023, %	4.5	3.9	2.5
Volume of electricity consumption, 2023, billion kWh annually	66.8	6.6	8.8
Annual growth rate of electricity consumption, 2018-2023, %	3.8	2.8	2.1
Consumption breakdown, 2023, %			
− industry	61.1	30.6	28.0
− transport	7.6	22.1	29.3
− population	15.9	18.2	11.6
Weighted average unregulated price of electricity (power) for consumers, 2023, RUB/kWh	2.2	2.4	2.5
Housing development, 2018-2023, m^2 per capita	3.0	1.9	1.7
Electricity consumption, 2023, kWh per capita, annually	4 538.0	1 236.8	1 032.3
Residential tariff, 2023, Rub/kWh	1.42	3.46	3.60
Annual residential tariff indexation, 2018-2023, %	6.5	4.7	6.9

Source: compiled by the authors based on the data in [11-12, 17-24].

electricity generation could meet domestic demand in full but because of high electricity costs, a portion of this demand is covered by electricity imported from neighboring systems.

Currently, Buryatia and the Transbaikal Territory have no load centers that are at risk of power shortage. In the near future, however, the southeastern part of IPS Siberia could face electricity shortage if new consumers emerge. The current power system is expected to face a shortfall of 246 to 820 MW in the normal scenario from 2026 to 2029 and between 13 and 1 225 MW in the repair scenario from 2024 to 2029 [16]. Therefore, it is essential to introduce new energy capacity of at least 1 225 MW in addition to the planned ones.

The underdeveloped local network endangers power supply in Buryatia and the Transbaikal Territory. The lack of backup power lines causes frequent power outages in the Tunka and Oka districts in Buryatia. Planned repairs of Klichka-Priargun power plant put significant pressure on the power system in Priargun load center.

Despite excessive capacities, the current power systems of Buryatia and the Transbaikal Territory fall short not only compared to the Irkutsk Region but also compared to the southern FEFD neighbors (the Amur Region and the Republic of Sakha (Yakutia)). This situation can be attributed to several factors: a) generating capacities

TABLE 3. Economic accessibility of electricity in the Baikal region

Indicators	Year	Irkutsk Region	Buryatia	Transbaikal Territory	FEFD (reference)
Electric capacity of GRP, kWh/RUB in constant prices of 2018	2018	0.038	0.008	0.023	0.012
	2022	0.039	0.009	0.023	0.012
Electric energy share in the total GRP, %	2018	4.3	3.8	4.2	3.2
	2022	3.5	3.0	2.5	2.6
Industry share in the total GRP, %	2018	45.4	17.9	21.7	38.4
	2022	44.3	25.6	29.5	39.1
Processing industry share in the total industry, %	2018	40.9	54.0	14.0	24.1
	2022	39.4	55.2	11.7	28.0
Electricity share in material costs, %	2018	18.5	3.6	7.5	4.5
	2022	14.5	2.2	5.3	3.6
Average population income per capita, thousand RUB/month	2018	24.5	24.1	24.0	35.9
	2023	42.3	38.3	42.4	57.1
Purchasing power of population, thousand kWh/month	2018	23.7	8.8	9.3	10.8
	2023	29.8	11.0	11.8	14.4

Source: compiled by the authors based on the data in [1-2; 23; 28].

consist mainly of thermal power plants (Table 1); b) the average age of equipment is above 33.9 years (Far Eastern average), leading to significant wear and tear, outages, and excessive fuel consumption – all of which contribute to rising costs; and c) the networks are still underdeveloped.

IV. Economic Accessibility of Electricity in the Baikal Region

Preferential regimes in the FEFD are aimed at stimulating economic activity in the region. Since demand for electricity depends on the scale of economic activity, an increase in economic activity naturally leads to a rise in consumption. From 2018 to 2023, the annual growth rate of electricity consumption in Buryatia (+2.8%) and the Transbaikal Territory (+2.1%) fell short when compared to the more developed Irkutsk Region, which boasted a growth rate of 3.8%. Moreover, the maximum and total consumption of electricity in the Irkutsk Region surpasses that of Buryatia and the Transbaikal Territory by nearly 7 to 10 times (Table 2).

The population continues to be the primary consumer of electricity across the entire Baikal region. The scale of electricity consumption in the Irkutsk Region, however, is almost 3-4 times larger than that in Buryatia and the Transbaikal Territory, outpacing even the rate of housing development. “The growth in electricity consumption is explained by new private low-density residential construction that uses electrical heating” [25, p. 27-28]. From 2018 to 2023, there was 1.5 times more housing development in the Irkutsk Region than that in Buryatia and the Transbaikal Territory combined. This is in spite of Far Eastern mortgage rates that were supposed to stimulate housing development in the FEFD. The other reason for increased consumption was “chaotic development of cryptocurrency mining” [26], mainly affecting southern areas in the Irkutsk power system that has the lowest rates. “The annual consumption in the city of Irkutsk grows 15% on average, while development of electrical network lags behind” [10, p.62]. The rise in household consumption places greater pressure on the local electricity supply. The existing reserves are sufficient to meet an annual consumption growth of 1.5-2%. However, with the estimated growth rates of 5-10%, the risk of electricity shortage rises significantly [25].

The potential to meet the growing demand depends on both the level of consumption and electricity prices. Both are used in the calculations of indicators for economic accessibility of electricity across various consumer groups. For the overall economy, we analyze the ratio of electricity to Gross Regional Product (GRP) and the share of electricity production within GRP [27]. For the industrial consumers, we assess the share of electricity expenses in material costs, while for the population, we consider purchasing power.

The existing energy systems of Buryatia and the Transbaikal Territory cannot compare to the Irkutsk Region in economic accessibility of energy. The Irkutsk Region boasts one of the highest electricity-to-GRP ratios among Russia’s regions. This is explained by lower prices thanks to hydropower and a dense concentration of electricity-intensive industries in the region, including metallurgy, chemical production, paper manufacturing, and machinery and equipment production (Table 3).

In contrast to the Irkutsk Region, Buryatia and the Transbaikal Territory have a more limited range of electricity-intensive industries. Buryatia can boast a high share of machinery production, while the Transbaikal Territory is notable for its chemical industry alongside machinery production and repair. The scale of processing industry in the Irkutsk Region is 6 times larger than that of Buryatia and 20 times greater than that in the Transbaikal Territory. The absence of new electricity-intensive manufacturing signifies that there is no urgent need for new institutional measures to develop the economies of Buryatia and the Transbaikal Territory.

The differences in economic development of the territories create different opportunities for local communities to afford public utilities, including electricity. The northern and eastern FEFD subjects have nominally high income, primarily driven by lucrative extraction industries, and low poverty rate, which can be attributed to the relocation of the retired from the region [29].

The Baikal region is characterized by both high-income and low-income positions, which are predominantly found in rural and remote areas, resulting in income levels that are nearly a quarter below the national average, as illustrated in Table 3. In the Irkutsk Region, 13.2% of population lives below the subsistence income levels, the Transbaikal Territory reports 15.4%, and Buryatia faces 17.3%, while the national average for Russia stands at a mere 8.5%.

TABLE 4. Purchasing power of the population in the Baikal region, thousand kWh/month

Regions	Electricity volume that could be purchased by population, divided into 20% groups by average income per capita									
	First (lowest income)		Second		Third		Fourth		Fifth (highest income)	
	2018	2023	2018	2023	2018	2023	2018	2023	2018	2023
Irkutsk Region	7.2	9.3	13.3	16.5	19.0	23.7	27.2	34.1	51.3	65.2
Republic of Buryatia	2.7	3.5	4.8	6.1	6.9	8.8	10.0	12.7	19.4	24.2
Transbaikal Territory	3.0	3.7	5.2	6.6	7.4	9.4	10.7	13.5	20.2	25.7

Source: author’s calculation based on the data from [2, 23, 30].

Economic accessibility, defined as a purchasing power of average income, also varies across different territories (Table 2). In 2023, the population of the Irkutsk Region could buy the largest volume of electricity per month (29.8 thousand kWh). This figure is not only double the national average (14.8 thousand kWh) but also outpaces 2.5-2.7 times purchasing power of the people in Buryatia and the Transbaikal Territory (11.0 and 11.8 thousand kWh, respectively) (Table 3). It is also important to note that across 11 FEFD subjects, the economic accessibility of electricity in Buryatia and the Transbaikal Territory was the lowest in 2018, when they just joined, and remains the lowest today, exacerbating income inequalities in the marcoregion.

Average indicators of income per capita lower the differences in electricity accessibility for different population groups. The purchasing power of the lowest-income 20% group in the Irkutsk Region thanks to the lowest tariffs in 2023 was 9.3 thousand kWh per month per capita (Table 4). In Buryatia and the Transbaikal Territory, this purchasing power is inaccessible even for the 3rd income 20% group, who could only buy 8.8 and 9.4 thousand kWh per person monthly, respectively. Thus, the purchasing power of 60% of the population in these two regions is 80% lower than the average in the Baikal region, leading to significantly poorer living conditions compared to the Irkutsk Region.

Although the three subjects of the Baikal region have comparable income levels, the purchasing power in Buryatia and the Transbaikal Territory falls below even the national average. For the lowest-income group, the purchasing power lags by 5-10%, while for the highest-income group, it is 27-30% lower.

Thus, despite the growing welfare and increasing nominal and real income between 2018 and 2023, the purchasing power in Buryatia and the Transbaikal Territory remains one of the lowest in the FEFD. This makes the two territories outsiders in the larger region when looking at them through the lens of economic welfare.

V. CONCLUSION

The study has led to the following significant conclusions. First, the physical availability of electricity in Buryatia and the Transbaikal Territory has not changed significantly throughout the considered period. Second, while economic accessibility has improved, it still lags behind that in the other FEFD subjects.

The Baikal region continues to grow and develop in different economic and institutional landscapes. The Irkutsk Region remains part of the Siberian Federal District, whereas Buryatia and the Transbaikal Territory joined the Far Eastern Federal District in 2018, benefiting from stimulating measures.

Buryatia benefitted from the preferential regimes in the FEFD, while the Transbaikal Territory experienced a boost in economic activity driven by stimulation efforts, ultimately reducing material costs. Despite the implementation of these preferential regimes and incentives, there has been no significant improvement in the economic trends in Buryatia and the Transbaikal Territory. This is especially evident when compared to the Irkutsk Region, which has an objectively superior energy supply and a stronger economy.

Energy systems of all the Baikal region subjects remain inertial and exhibit no significant changes.

The energy supply accessibility in Buryatia and the

Transbaikal Territory is lower than in the Irkutsk Region and neighboring southern FEFD areas due to two key factors:

1) The limited physical availability of electricity, which is a result of frequent outages caused by aging energy equipment and poorly developed power lines;

2) The inadequate economic accessibility of electricity, caused by elevated electricity tariffs that lower purchasing power of population, leading to a decline in overall quality of life.

These factors indicate that Buryatia and the Transbaikal Territory lack competitive advantages compared to their neighbors, which affects living conditions here and lowers their attractiveness as a place to live. This, in turn, influences the motivation of local population either to stay or leave, and deters new migrants who seek areas with better conditions.

In the coming years, Buryatia and the Transbaikal Territory are not anticipated to face any challenges related to physical availability of electricity. However, local shortages may persist, and limited capacity of distribution networks and ecological concerns, caused by overreliance on coal-fired thermal power plants, will continue to be pressing. The economic accessibility of electricity depends on the government's priorities and financial resources. State support for the population is justified by the critical social importance of energy supply, while assistance to industrial consumers serves as an effective measure that enhances competitiveness.

References

[1] «Gross regional product. 2022» Federal State Statistics Service, Moscow, Russia. [Online]. Available: https://rosstat.gov.ru/statistics/accounts (In Russian) (accessed 15.05.2024)

[2] «Regions of Russia. Socioeconomic indicators» Federal State Statistics Service, Moscow, Russia. [Online]. Available: https://rosstat.gov.ru/folder/210/document/13204 (In Russian) (accessed 14.05.2024)

[3] Decree of the President of the Russian Federation (November 3, 2018) No. 632, On Amendments to the List of Federal Districts Approved by Decree of the President of the Russian Federation (May 13, 2000) No. 849 [Online]. Available: http://publication.pravo.gov.ru/Document/View/0001201811040002 (In Russian) (accessed 27.06.2024)

[4] «Business support» Far East and Arctic Development Corporation. [Online]. Available: https://erdc.ru/supports/ (In Russian) (accessed 27.06.2024)

[5] Resolution of the Government of the Russian Federation (17 July 2017) No. 842, On Amendments to the Rules of the Wholesale Market of Electric Energy and Capacity and to the Consolidated Forecast Balance of Production and Supply of Electric Energy (Capacity) within the Unified Energy System of Russia by Subjects of the Russian Federation [Online]. Available: http://publication.pravo.gov.ru/document/0001201707210022 (In Russian) (accessed 27.06.2024)

[6] Order of the Government of the Russian Federation (December 29, 2021) No. 3965-r [Online]. Available: http://publication.pravo.gov.ru/document/0001202112310071 (In Russian) (accessed 27.06.2024)

[7] Order of the Government of the Russian Federation (December 28, 2022) No. 4295-r [Online]. Available: http://publication.pravo.gov.ru/document/0001202212290064 (In Russian) (accessed 27.06.2024)

[8] Order of the Government of the Russian Federation (December 27, 2023) No. 3964-r [Online]. Available: http://publication.pravo.gov.ru/document/0001202312290100 (In Russian) (accessed 27.06.2024)

[9] Order of the Government of the Russian Federation (July 13, 2015) No. 1339-r (as amended on February 3, 2020), On budgetary allocations provided by the Ministry for the Development of the Russian Far East to financial support for the costs of creating and (or) reconstructing infrastructure facilities, as well as for the technological connection of energy-receiving devices to electrical networks and gas-using equipment to gas distribution networks for the purpose of implementing investment projects in the territories of the Far East and the Baikal region [Online]. Available: http://publication.pravo.gov.ru/document/0001201507160009 (In Russian) (accessed 27.06.2024)

[10] V. Stennikov, V. Golovshchikov, «Energy industry of the Irkutsk region: trends, challenges, and threats in the current context» Energy policy, no. 12, pp. 56-71, 2022. Available: https://doi.org/10.46920/2409-5516.2022_12178.56 (in Russian)

[11] «Scheme and program for the development of electric power systems of Russia for 2024-2029: Power system of the Zabaikalsky Krai» System operator of the Unified Energy System of Russia. [Online]. Accessed on May 16, 2024. Available: https://www.so-ups.ru/fileadmin/files/company/future_plan/public_discussion/2024/final/12_Zabaikalskii_krai.pdf (In Russian) (accessed 16.05.2024)

[12] «Scheme and program for the development of electric power systems of Russia for 2024–2029: Energy system of the Republic of Buryatia» System operator of the Unified Energy System of Russia. [Online]. Accessed on May 17, 2024. Available: https://www.so-ups.ru/fileadmin/files/company/future_plan/public_discussion/2024/final/45_Respublika_Burjatija.pdf (In Russian) (accessed 17.05.2024)

[13] N. Sysoeva, K. Tszian, V. Krotova, «Institutional structure of the energy industry in the Baikal region» E3S Web of Conferences, 2023. vol. 470, p. 01016. Available: https://doi.org/10.1051/e3sconf/202347001016

[14] G.O.Borisov, «Problems and prospects of energy development in Buryatia,» ECO, no. 10, pp. 49–54, 2018. (In Russian)

[15] Ye.P. Maisyuk, «Key directions of maintaining ecological stability in the Baikal region» Izvestiya of Irkutsk State Economics Academy (Baikal State University of Economics and Law), no. 1, 2011. Available: http://brj-bguep.ru/classes/pdfDL.ashx?id=7572 (In Russian) (accessed 27.06.2024)

[16] «Scheme and program for the development of electric power systems of Russia for 2024-2029: Consolidated report on the UES of Russia» System operator of the Unified Energy System of Russia. [Online].Available: https://www.so-ups.ru/fileadmin/files/company/future_plan/public_discussion/2024/final/sipr_ups_2024-29_fin.pdf (In Russian) (accessed 15.05.2024)

[17] «Average weighted unregulated prices for the first price category» Website of the Irkutsk Energy Sales Company. [Online]. Available: https://sbyt.irkutskenergo.ru/qa/3626.html (In Russian) (accessed 28.04.2024)

[18] «Maximum levels of unregulated prices for electrical energy (capacity) supplied to consumers in 2023 - Zabaikalsky Krai» Website of JSC «Chitaenergosbyt». [Online]. Available: https://e-sbyt.ru/info/raskrytie-informacii-subektom-rynkov-elektroenergii/zabaikalskii-krai/predelnye-urovni-nereguliruemyh-cen-na-elektricheskuyu-energiyu-moschnost-postavljaemuyu-potrebiteljam/2023-god (In Russian) (accessed 08.04.2024)

[19] «Maximum levels of actual unregulated prices for electric energy (capacity), differentiated by price categories in 2023. Republic of Buryatia» Website of JSC «Chitaenergosbyt». [Online]. Available: https://e-sbyt.ru/info/raskrytie-informacii-subektom-rynkov-elektroenergii/respublika-burjatija/predelnye-urovni-nereguliruemyh-cen-na-elektricheskuyu-energiyu-moschnost-differencirovannye-po-cenovym-kategorijam/2023-god (In Russian) (accessed 08.04.2024)

[20] «Report on the functioning of the Unified Energy System of Russia in 2023 (based on operational data)» System Operator of the Unified Energy System. [Online]. Available: https://www.so-ups.ru/fileadmin/files/company/reports/disclosure/2024/ups_rep2023.pdf (In Russian) (accessed 28.05.2024)

[21] «Scheme and program for the development of electric power systems of Russia for 2024-2029: Power system of the Irkutsk region» System Operator of the Unified Energy System. [Online]. Available: https://www.so-ups.ru/fileadmin/files/company/future_plan/public_discussion/2024/final/14_Irkutskaja_oblast.pdf (In Russian) (accessed 05.05.2024)

[22] «Electric balance and electricity consumption in the Russian Federation in 2005-2023» Federal State Statistics Service, Moscow, Russia. [Online]. Available: https://rosstat.gov.ru/enterprise_industrial (In Russian) (accessed 01.05.2024)

[23] «Average consumer prices (tariffs) for goods and services» Unified Interdepartmental Information and Statistical System, Moscow, Russia. [Online]. Available: https://www.fedstat.ru/indicator/31448 (In Russian) (accessed 17.05.2024)

[24] «Consumer price indices for goods and services (percent)» Unified Interdepartmental Information and Statistical System, Moscow, Russia. [Online]. Available: https://www.fedstat.ru/indicator/31074 (In Russian) (accessed 02.05.2024)

[25] V. Stennikov, V. Golovshchikov, A.Osak, «Problems and prospects for the development of electric power industry in the eastern regions of Russia,» Energy Policy, no. 6, pp. 20-37, 2023. (in Russian)

[26] D.V. Mayakov, V.N. Kornilov, «Irkutsk - the capital of mining: new challenges for the energy system» Bigpower Daily, 12/16/2022. [Online]. Available: https://www.bigpowernews.ru/interview/document106777.phtml?1&q=0JzQkNCZ0J3QmNCd0JMg0JjQoNCa0KPQotCh0Jo= (in Russian) (accessed 05.05.2024)

[27] I.A. Bashmakov, «"Economics of the constants" and long cycles of energy prices dynamics» Voprosy Economiki, no. 7, pp. 36-63, 2016. Available: https://doi.org/10.32609/0042-8736-2016-7-36-63 (In Russian)

[28] «Costs of production and sales of products (goods, works, services) since 2017» Unified Interdepartmental Information and Statistical System, Moscow, Russia. [Online]. Available: https://www.fedstat.ru/indicator/58552 (In Russian) (accessed 15.05.2024)

[29] P.A. Minakir, S.N. Naiden, «Social Dynamics in the Russian Far East: Failure of the Institutional Paradigm» Regional Research of Russia, vol. 11, no. 2, pp.139-150, 2021. Available: https://doi.org/10.1134/S2079970521020118

[30] «Inequality and Poverty: Distribution and Differentiation of Monetary Incomes of the Population» Federal State Statistics Service, Moscow, Russia. [Online]. Available: https://rosstat.gov.ru/enterprise_industrial (In Russian) (accessed 22.05.2024)

Olga Valeryevna Dyomina, Ph.D. in Economics**,** serves as a Senior Researcher at the Economic Research Institute, FEB RAS (Khabarovsk, Russia). With a research background spanning 15 years, her research interests include regional economy, energy economics, with a focus on the energy sector of the Russian Far East. She has authored over 110 publications, including 8 papers indexed by Scopus and Web of Science. O.V.Dyomina can be reached via e-mail at demina@ecrin.ru

Svetlana Nikolaevna Naiden, D.Sc. in Economics, Professor of the Russian Academy of Sciences, holds the position of Deputy Director for Research and Head of the Social Development Department at the Institute of Economic Research of the Far Eastern Branch of the Russian Academy of Sciences (Khabarovsk, Russia). Her research interests include regional economy, welfare of the population, housing and municipal infrastructure, social development, and human capital of the Russian Far East. S.N.Naiden can be reached via e-mail at naidensvetlana@mail.ru

Environmental Prospects for Energy Sector Development in the Irkutsk Region

E.P. Maysyuk[*,1]

[1] Melentiev Energy Systems Institute, SB RAS, Irkutsk, Russia

***Abstract* — The future growth of the energy sector in the Irkutsk region hinges on prioritizing high-tech advancements in energy industries, enhancing raw material processing, expanding gas supply systems, and ensuring favorable environmental conditions. As it stands now, environmental conditions in the region are considered unfavorable, and energy facilities (most importantly, power generation facilities) affect all components of the environment in a significant way. Further expansion of coal-fired generation will contribute to more emissions of pollutants and greenhouse gases into the atmosphere, as well as the production and accumulation of coal combustion residuals. Environmental issues of the energy sector can be partially addressed by large-scale transitioning to natural gas. Natural gas conversion of three major thermal power plants alone will reduce pollutant emissions in the region by 1.5 times. However, the commissioning of a modern coal-fired power plant can offset this effect, which eventually sets the region back to the baseline in terms of pollutant emissions. Furthermore, it also entails a 2.5-fold increase in greenhouse gas emissions and a 2-fold increase in the production of coal combustion residuals. Gas infrastructure expansion can prove instrumental in addressing environmental challenges facing the energy sector locally, i.e., in the southern districts of the region. The growth of coal-fired power generation will hinder the compliance with the requirements of the Clean Air Project, which is currently being implemented in the Irkutsk region.**

***Index Terms* — Energy facilities, environmental performance, coal-fired generation, gas infrastructure expansion.**

I. Introduction

Environmental issues facing the Irkutsk region are primarily related to the increasing emissions of pollutants into the atmosphere, resulting from economic activities of industrial enterprises. Overall, emissions in 2022 totaled 800 400 tons, of which 739 300 tons were from stationary sources. Over the period of 2018 to 2022, the region's stationary source emissions exhibited an upward trend, reaching a 15% increase. In contrast, emissions from mobile sources in the region steadily declined during the same period. The reduction in emissions from mobile sources can be attributed to a rising adoption of electric vehicles, along with a steady rise in the use of natural gas vehicle (NGV) fuel, especially in the northern areas of the region.

Energy companies involved in electricity and heat generation, as well as extraction of fuel and energy resources (such as coal and hydrocarbons) are among the industrial enterprises significantly influencing the indicators of environmental performance in the Irkutsk region.

This study provides an environmental assessment of the potential for energy development in the region, focusing on power generation facilities such as thermal power plants

[*] Corresponding author.
E-mail: maysyuk@isem.irk.ru

http://dx.doi.org/10.25729/esr.2024.04.0002

Received November 20, 2024. Accepted November 29, 2024. Available online December 28, 2024.

and boiler plants. The environmental performance indicators assessed include the emissions of pollutants into the atmosphere and production of coal combustion residuals. Additionally, carbon dioxide emissions are estimated with a view to complying with the directives of low-carbon development of the energy sector.

II. Calculation Methods

The analysis of current environmental conditions in the Irkutsk region involves processing the data from statistical publications on atmospheric air quality indicators [1, 2], state reports on environmental conditions and environmental protection [3, 4], and official data released by individual companies operating in the region [5, 6].

Environmental assessment of the prospects for the energy development in the region includes the calculation of pollutant emissions for four primary components specific to the energy sector: particulate matter, sulfur dioxide, nitrogen oxides, and carbon monoxide. The calculation is based on the procedures approved in the Russian Federation for the calculation of gross emissions from TPPs and boiler plants [7–9]. The calculations within this study employ the data on the quantity and quality of fuel combusted, as well as specifications of different types of power generation facilities. The quantity-related data are derived from the data on consumption of fuel and energy resources by TPPs and boiler plants in the Irkutsk region in 2022 (the statistical reporting form 4-TER).

The estimates of greenhouse gas emissions from energy facilities in the Irkutsk region rely on the procedure for quantitative assessment of greenhouse gas emissions approved by the Ministry of Natural Resources and Environment of the Russian Federation No. 371 dated 27.05.2022 [10]. It is important to emphasize that estimates of greenhouse gases resulting from combustion of biomass and biomass products by stationary power plants are not taken into account in Russia. The calculation is based on emission factors recommended by both the International Panel on Climate Change (IPCC) and Russian experts [11].

III. The Influence of the Energy Sector in the Irkutsk Region on Its Environmental Indicators

According to the state report of the Ministry of Environment and Natural Resources of the Irkutsk region, the emissions of pollutants into the atmosphere by three major energy enterprises alone (OOO Baikal'skaya Energeticheskaya Kompaniya, OOO Kompaniya Vostsibugol', and OOO INK [5]) amounted to 388.4 thousand tons, or 52% of the total emissions in the region in 2022 [4].

Statistical data on air pollutant emissions from boiler plants are not available (not intended for public disclosure). However, according to the studies conducted at the Melentiev Energy Systems Institute SB RAS, calculated emissions from numerous and predominantly coal-fired boiler plants are estimated at 100–120 thousand tons annually [12]. Consequently, when factoring in the emissions from boiler plants, the contribution of energy enterprises, including heat and electricity generation as well as coal and hydrocarbons extraction, will rise to 70–75% of all pollutant emissions into the atmosphere. The contribution of energy enterprises to the waste generation during the production and consumption processes is also significant: up to 55% of the waste produced in 2022, which is equal to 191 million tons [2–4].

One of the primary environmental concerns in the region is the influx of sulfur dioxide into the air basin. This pollutant can travel long distances, undergo atmospheric oxidation, and eventually fall out in the form of acid precipitation, impacting areas such as the waters of Lake Baikal. One of the major SO_2 emitters in the Irkutsk region is OOO Baikal'skaya Energeticheskaya Kompaniya, whose energy enterprises contribute up to 83% of all SO_2 emissions.

The issues arising in the course of operation of energy facilities most notably include generation of waste resulting from production and consumption. In the case of power generation, it is coal combustion residuals with a hazard rating of 4 or 5 in the amount of 2 million tons, which are partially disposed by large energy facilities. Waste storage and disposal require significant space for ash ponds, which have already been largely filled up. Coal mining precludes all other economic activities on vast areas either. Even though its waste is low-hazardous, it nonetheless requires measures for land reclamation. The waste-related issues associated with hydrocarbon production call for activities to address not only the disposal of significant amounts of highly hazardous waste with a hazard rating of 2 or 3, but also their deactivation.

Another environmental issue facing the energy sector of the Irkutsk region is the emission of greenhouse gases into the atmosphere. The thermal power plants operated by OOO Baikal'skaya Energeticheskaya Kompaniya are responsible for nearly 19.6 million tons of CO_2 emissions in 2022 [6]. The amount of carbon dioxide emitted by boiler plants, given their fuel consumption, is estimated at 4–4.5 million tons. Accordingly, the total CO_2 emissions from fossil fuel combustion at energy facilities of the Irkutsk region are estimated at 23–25 million tons. An aggregated assessment of greenhouse gas emissions from fuel and energy enterprises in the Irkutsk region shows that in the case of coal production by open-pit mining (as based on data on production volumes in 2022), they reach 30–32 million tons of CO_2-eq; and in the case of hydrocarbon production, emissions range from 14 to 18 million tons of CO_2-eq (as based on the data on specific greenhouse gas emissions from flaring reported by the INK group [5]).

As a result, up to 70–74 million tons of CO_2-eq are emitted into the atmosphere by the facilities of the Irkutsk region's energy sector alone.

Thus, even despite the implementation of annual environmental protection measures and the use of environmentally friendly renewable sources, energy enterprises of the region still have to address environmental issues since they are significant contributors to the high level of atmospheric pollution in cities and major industrial centers. Furthermore, they are responsible for the growth and accumulation of waste resulting from the extraction of fuel and energy resources. The main causes of the environmental issues are a) the high share of coal in the fuel and energy balance of the region; b) the inadequate treatment of flue gases, in particular, the absence of gas-capturing equipment at large TPPs, and improper ash handling, or a complete lack thereof altogether, at boiler plants of the region; c) production growth and waste accumulation.

IV. Prospects for Energy Sector Development in the Region

The prospects for the energy sector development in the region are linked to the plans for socio-economic development of the area, which is reflected in the Strategy for Socio-Economic Development of the Irkutsk Region to 2036, approved by the Legislative Assembly of the Irkutsk Region on January 10, 2022, under No. 15-OZ. The main areas of prospective socio-economic development of the region focus on the creation and prioritized development of high-tech, knowledge-intensive industries with advanced processing of raw materials, expansion of gas supply systems, and enhancement of environmental conditions, which in turn requires an almost twofold increase in energy consumption. Individual economic sectors have the greatest demand for electricity and heat, gas and oil products. This demand for energy resources can be met by developing local mining enterprises and expanding self-generation capabilities, or by sourcing supplies from neighboring regions.

Pursuing the development of self-generation facilities involves, as before, the expansion of coal-fired generation by large TPPs, subject to modernization and renovation of a number of coal-fired power facilities as well as commissioning of a new large coal-fired plant. For example, the development program of OOO Baikal'skaya Energeticheskaya Kompaniya for certain coal-fired plants provides for the commissioning of new coal-fired units at existing TPPs (CHPP-10 and CHPP-11). The environmental priorities set for these units are: flue gas treatment to remove not less than 95–96% of emissions of particulate matter; 60–80% inhibition of sulfur oxides formation (furnace injections of limestone [13, 14]); and 55% suppression of nitrogen oxides, which implies fuel combustion at low excess air and recirculation of flue gases [14–16].

Commissioning of a new large coal plant leads to an increase in pollutant emissions by estimated 80 thousand tons per year. This factors in the adoption of the best available technologies (BAT) at the plant, such as a system of capturing at least 99% of particulate matter and a highly efficient desulfurization system that achieves the efficiency of at least 90% in capturing and reducing SO_2 and NOx [17, 18].

The plans for heat sources include modernizing large coal-fired boiler plants and equipping them with ash handling equipment with an efficiency of at least 85–90%. Additionally, small-capacity boiler plants will be converted to automated ones, such as “Termorobot” or “Prometheus,” which will reduce pollutant emissions into the atmosphere by 20% even when they run on coal.

The assessment of environmental performance of the region's energy sector development assumed that the fuel consumption structure is dominated by coal at both TPPs and boiler plants. The findings indicate a significant 45–50% increase in pollutant emissions and a twofold growth

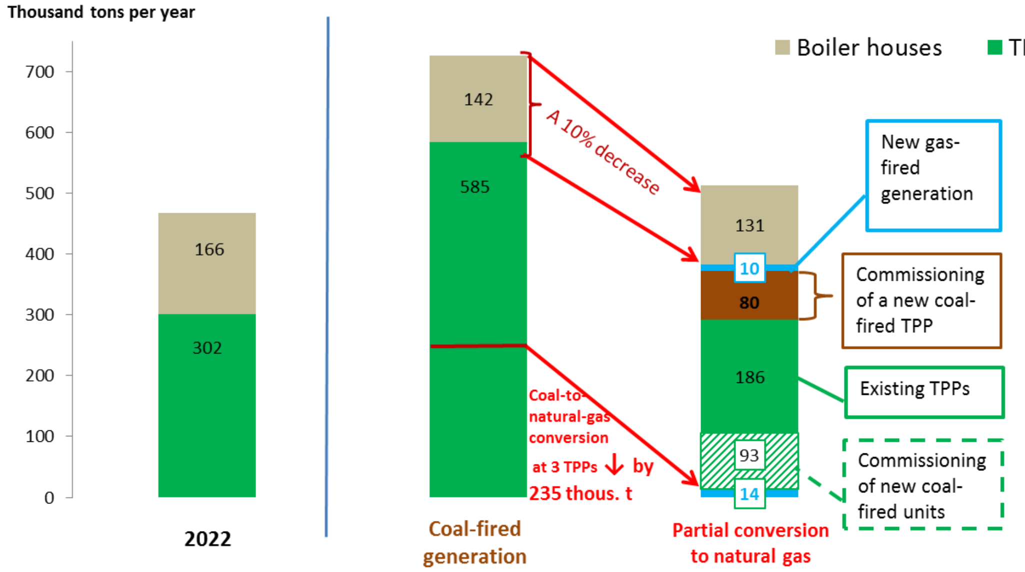


Fig. 1. Environmental effect of partial conversion of energy facilities to natural gas in the Irkutsk region.

in carbon dioxide emissions into the atmosphere. The rise in the amount of waste generated is proportional to the increase in coal combustion. For example, meeting the region's projected energy demand will require an increase in the amount of coal burned from 7 to 19.5 million tce. The main sources of pollutants into the atmosphere will remain large power generation facilities (TPPs), whose operation will contribute up to 74% of the total pollutant emissions in the region.

The greatest environmental effect can be achieved through the expansion of gas infrastructure. For example, conversion to gas of NI-CHPP and coal-fired units of CHPP-9 and CHPP-10 will reduce pollutant emissions by 1.5 times (or by 235 thousand tons/year) compared to coal-fired generation. Large-scale use of natural gas will allow more boiler plants to switch to gas (reducing emissions by 10%) and ensure commissioning of three new gas-fired plants (Lenskaya TPP, Pravoberezhnaya TPP, and the TPP located in the Irkutsk-Cheremkhovo district that runs on the Kovykta gas), whose contribution to emissions is insignificant and does not exceed 10 thousand tons/year, see Figure 1.

Converting power plants and boiler plants to natural gas will reduce coal consumption. However, the commissioning of a new large coal-fired plant will lead to a twofold increase in coal consumption relative to 2022, from 7 to 14.1 million tce, which will affect correspondingly the environmental conditions in the region, even with the implementation of BAT.

Comparison of coal-fired generation and partial natural gas conversion of the region's energy facilities indicates that the environmental effect of switching to natural gas even of the three plants and several boiler plants will total 246 thousand tons per year. Construction of new gas-fired plants cannot change drastically the environmental conditions. The biggest impact may be that of the construction of a large, albeit modern, coal-fired plant, which is required to meet prospective energy demand for high-tech development of the region's economy. This approach will not bring about any changes to the environmental conditions in the Irkutsk region as compared to the 2022 baseline. The amount of pollutant emissions will remain approximately the same, but carbon dioxide emissions will increase 2.5 times, and the amount of coal combustion residuals generated is expected to double.

The environmental assessment of the prospects for the Irkutsk region's energy sector development shows that the expansion of coal-fired power generation precludes from complying with the requirements of the “Clean Air” project, which is being implemented as part of the federal project “Ecology”. This is due to an increase in pollutant emissions at almost all energy facilities in the region.

It is worth noting that the operating energy facilities is not the sole reason behind the implementation of the Clean Air Project to improve the environmental conditions in the region. For example, apart from the energy facilities operated by OOO Baikal'skaya Energeticheskaya Kompaniya (CHPP-6 and CHPP-7) in Bratsk, the major contributors to the pollution of the atmosphere are industrial facilities owned by PAO RUSAL, an AO Gruppa Ilim branch, OOO Bratsky Zavod Ferrosplavov, and motor transport enterprises. Therefore, it is crucial to understand the role of the energy sector in addressing the issues related to emissions in the above cities. Table 1 presents a comparison of emissions generated by each city included in the Clean Air Project [2], highlighting the contributions from large energy facilities located there [4].

Large energy facilities play a significant role only in three cities: Angarsk (CHPP-9, CHPP-10), Usolye-Sibirskoye (CHPP-11), and Cheremkhovo (CHPP-12). It is these cities that need urgent measures in the energy sector to meet the state environmental requirements under the Clean Air Project. Of course, natural gas conversion of the three plants will both reduce emissions almost twofold and ensure full compliance with the project requirements in the cities of Irkutsk and Angarsk. Emissions in these cities will decrease by a factor of 13.

In the cities of Bratsk and Shelekhov, the main efforts should focus on reducing emissions from the aluminum industry.

In all likelihood, the pollution in Zima is due to the emissions from the Novo-Ziminskaya CHPP located in Sayansk. Hence, it is evident that the energy sector is responsible for 95% of pollutant emissions into the atmosphere (given the emissions in Zima and Sayansk of 30.9 thousand tons and the emissions by NZ-CHPP of 29.4 thousand tons), which calls for appropriate environmental measures. Conversion of Novo-Ziminskaya CHPP in Sayansk to natural gas could resolve this issue.

V. Conclusion

Current environmental issues of the energy sector in the region are related to the high penetration of coal-fired generation. This, in turn, causes a high atmospheric pollution by TPPs, contributing mostly sulfur dioxide, and boiler plants, emitting particulate matter. Along with pollutants, the atmosphere absorbs greenhouse gases, which are currently estimated at 24–25 million tons of CO_2-eq emitted by all energy facilities in the region. When factoring in the contribution by enterprises involved in extraction of fuel and energy resources, the number reaches 70–74 million tons of CO_2-eq per year. Furthermore, coal combustion produces up to 2 million tons of coal combustion residuals annually.

The prospects for the region's energy sector development are related to higher coal consumption, which significantly aggravates the existing environmental challenges. However, the use of natural gas as part of the fuel and energy balance will improve the situation to some extent. Natural gas conversion of three TPPs in the region with the existing coal-fired plants kept in operation and modernized, alongside the natural gas conversion of boiler plants and commissioning of a new coal-fired plant to meet a given demand for energy, change little, if at all, the current level of pollutant emissions into the atmosphere.

Table 1. Comparison of Reported Emissions for Cities Covered in the Clean Air Project with Pollutants Contributed by Operating Energy Facilities in 2022

City	Emissions in cities (2022), thousand tons	Generation facilities in cities	Emissions from energy facilities	
			thousand tons	%
Angarsk	113.2*	CHPP-9, CHPP-10	134.7	-
Bratsk	101.2	CHPP-6, CHPP-7	13.7	14
Zima	1.5	boiler plants	no data	-
Irkutsk	132.4	NI-CHPP	52.4	40
Svirsk	0.4	boiler plants	no data	-
Usolye-Sibirskoye	19.4	CHPP-11	18.8	97
Cheremkhovo	3.2	CHPP-12	2.3	72
Shelekhov	40.9	NI-CHPP (Shelekhov section)	5.7	14

Note: * – Statistical data provided by Rosprirodnadzor are presented for the Angarsk urban district

Conversion of the three thermal power plants and some boiler plants to natural gas reduces emissions by 246 thousand tons/year. Construction of new gas-fired plants cannot affect the environmental situation in any significant way.

It is important to indicate, however, that natural gas conversion can improve the environmental conditions locally in some areas of the Irkutsk region. Most notably, this is the case of the southern part of the region, where the potential for reduction in pollutant emissions into the atmosphere is estimated at 1.5 times.

Resolving environmental issues in the energy sector of the region requires various measures ranging from simple and affordable to large-scale and costly. Available low-cost measures include leveraging fuel preparation technology prior to combustion, optimizing and maintaining optimal fuel combustion conditions, and replacing high-ash and high-sulfur coal varieties with more environmentally friendly alternatives. Large-scale measures include:

- utilizing natural gas and increasing its share in the fuel and energy balance;
- ensuring district heating in large cities of the region, while phasing out small coal-fired boiler plants;
- installing gas treatment (desulfurization) equipment at large thermal power plants.

Coal-fired boiler plants (especially those of large capacity) have to reduce particulate emissions through upgrading and installing advanced ash handling equipment. The effort should also be focused on the expansion of gas infrastructure and the modernization of small-capacity boiler plants into state-of-the-art automated ones.

Acknowledgements

This research was conducted as part of the State Assignment Project (no. FWEU-2021-0004) under the Basic Research Program of the Russian Federation for 2021–2030 and utilized the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

References

[1] The state of atmospheric pollution in cities of Russia for 2022: Yearbook. St. Petersburg, Russia: Federal Service for Hydrometeorology and Environmental Monitoring (Rosgidromet), Federal State Budgetary Institution “Voeikov Main Geophysical Observatory” (FSBI MGO under Rosgidromet), 2023, 256 p. (In Russian)

[2] Information on protection of atmospheric air. Form No. 2-TP (air) for 2022. Federal Service for Supervision of Natural Resources (Rosprirodnadzor). [Online] Available: https://https.rpn.gov.ru/open-service/analytic-data/statistic-reports/air-protect/. Accessed on: Oct. 24, 2023. (In Russian)

[3] On current environmental conditions and environmental protection of the Russian Federation in 2021. State report. Moscow, Russia: Ministry of Natural Resources of Russia; M. V. Lomonosov Moscow State University, 2022, 684 p. (In Russian)

[4] State report “On current environmental conditions and environmental protection of the Irkutsk Region in 2022.” Irkutsk, Russia: OOO Maksima, 2023, 285 p. (In Russian)

[5] Consolidated annual report of AO INK-Kapital for 2022. Corporate website of OOO Irkutskaya Neftyanaya Kompaniya. [Online] Available: https://irkutskoil.ru/upload/iblock/266/65hx0vkbmr0zgirkf0jvd7dzhqr6gws9.pdf. Accessed on: Oct. 06, 2023. (In Russian)

[6] Environmental impacts. Environmental performance in 2020-2021. Corporate website of OOO Baikal'skaya Energeticheskaya Kompaniya. [Online] Available: https://bec-company.ru/ekologiya/vozdeystvie-na-okruzhayushchuyu-sredu/. Accessed on: Jun. 21, 2023. (In Russian)

[7] Procedure for calculating gross emissions of air pollutants from TPP boiler plants, RD 34.02.305-98, All-Russia Thermal Engineering Institute (VTI), Moscow, Russia, 1998. (In Russian)

[8] Order of the State Committee on Environmental Protection of the Russian Federation (1999, Jul. 09). Procedure for calculating pollutant emissions from fuel combustion in boiler plants with a capacity below 30 tons of steam per hour, or 20 Gcal/h. St. Petersburg, Russia: Integral, 1999, 53 p. (In Russian)

[9] A methodological letter No.335/33-07 of May 17, 2000 “On calculations of harmful emissions into the atmosphere as per the Procedure for calculating pollutant emissions from fuel combustion in boiler plants with a capacity below 30 tons of steam per hour, or 20 Gcal/h,” JSC NII Atmosphere, St. Petersburg, Russia, 2000, 20 p. (In Russian)

[10] Order of the Ministry of Natural Resources and Environment of the Russian Federation (2022, May 27). No. 371, On approval of procedures for quantitative assessment of greenhouse gas emissions and greenhouse gas removals. [Online] Available: https://carbonreg.ru/pdf/Общие%20НПА/Приказ%20Минприроды%20РФ%20от%2027.05.2022%20N%20371.pdf. Accessed on: Sep. 25, 2023. (In Russian)

[11] Order of the Ministry of Natural Resources of Russia (2015, Jun. 30). No. 300, On approval of methodological guidelines and a manual on quantification of amounts of greenhouse gas emissions by the entities involved in economic and other activities in the Russian Federation. [Online] Available: https://www.rosteplo.ru/Npb_files/npb_shablon.php?id=1740. Accessed on: Jul. 20, 2020. (In Russian)

[12] B. G. Saneev, E. P. Maysyuk, "Environmental impact assessment of the energy sector of the Irkutsk region," Bulletin of Baikal State University, vol. 28, no. 2, pp. 249–256, 2018. DOI: 10.17150/2500-2759.2018.28(2).249-256. (In Russian)

[13] L. I. Pugach, Analysis and quantitative assessment of the effect of fuel quality on the efficiency of ash treatment and ash removal systems of TPPs and their environmental performance: Textbook. Novosibirsk, Russia: Novosibirsk State Technical University, 1995, 153 p. (In Russian)

[14] P. V. Roslyakov, "State of the art of air protection technology at thermal power plants (review)," Thermal Engineering, no. 7, pp. 46–62, 2016. (In Russian)

[15] I. Ya. Sigal, O. I. Kosinov, A. N. Duboshiy, S. S. Nizhnik, "Enhancing efficiency of the methods for reducing the buildup of nitrogen oxides in boiler furnaces," Thermal Engineering, no. 7, pp. 6–9, 1986. (In Russian)

[16] L. I. Kropp, L. A. Mamrukova, "Topical issues of standardizing and reducing TPP emissions," Thermal Engineering, no. 3, pp. 2–5, 1989. (In Russian)

[17] Investment program of a PAO OGK-2 branch. [Online] Available: https://ogk2.ru/investitsionnaya-programma/obekty-dpm/psu-660-territoriya-troitskoy-gres/. Accessed on: Jun. 19, 2024. (In Russian)

[18] PAO OGK-2 commissioned an efficient desulfurization system at the Troitskaya condenser-type thermal power plant. [Online] Available: https://www.in-power.ru/news/novostitek/24393-na-troickoi-gres-pao-ogk-2-vvedyon-v-ekspluataciyu-effektivnyi-kompleks-seroochistk.html. Accessed on: Jun. 19, 2024. (In Russian)

Elena P. Maysyuk, Ph.D. in Economics (2002), is a Senior Researcher of the Energy Supply to Off-Grid Consumers Subdepartment at the Melentiev Energy Systems Institute SB RAS, Irkutsk. She graduated from the Energy Department of Irkutsk Polytechnic Institute with a major in Thermal Power Plants Engineering (1989). Her research interests include environmental issues of energy systems development in East Siberia and the Russian Far East. She has authored and co-authored more than 90 publications, including chapters and sections in 22 edited volumes.

The Coal Industry of the Irkutsk Region: Development Trends and Challenges

L.N. Takaishvili [1,*]

[1] Melentiev Energy Systems Institute, SB RAS, Irkutsk, Russia

***Abstract* — The paper provides an update on the state of the coal industry of the Irkutsk region. It reviews the trends in coal production and supply with a breakdown by uses of coal. The main consumers of Irkutsk coal are power plants located in the Irkutsk region, while about 20% of the coal is exported. The analysis covers the factors that contribute to sustaining and growing the supply of Irkutsk coal, including the availability of commercial reserves of coal. The study highlights the priority areas and limitations of the coal industry development in the region.**

***Index Terms* — Irkutsk region, coal, mining, coal preparation, trends, commercial reserves, outstanding issues.**

I. Introduction

The emergence of the coal industry in the Irkutsk Governorate was enabled by the construction of the Trans-Siberian railroad in the late 19th century (in 1896) [1]. Initially, coal was mined at the Cheremkhovskoye coal deposit, later at other deposits in the Cheremkhovsky district. The growth in coal mining made the coal industry second only to gold mining in terms of importance. The history of coal production saw both increases and decreases. In the first half of the 20th century, coal was predominantly extracted via underground mining, which was gradually replaced by the more cost-effective open-pit mining method. Since 1980, open-pit mining has been the only form of coal mining in the Irkutsk region.

At the early stages, the main consumer of coal was the railroad, which accounted for up to 85% of demand, and the other 15% was consumed by industrial enterprises and households. The large-scale industrialization of the region following the Great Patriotic War included the commissioning of coal preparation plants and construction of large-capacity coal-fired power plants running on Irkutsk coal as their main fuel. Starting in 1956, HPPs of the Angara cascade were gradually put into operation one after another, and the share of coal-fired generation in the regional energy balance decreased accordingly. The share of coal in fuel consumption of the region is high compared to other types of fuel and amounts to about 80%, in contrast to Russia as a whole, where this share does not exceed 20%. CHPPs of the Irkutsk region have been to date the main consumers of the coal produced locally.

The current state and development opportunities of the coal industry in the Irkutsk region affect the reliability and performance of the regional energy sector. Many challenges faced by the coal industry of the region are common to other regions of Russia, mainly in the Asian part of the country (Siberian and Far Eastern Federal Districts), which is responsible for the majority of the country's coal production and consumption [2]. Coal industry enterprises are key employers in towns such as Cheremkhovo and Tulun.

This study aims to analyze the trends in the development of the coal industry of the Irkutsk region; assess the

* Corresponding author.
E-mail: luci@isem.irk.ru

http://dx.doi.org/10.25729/esr.2024.04.0003

Received November 20, 2024. Accepted November 29, 2024. Available online December 28, 2024.

resources and reserves of coal as a fossil fuel from the standpoint of the development of the industry; and identify the key development challenges, threats, and prospects, as well as the factors contributing to and inhibiting such development.

II. Trends in the Development of the Coal Industry

Most of the coal is produced at large coal deposits such as Cheremkhovskoye, Azeyskoye, and Mugunskoye, whose production capacity is over a million ton per year. In 2022, there were 22 holders of licenses to mine coal deposits and subsoil areas in the Irkutsk Region. Coal was mined by 14 operating open-pit mines and 5 open-pit mines under construction [3]. The great bulk of production (more than 80%) was contributed by major enterprises such as OOO Kompaniya Vostsibugol', OOO Mugunsky Yuzhny Razrez, and OOO Razrez Cheremkhovugol'. Some areas of their deposits have the reserves-to-production ratio ranging from 15 to 65 years (the ratio of recoverable reserves that are the working inventory at producing mines to the production volume reported for the last year).

Key features of the coal industry in the Irkutsk region are a large number of independent enterprises of small capacity and EN+ GROUP ownership over major enterprises, such as OOO Kompaniya Vostsibugol' and OOO Razrez Cheremkhovugol' [4]. EN+ GROUP is an international company that is a world leader in the production of low-carbon aluminum and renewable energy, and coal mining and coal processing are not among its key business activities. The mix of small-capacity enterprises developing relatively small coal deposits is never stable: new enterprises emerge, some of them operate for a long time, and some of them cease operations for various reasons, including the depletion of deposits.

Since 2016, coal production in the Irkutsk Region has been on an upward trend (Fig. 1), mainly due to the growth of exports accompanied by a decrease in supplies to other regions of Russia. Statistical data reported in different official sources are inconsistent, but, in any case, they allow grasping the trends in the development of the industry.

According to Rosstat, coal production in 2022 was 16.10 million tons, including 14.66 million tons by major enterprises and 1.44 million tons by small-sized businesses (including micro-enterprises). According to the data by Federal Subsoil Resources Management Agency, Russian Federal Geological Depository, 35.4% of coal production in 2022, was lignite mining [3]. The total production capacity of operational and under-construction enterprises was 18.3 million tons per year.

As a rule, coal mining companies have up to 90 other registered business activities, mostly unrelated to coal mining. For example, OOO Transugol' that reported the reserves-to-production ratio of 7 years [3] has “Open-pit anthracite mining” as its main business activity [6] and also lists the following additional business activities: “Open-pit metallurgical coal mining”; “Open-pit coal mining, excluding anthracite, metallurgical coal and lignite mining”; “Ore and mineral sands mining of precious metals (gold, silver, and platinum-group metals)”; “Stone, sand and clay mining”, along with 22 other activities not related to mining, but related to trade, construction, renting, and other. In addition to coal mining, OOO Yumiks carries out business activities in 52 other areas [7] and has the coal reserves-to-production ratio of 0 years [3] (no coal mining in 2022). Such companies, when the reserves of the areas of deposits licensed to them are depleted, continue to operate, and may not produce coal every year. The largest company OOO Kompaniya Vostsibugol' is not an exception either: it is involved in 70 other areas of business activities, both related and unrelated to its main business activity [8].

EN+ GROUP's coal mining enterprises provide coal to the CHPPs owned by the company, serve EN+ GROUP's internal demand for coal, with part of the coal supplied (sold) to third-party companies and exported.

Most coal production comes from the large deposits of the Irkutsk coal basin: the Azeyskoye, Mugunskoye, and Cheremkhovskoye deposits, where coal has been extracted for over a century. The development started in the subsoil areas that were best in terms of mining and geological conditions, coal quality parameters, etc. This has resulted in a decline in quality (in terms of sulfur and ash content) of the coal produced presently at the deposits that have been in operation for dozens of years (Table 1). High sulfur content is one of the key issues restricting the use of Cheremkhovskoye deposit coal and lignites from the Mugunskoye and Azeyskoye deposits. This leads to the use of off-spec fuel at coal-fired CHPPs, which, despite compromising the equipment, has been an established practice for many years [9].

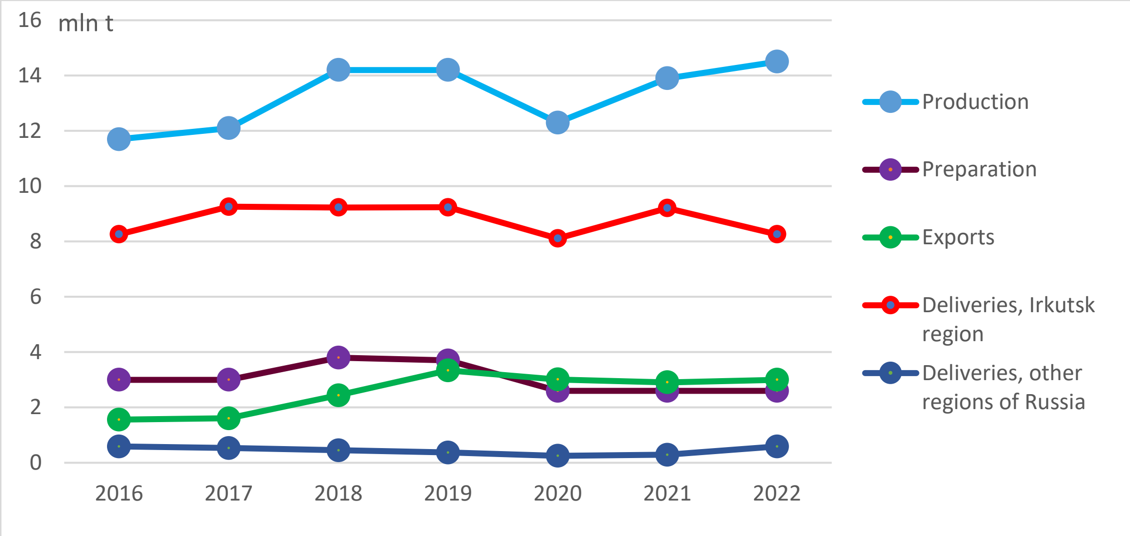


Fig. 1. Characteristics of the coal industry of the Irkutsk region.

Coal preparation in the region is carried out at the Kasyanovskaya central preparation plant, which produces coal concentrate. The plant receives about 80% of the coal produced at the Cheremkhovskoye deposit. Coal is processed by beneficiation in heavy media and jigging, even though there exist more economical and more effective methods [12–17] adopted worldwide, including dry coal beneficiation technologies.

III. Supply and Consumption

Irkutsk coal is supplied to the domestic market (mainly to consumers within the region), while also being exported in significant amounts, and delivered in small quantities to areas beyond the region. The main consumers of Irkutsk coal are CHPPs and boiler plants of the Irkutsk region (Table 2) that consumed 89.9% and 9.8%, respectively in 2022. The Irkutsk region energy system includes 14 operating thermal power plants (TPPs), 13 of which run mostly on coal, and 4 hydroelectric power plants (HPPs) of the Angara cascade. HPPs and CHPPs of the Irkutsk region

Table 1. Quality Parameters of Hard Coal and Lignites of the Irkutsk Coal Basin

Year	Coal quality		
	Content, %		Calorific value
	ash	sulphur	MJ/kg
2015	7–15	1.5–5	17.6–22.6
2021	12–35	0.4–7.8	10.0–25.0

Sources:[10, 11]

are owned by EN+ GROUP.

As of January 1, 2022, the installed capacity of Irkutsk region CHPPs and HPPs is 70% HPPs and 30% coal-fired CHPPs [18]. Accordingly, coal supply (consumption) to power plants, which are the balancing facilities of the power system, are subject to significant fluctuations of around one million tons (0.8 million tce) relative to the previous year. This is primarily due to hydrological conditions (water content of rivers and reservoirs). Climate conditions (cold or warm winters) also have a great impact, as CHPPs operate in the cogeneration mode, producing both electrical and thermal energy.

Coal supplied by small enterprises is consumed by the nearest boiler plants, used by the population, or is exported. Moreover, small enterprises account for about 70% in coal exports.

Off-grid areas, mostly the ones in the far north or those considered as such, use coal as boiler and furnace fuel. Coal is transported to these areas mainly in the navigation season by water transport. Limited amounts of coal and other fuel and energy resources are delivered by rail and road transport as well. Ice roads are also used during the heating season for transportation. The coal price in such areas is quite high because of the transportation costs. Weather conditions affect the organization of the northern supply haul (duration of the navigation season and the operating window of ice roads) [19, 20].

Exports of Irkutsk energy coals have increased compared to the last century (Fig. 2), when only the coal of

TABLE 2. Coal Consumption in the Irkutsk Region, Mln TCE

End user	Year								
	2010	2015	2016	2017	2018	2019	2020	2021	2022
Total, including	8.16	6.96	6.91	7.18	7.77	7.31	7.03	6.96	7.74
TPPs	7.05	5.99	5.93	6.22	6.81	6.45	6.22	6.18	6.96
Boiler plants	1.01	0.86	0.87	0.85	0.85	0.76	0.70	0.68	0.76
Others	0.09	0.11	0.11	0.11	0.12	0.11	0.10	0.10	0.02

Sources: Statistical reporting forms: Use of fuel and energy resources for certain types of products, works (services), Irkutsk region, 2010–2022

the Cheremkhovskoye deposit was supplied in the amount of about 0.3 million tons. The share of Cheremkhovskoye deposit coal in exports is currently about 30%. The remaining 70% is exported by small enterprises producing hard coal that is superior in quality to Cheremkhovskoye deposit coal, primarily in terms of sulfur content (with sulfur content less than 1% and ash content less than 20%).

Despite the growth in Irkutsk coal exports, their share in Russian coal exports to individual countries in 2021 amounted to 1 to 3.6%. China, being the largest importer of Irkutsk coal, accounted for 3.3% alone, while being the destination of about 50% of coal exports from the Irkutsk region.

IV. COAL RESOURCES FOR INDUSTRY DEVELOPMENT

The Irkutsk region has significant coal resources and coal reserves. Most of the coal reserves are those of energy coal, whereas coking coal accounts for only about 9% of coal reserves. As of January 1, 2023, Irkutsk region's proven commercial A+B+C1-reserves of coal amount to 8.1 billion tons, C2-reserves are 6.8 billion tons; and non-commercial reserves are 10 billion tons. 80% of A+B+C1-reserves of coal are hard coal, of which 12% of reserves are metallurgical coal and 20% are lignite.

The inferred coal resources are estimated at 29.3 billion tons [21]. The analysis of coal sources available in the Irkutsk region shows that they are generally well explored. The share of commercial reserves in the inferred resources is 28%, which indicates that commercial reserves can be replenished from forecasted resources as well as from non-commercial reserves.

The commercial coal reserves include developed producing reserves and undeveloped reserves with approved development, which are divided into licensed and non-licensed reserves. The licensed reserves include subsoil areas granted for use to enterprises under licenses with mining operations ongoing there (recoverable reserves of enterprises). As of January 1, 2023, developed producing coal reserves and undeveloped reserves with approved development account for only 6.6% of the commercial A+B+C1-reserves of coal in the Irkutsk region [3]. Table 3 shows the grade composition of Irkutsk coal.

In 2022, the breakdown of energy coal production in the

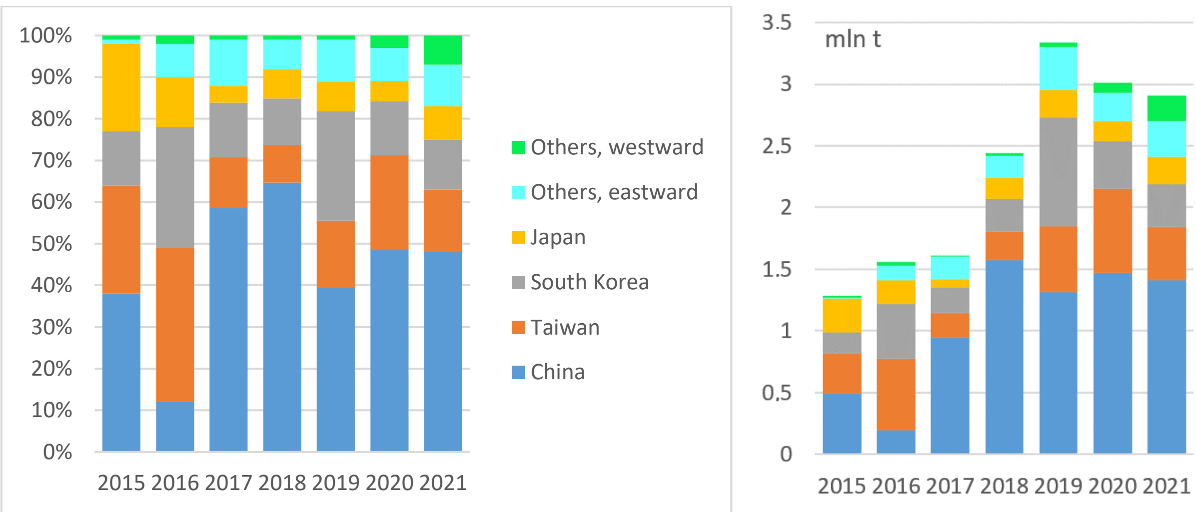


Fig. 2. Coal exports from the Irkutsk region (customs statistics data), mln tons.

TABLE 3. Irkutsk Region Coal Reserves by Grade, Bln T (as of January 1, 2023)

Coal grade	A+B+C1		C2		A+B+C1+C2		Share in total reserves, %	
	total	open-pit mining	total	open-pit mining	total	open-pit mining	total	open-pit mining
Total	8.07	7.72	6.67	4.58	14.74	12.29	100	100
Lignite	2.11	1.88	0.78	0.56	2.89	2.45	20	20
3B	1.84	1.72	0.46	0.24	2.3	1.96	16	16
1B+2B+B	0.27	0.16	0.33	0.32	0.59	0.48	4	4
Hard coal	5.96	5.83	5.89	4.01	11.85	9.85	80	80
Metallurgical coal (most valuable grades)	0.75	0.67	0.56		1.31	0.67	9	5
D	4.04	4.04	3.62	3.62	7.66	7.66	52	62
C	1.04	0.92	0.64	0.08	1.68	1.00	11	8
G, GZh metall.	0.66	0.66	0	0	0.66	0.66	4	5
DG, D, T, SS, KZh, A, oxidized	0.22	0.21	1.63	0.31	1.84	0.52	12	4

Source: [3]

Irkutsk region by type and grade was as follows: 7.2 million tons of brown coal, mainly grade 3B; 6.2 million tons of hard coal, of which 4.8 million tons were grade G coal, 0.3 million tons – grade D coal, 0.9 million tons – grade DG coal, and 0.2 million tons – oxidized hard coal. The breakdown of coal production by grade in 2021 yielded approximately the same ratios as in previous years [3].

As a result of the development of both small and large coal deposits in 2023, the commercial reserves of coal in 2023 decreased by 0.01 billion tons, compared to 2022, which was mainly due to a reduction in the commercial A+B+C1-reserves of hard coal for open-pit mining [3]. The change in commercial reserves mainly concerns the most demanded grades of lignite (3B) and hard coal (G) that account for 16% and 8% of reserves for open-pit mining, respectively.

Analysis of the dynamics of changes in A+B+C1+C2-reserves of coal that are either developed producing or prepared for development (Fig. 3) reveals an insignificant increase in total reserves with a tendency to lower levels of reserves of existing enterprises and a small share of coal mining facilities under construction.

Coal resources for the development of the industry can be provisionally divided into resources for the expansion of coal exports and resources for thermal power generation, which is the main use of Irkutsk coal. Coal of grades 3B and G is mainly used for domestic consumption. Coal of grades G, D, and DG is exported. Accordingly, coal

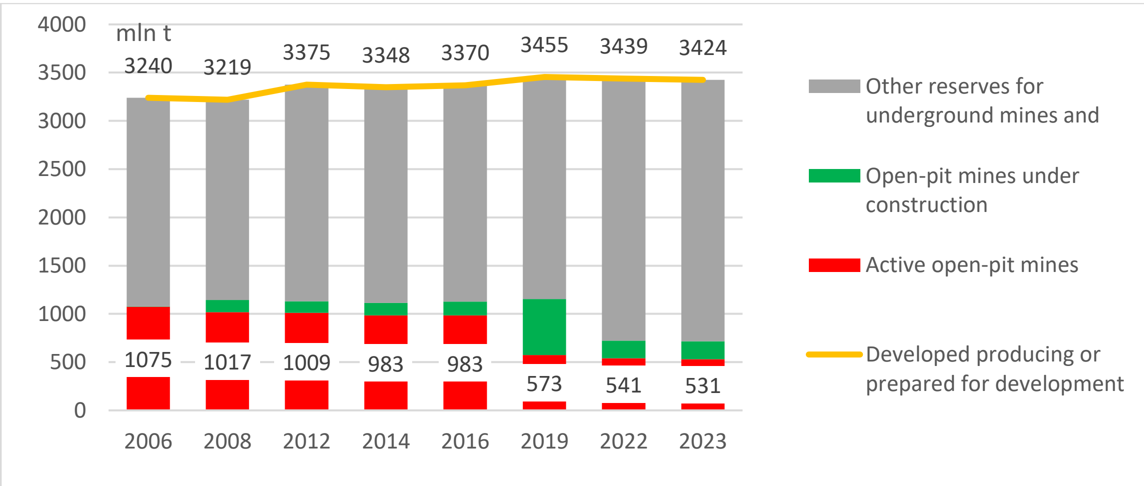


Fig. 3. Changes in A+B+C1+C2-reserves of coal in the Irkutsk region that are either developed producing or prepared for development.

Source: [3, 22–28]

TABLE 4. Coal Reserves-to-Production Ratio

COAL RESERVES	Coal reserves, bln t	Production in 2022, mln t	Reserves-to-production ratio, years
Commercial A+B+C1-reserves	8.07	14.13	571
Commercial A+B+C1+C2-reserves	14.74	14.13	1 043
Commercial A+B+C1+C2-reserves + non-commercial reserves	24.74	14.13	1 751
Commercial A+B+C1+C2-reserves of grade 3B	2.30	7.23	319
open-pit mining	1.97	7.23	272
currently operating enterprises	0.36	7.23	50
Commercial A+B+C1+C2-reserves of grade G	1.69	4.83	349
open-pit mining	1.00	4.83	207
currently operating enterprises + enterprises under construction	0.26	4.83	54
Commercial A+B+C1+C2-reserves of grade D (open-pit mining)	7.66	0.62	12 395
Commercial A+B+C1+C3-reserves of grade DG (open-pit mining)	0.77	0.89	861
Commercial A+B+C1-reserves	8.07	14.13	571
Commercial A+B+C1+C2-reserves	14.74	14.13	1 043
Commercial A+B+C1+C2-reserves + non-commercial reserves	24.74	14.13	1 751

Source: [3] + calculations by the author

production and change in coal reserves varies significantly with the coal grade.

The overall reserves-to-production ratio, regardless of the method of extraction and the grade of coal mined, is high (Table 4), but it is much lower for the most demanded grades of coal, especially at the currently operating enterprises.

The coal reserves-to-production ratio was calculated for the 2022 production levels. If higher production volumes are required in the future, provided that there is no replenishment of commercial reserves through additional exploration activities, the reserves-to-production ratio decreases.

According to 2022 data, enterprises with small production capacity ranging from 25 to 500 thousand tons per year had the recoverable reserves-to-production ratio of 0 to 23 years, with the mode value being around 10, with a possible variation of 1 to 4 years.

OOO Iretsky razrez is one such enterprise: the company mines two subsoil areas with production capacity of 1.1 million tons per year and recoverable reserves-to-production ratio of 12 and 42 years.

The Irkutsk region has reserves of fuel and energy resources in some northern off-grid areas, including both licensed and non-licensed coal reserves.

The Novosel’sky open-pit mine operates at the Kuryatsky hard coal deposit in the Nizhneudinsk municipal district. The mine produced 117 tons of coal in 2022 and an open-pit mine is under construction at the Uvatsky site [3]. That same deposit has both licensed and non-licensed areas. The total A+B+C1-reserves of the Kuryatskoye coal deposit amount to more than 5 million tons, which is enough to meet the demand for coal in some settlements of the Nizhneudinsk district for a sufficiently long period of time.

Erbogachenskaya ploshchad' is a deposit of hard coal in the Katanga municipal district. The deposit is non-licensed, and its coal is of reasonably good quality by thermal power generation standards: the sulfur content is 0.3–0.9% and calorific value is 18 MJ/kg [3]. The deposit can be developed by open-pit mining. The Khandinskoye lignite deposit is located in the Kazachinsk-Lensky municipal district and is also non-licensed. Quality parameters of its coal (the sulfur content of 1.5% and calorific value of 6.8 MJ/kg) are less attractive for its use in thermal power generation [3]. The feasibility of development of existing coal deposits requires thorough study, as the deposits are located in economically underdeveloped areas with limited infrastructural resources. For example, the Yerbogachenskaya ploschad' deposit can be connected to the nearest settlement (Yerbogachen village) only by an ice road [29].

Both the deposits that are either likely to be developed in the future or already producing deposits are mainly located in areas with developed infrastructure. They are suitable for the more economical open-pit mining. However, this comes at the cost of the expropriation of agricultural and woodland areas, alteration of the local hydrological regime, and other negative effects of mining.

Deposits differ significantly in terms of mining conditions, presence of associated valuable and rare elements, and other characteristics, which makes each deposit unique and renders standardization of deposit development projects impossible.

V. Prospects for the Development of the Coal Industry of the Irkutsk Region

The prospects for the development of the coal industry depend on the construction of coal-fired power plants and higher exports. Despite the fact that Russia has developed and adopted documents (programs) on decarbonization of the Russian economy [30], coal-fired power remains economically feasible in the Asian regions of Russia and ensures the reliability of electricity generation and heating, which does not contradict the scenarios laid down in these documents.

EN+ GROUP plans to construct a coal-fired power plant running on the coal from the Mugunskoye deposit in compliance with environmental safety requirements [31]. The company also plans to modernize the equipment of coal-fired TPPs of the Irkutsk region and involve ash ponds in coal preparation.

OOO Russkiy Ugol' Sibiri signed a cooperation agreement with the Government of the Irkutsk region, which envisages the development of the Zheronsky hard coal deposit in the Ust'-Ilimsk district [32]. The deposit development project aims to expand coal exports and includes the construction of two coal mines with a total capacity of 5.6 million tons of coal per year and two coal preparation plants with a capacity of 1.53 million tons each.

VI. Factors Contributing to the Development of Coal Mining in the Irkutsk Region

The availability of large reserves of hard coal (80%) and lignites (20%) is essential for ensuring the development of the coal industry in the Irkutsk region. The reserves are mainly concentrated in large deposits, more than 80% of which are available for open-pit mining.

The production capacities of the existing enterprises are underutilized, and it is possible to increase production at the existing coal mining enterprises.

There has been a stable demand for coal products for a long period of time, primarily by power generation facilities.

The growth in coal exports potential is due to the expansion of development of some relatively small deposits of hard coal, whose quality parameters (even in the case of run-of-mine coal) meet international requirements for exports.

One factor that contributes to the leading position that coal maintains in the fuel supply of CHPPs in the region is the availability of domestic equipment for coal-fired CHPPs, which makes it import-independent [33, 34], unlike gas power generation.

Since there is no piped gas in the Irkutsk region and gas-fired power generation is import-dependent, coal remains the preferred fuel in terms of its economic performance.

VII. Threats and Risks of Coal Mining Development in the Irkutsk Region

Commercial coal reserves of the Irkutsk region, including developed producing reserves and those prepared for development by operating enterprises, tend to decrease due to little, if not altogether non-existent (as was the case in 2022), geological exploration effort. At the same time, the reduction in coal reserves mainly concerns the most demanded grades of hard coal (G) and lignites (3B), which make up the great bulk of production.

Factors limiting the development of coal sources include:

- reduction in the coal reserves of operating enterprises that are either developed producing reserves or those prepared for development;
- challenging mining, geological, and hydrological conditions;
- deterioration of mining and geological conditions at operating enterprises;
- possible irreversible negative environmental impacts;
- high sulfur content in coal from the deposits that are the main suppliers of coal to the regional power plants;
- year-over-year deterioration in the quality of extracted energy coal (calorific value, ash, and sulfur content) due to the extension of mining operations to inferior areas to make up for the depleted ones;
- lack of incentives for the use of advanced coal processing or fuel handling technologies;
- increase in the cost of coal mining and processing due to the complicated geopolitical situation;
- import dependency for equipment and spare parts [36–38];
- personnel shortage [39].

It is also important to note that the demand for coal in the domestic and global markets is subject to fluctuations.

- In the domestic market, the demand of coal-fired power generation depends on water availability at the Angara Cascade HPPs, whereas the demand of heat generation depends on average annual temperatures, i.e., cold and warm winters.

- In the global market, demand fluctuations are a function of coal prices and transportation infrastructure capabilities [35];

Coal mining is accompanied by the negative impact on the environment (especially in case of open-pit mining) and disturbance of significant areas of land resources. An essential aspect of the activities of coal mining enterprises is the reclamation of disturbed lands. The annual report of the EN+ GROUP [4] was in line with the "Strategic Environmental Risk Management Plan of the Energy Segment," which also included land reclamation and restoration. The 2022 report of EN+ GROUP [4] noted that "Enterprises of the coal segment regularly carry out land reclamation after the completion of coal mining and closure of ash ponds". The report stated the total area of 227 hectares of disturbed land in 2022 that resulted from open-pit coal mining. The total area of disturbed land requiring further reclamation as of December 31, 2022, was 12 221 hectares, according to the EN+ GROUP report, and no land has been reclaimed [4]. The low to nonexistent land reclamation, following the completion of coal mining, enlarges the total area of disturbed land.

VIII. Priorities of the Coal Industry Development

1. Development of the mineral resource base of the coal industry.

2. Development of production potential of the coal industry through a) modernizing the fleet of special-purpose machinery for coal mining and mitigation of environmental consequences of coal mining; b) expanding capacities for coal processing, c) increasing the skill levels of the personnel.

3. Development of "clean" coal-fired generation based on the adoption of innovative coal combustion technologies at thermal power plants.

4. Improvement of working and living conditions for coal industry employees to ensure social stability in the industry, which includes:

- monitoring of industrial and environmental safety;
- development of social services to meet the needs of industry employees and their families in proper recreation, wellness, and rehabilitation, namely: hospitals, polyclinics, sanatoriums, tourist centers, as well as educational, athletic, cultural and educational institutions and activities aimed at creating a comfortable social environment.

5. Cooperation with educational organizations to recruit employees skilled in various domains related to the industry, including leveraging Information technology.

6. Cooperation with academic institutions for field testing and adoption of scientific innovations related to coal mining and processing.

7. Improvement in fuel competitiveness in the domestic and foreign markets through the adoption of modern, advanced methods of coal processing.

8. Full inventory count of disturbed lands and identification of areas where further mining operations are not feasible. Reclamation and derecognition of disturbed and reclaimed lands of mining enterprises.

IX. Conclusion

Coal produced in the Irkutsk region was and will remain the main fuel for power plants in the Irkutsk region.

The use of Irkutsk coal for thermal power generation contributes to

- resilience of the region's energy sector to external and internal economic, man-made, and natural threats;
- reliable fuel and energy supply and heating;
- the ability of the energy sector to minimize the damage caused by the manifestation of various destabilizing factors, such as the geopolitical situation, COVID-19 pandemic, etc.

The basis for a stable coal supply is the following:

- availability of coal reserves, which are secured for hundreds of years, unlike gas reserves;
- no import dependency for coal-fired power generation;
- climate conditions that make it indispensable to have stable power supply and heating;
- rising gas prices and import dependency of gas-fired power generation;
- opportunities and prospects for improving the processes of coal mining and utilization, specifically, through the formation of industrial clusters on the basis of coal deposits.

Stable operation of coal mining enterprises requires the development of the machine-building industry aimed at phasing out equipment imports.

The latest developments in modernization of equipment for coal-fired power plants can make coal-fired power generation more competitive. Such developments aim at improving the efficiency and environmental friendliness of coal-fired generation. Another contributing factor is the adoption of technologies for the integrated use of coal.

Acknowledgment

The research was carried out under State Assignment Project (No. FWEU-2021-0004) using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project No. 13.CKP.21.0038).

References

[1] M. A. Vinokurov, A. P. Sukhodolov, “Coal mining industry,” in Economy of the Irkutsk region: in 4 vols, vol. 2. Irkutsk, Russia: Publishing House of Baikal National University of Economics and Law, 1999, 310 p. Available: http://irkipedia.ru/content/ugledobyvayushchaya_promyshlennost_vinokurov_ma_suhodolov_ap_ekonomika_irkutskoy_oblasti. (In Russian)

[2] G. B. Meshkov, I. E. Petrenko, D. A. Gubanov, “Results of the Russian coal industry for 2023,” Ugol', no. 3, pp. 18–29, 2024. DOI: 10.18796/0041-5790-2024-3-18-29. (In Russian)

[3] State balance of mineral reserves of the Russian Federation as of January 1, 2023, issue 91, Coal, vol. VII, Siberian Federal District, part 2. Moscow, Russia: Ministry of Natural Resources and Environment of the Russian Federation, Federal Subsoil Resources Management Agency, Russian Federal Geological Depository, 2023, 222 p. [Online]. Available: https://rfgf.ru/info-resursy/raboty-po-izucheniyu-nedr. Accessed on: Oct. 26, 2023. (In Russian)

[4] Consolidated report of En+ for the year 2022. The Energy of Transformation. [Online]. Available: https://rspp.ru/upload/uf/4ab/z9gk9mzcqkcqrprxjnginzh9dw605jgd/OUR-En_-Group.pdf. Accessed on: Apr. 18, 2024. (In Russian)

[5] “Customs statistics of foreign trade of the Russian Federation,” Customs Online, 2023. [Online]. Available: https://customsonline.ru/search_ts.html. Accessed on: Mar. 12, 2023. (In Russian)

[6] OOO Transugol'. [Online]. Available: https://www.list-org.com/company/7194687. Accessed on: Apr. 18, 2024. (In Russian)

[7] OOO Yumiks. [Online]. Available: https://www.list-org.com/company/6249053. Accessed on: Apr. 18, 2024. (In Russian)

[8] OOO Kompaniya Vostsibugol'. [Online]. Available: https://www.list-org.com/company/54811. Accessed on: Apr. 18, 2024. (In Russian)

[9] N. A. Zroychikov, A. O. Perfiliev, A. M. Gribkov, V. Ya. Putilov, D. V. Gorburov, “Study of the effect of sulfur content in fuel on the efficiency and environmental safety of boiler operation during combustion of off-spec fuels,” International Scientific Journal for Alternative Energy and Ecology (ISJAEE), vol. 1–3, pp. 103–117, 2018. DOI: 10.15518/isjaee.2018.01-03.103-117. (In Russian)

[10] Official report “On the state and use of mineral resources of the Russian Federation in 2015,” Ministry of Natural Resources and Environment of the Russian Federation. Moscow, Russia: 2016, 344 p. (In Russian)

[11] Official report “On the state and use of mineral resources of the Russian Federation in 2021,” Ministry of Natural Resources and Environment of the Russian Federation. Moscow, Russia: 2016, 626 p. (In Russian)

[12] D. Bendin, “Central Preparation Plant “Krasnokamenskaya”: the constant search for and adoption of the most efficient technologies of coal preparation, improvement of working conditions, and minimization of environmental impact,” no. 1(75), pp. 86–92, 2023. [Online]. Available: https://st.vnedra.ru/wp-content/uploads/2023/03/globus75.pdf. Accessed on: Apr. 18, 2024. (In Russian)

[13] W. Mija, B. Tora, “Development of dry coal gravity separation techniques,” in IOP Conference Series: Materials Science and Engineering, vol. 427, Mineral Engineering Conference, Sep. 26–29, 2018, Zawiercie, Poland. [Online]. Available: https://iopscience.iop.org/article/10.1088/1757-899X/427/1/012003. Accessed on: Nov. 14, 2023.

[14] Y. Zhao, X. Yang, Z. Luo, C. Duan, S. Song, “Progress in developments of dry coal beneficiation. Progress in developments of dry coal beneficiation,” International Journal of Coal Science & Technology, vol. 1, pp. 103–112, 2014. DOI: 10.1007/s40789-014-0014-5. Accessed on: Nov. 14, 2023.

[15] A. I. Skryl', “Reserves for enhancing the performance of coal products and increasing its utilization efficiency,” Ugol', no. 9, pp. 12–17, 2018. DOI: 10.18796/0041-5790-2018-9-12-17. (In Russian)

[16] A. Khalbashkeev, “The termokoks technology: a new panacea for the coal industry?”, Mining Industry, no. 1(37), pp. 94–98, 2023. Available: https://dprom.online/chindustry/termokoks-novaya-panatseya-dlya-ugolnoj-otrasli/. Accessed on: Apr. 02, 2024. (In Russian)

[17] E. Balabas, “Is there any smokeless coal?”, Kislorod.life. [Online]. Available: https://kislorod.life/question_answer/est_li_ugol_kotoryy_ne_dymit/. Accessed on: Apr. 02, 2024. (In Russian)

[18] Decree of Governor of the Irkutsk region (2022, Apr. 28), No. 71-ug, On Approval of the Master Plan and Program of the Irkutsk Region Electric Power Industry Expansion for Years 2023–2027. [Online]. Available: http://publication.pravo.gov.ru/Document/View/3800202204290009. Accessed on: May 26, 2024. (In Russian)

[19] “More than 90 thousand tons of fuel have been delivered to the districts of the Irkutsk region under the Northern Supply Haul,” Korabel.ru. [Online]. Available: https://www.korabel.ru/news/comments/v_rayony_irkutskoy_oblasti_v_ramkah_severnogo_zavoza_dostavleno_bolee_90_tys_tonn_topliva.html. Accessed on: Apr. 01, 2024. (In Russian)

[20] “All fuel for the northern districts of the Irkutsk region will be delivered by the end of the week,” https://www.ogirk.ru, Aug. 26, 2021. [Online]. Available: https://www.ogirk.ru/2021/08/26/vsjo-toplivo-dlja-severnyh-rajonov-irkutskoj-oblasti-privezut-do-konca-nedeli/. Accessed on: Apr. 01, 2024. (In Russian)

[21] Inferred resources of solid and solid fossil (coal) minerals of the Russian Federation as of January 1, 2019. Issue 4. Coal. Moscow, Russia: Ministry of Natural Resources and Environment of the Russian Federation, Federal Subsoil Resources Management Agency, Russian Federal Geological Depository, 80 p. [Online]. Available: https://rfgf.ru/info-resursy/raboty-po-izucheniyu-nedr. Accessed on: Oct. 26, 2023. (In Russian)

[22] State balance of mineral reserves of the Russian Federation as of January 1, 2022, issue 91, Coal, vol. VII, Siberian Federal District, part 2. Moscow, Russia: Ministry of Natural Resources and Environment of the Russian Federation, Federal Subsoil Resources Management Agency, Russian Federal Geological Depository, 2022, 236 p. [Online]. Available: https://rfgf.ru/info-resursy/raboty-po-izucheniyu-nedr. Accessed on: Oct. 26, 2023. (In Russian)

[23] State balance of mineral reserves of the Russian Federation as of January 1, 2013, issue 91, Coal, vol. VII, Siberian Federal District, part 2. Moscow, Russia: Ministry of Natural Resources and Environment of the Russian Federation, Federal Subsoil Resources Management Agency, Russian Federal Geological Depository, 2013, 304 p. [Online]. Available: https://rfgf.ru/info-resursy/raboty-po-izucheniyu-nedr. Accessed on: Oct. 26, 2023. (In Russian)

[24] State Balance of Mineral Reserves of the Russian Federation as of January 1, 2006, issue 91, Coal, vol. VII, Siberian Federal District, part 2. Moscow, Russia: Ministry of Natural Resources and Environment of the Russian Federation, Federal Subsoil Resources Management Agency, Russian Federal Geological Depository, 2006, 272 p. [Online]. Available: https://rfgf.ru/info-resursy/raboty-po-izucheniyu-nedr. Accessed on: Oct. 26, 2023. (In Russian)

[25] State Balance of Mineral Reserves of the Russian Federation as of January 1, 2008, issue 91, Coal, vol. VII, Siberian Federal District, part 2. Moscow, Russia: Ministry of Natural Resources and Environment of the Russian Federation, Federal Subsoil Resources Management Agency, Russian Federal Geological Depository, 2008, 282 p. [Online]. Available: https://rfgf.ru/info-resursy/raboty-po-izucheniyu-nedr. Accessed on: Oct. 26, 2023. (In Russian)

[26] State balance of mineral reserves of the Russian Federation as of January 1, 2012, issue 91, Coal, vol. VII, Siberian Federal District, part 2. Moscow, Russia: Ministry of Natural Resources and Environment of the Russian Federation, Federal Subsoil Resources Management Agency, Russian Federal Geological Depository, 2012, 294 p. [Online]. Available: https://rfgf.ru/info-resursy/raboty-po-izucheniyu-nedr. Accessed on: Oct. 26, 2023. (In Russian)

[27] State balance of mineral reserves of the Russian Federation as of January 1, 2014, issue 91, Coal, vol. VII, Siberian Federal District, part 2. Moscow, Russia: Ministry of Natural Resources and Ecology of the Russian Federation, Federal Subsoil Resources Management Agency, Russian Federal Geological Depository, 2014, 306 p. [Online]. Available: https://rfgf.ru/info-resursy/raboty-po-izucheniyu-nedr. Accessed on: Oct. 26, 2023. (In Russian)

[28] State balance of mineral reserves of the Russian Federation as of January 1, 2019, issue 91, Coal, vol. VII, Siberian Federal District, part 2. Moscow, Russia: Ministry of Natural Resources and Environment of the Russian Federation, Federal Subsoil Resources Management Agency, Russian Federal Geological Depository, 2019, 224 p. [Online]. Available: https://rfgf.ru/info-resursy/raboty-po-izucheniyu-nedr. Accessed on: Oct. 26, 2023. (In Russian)

[29] Russian Federal Geological Depository. [Online]. Available: https://www.rfgf.ru/gkm/index.php. Accessed on: Apr. 01, 2024. (In Russian)

[30] The Government has approved the Strategy for Socio-Economic Development of Russia with Low Greenhouse Gas Emissions to 2050. [Online]. Available: http://government.ru/news/43708/. Accessed on: Apr. 01, 2024. (In Russian)

[31] “En+ proposes to build a coal plant in the Irkutsk region,” PERETOK.RU: Energy in Russia and worldwide. [Online]. Available: https://peretok.ru/news/generation/26536/. Accessed on: Apr. 01, 2024. (In Russian)

[32] Investment projects for the development of coal and iron ore deposits are planned to be implemented in the Irkutsk region. [Online]. Available: https://irkobl.ru/news/2962366/. Accessed on: Apr. 01, 2024. (In Russian)

[33] TYAZHMASH, corporate website of the group of companies. [Online]. Available: https://www.tyazhmash.com/. Accessed on Jun. 07, 2024. (In Russian)

[34] Siloviye Mashiny, corporate website of the group of companies. [Online]. Available: https://power-m.ru/company/. Accessed on Jun. 07, 2024. (In Russian)

[35] L. N. Takaishvili, “The Eastern Polygon of Russian railroads for Russian coal exports: prospects for development and limitations,” Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering, vol. 334, no. 12, pp. 41–55, 2023. DOI: 10.18799/24131830/2023/12/4336. (In Russian)

[36] L. S. Plakitkina, Y. A. Plakitkin, K. Dyachenko, “Assessment of import dependency of Russian coal companies with respect to purchases of equipment manufactured abroad,” Russian Mining Industry, no. 3, pp. 35–39, 2018. (In Russian)

[37] A. A. Rozhkov, “Structural analysis of import substitution in the Russian coal industry: facts and projections,” Mining Industry, no. 6, pp. 4–13, 2017. (In Russian)

[38] A. A. Rozhkov, S. M. Karpenko, “Assessment of the level of import dependency of the Russian coal industry and the proficiency of its engineering personnel to secure the phase-out of imports of mining equipment,” Russian Mining Industry, no. 4, pp. 24–36, 2020. DOI: 10.30686/1609-9192-2020-4-24-36. (In Russian)

[39] Job: “coal mining” – vacancies in the Irkutsk region (788 vacancies). [Online]. Available: https://irkutskaya-oblast.gorodrabot.ru/%D0%B4%D0%BE%D0%B1%D1%8B%D1%87%D0%B0_%D1%83%D0%B3%D0%BB%D1%8F. Accessed on: Apr. 01, 2024. (In Russian)

Liudmila Takaishvili received a Ph.D. in engineering from the Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences in 1991. Currently, she is a senior researcher at the Melentiev Energy Systems Institute SB RAS. Her research areas include the studies on the coal industry development prospects and the development of software and information support for these studies.

Feasible Capacity of Renewable Energy Sources in the Irkutsk Region

I.Yu. Ivanova[1], T.F. Tuguzova[1], N.A. Khalgaeva[1,*]

[1] Melentiev Energy Systems Institute, SB RAS, Irkutsk, Russia

***Abstract* — The paper contributes a comparative quantitative assessment of solar and wind power potential in the Irkutsk region. The research findings on solar and wind power potential are presented cartographically. The Baikal Natural Territory proves an advantageous location for the implementation of renewable energy sources. We identify the locations where it is feasible to use solar power plants to serve remote off-grid communities in the Irkutsk region. Our study relies on an original technique for making fast estimates of the feasible capacity of solar power plants. The input data are surface observations coming from meteorological stations and the specifications of existing diesel power stations and future power plants. The total feasible capacity of solar power plants as part of hybrid energy systems for remote and isolated communities in the region is estimated at 1.5 MW. The economic effect of their deployment is fuel savings of 470–480 tons/year and reduction in budget subsidies by almost RUB43 million annually.**

***Index Terms* — Wind power potential, wind farms, solar power potential, feasible capacity, subsidy reduction, photovoltaic plants, fuel savings, issues.**

* Corresponding author.
E-mail: khalgaeva@isem.irk.ru

http://dx.doi.org/10.25729/esr.2024.04.0004

Received November 20, 2024. Accepted November 29, 2024. Available online December 28, 2024.

I. Introduction

This study discusses the use of renewable energy sources (RES) as one of the directions of socio-economic development outside the area served by the centralized power supply in the Irkutsk region. There are 64 settlements with a population of 9.1 thousand people in the region, which are supplied with electricity from 60 stand-alone municipal diesel power stations (DPS) with a capacity of 17.8 MW and 5 renewable energy sources (0.5 MW). Electricity generation is 32.7 million kWh. Annual diesel fuel consumption is estimated at 8.6 thousand tons. The obsolete equipment of DPSs compromises their technical and economic performance. Due to underdeveloped transportation infrastructure and complex logistics flow, diesel fuel prices in the most remote settlements reach 150 thousand RUB/ton. As a result, the share of the fuel component in the structure of electricity supply costs reaches 70%. High values of economically justified electricity tariffs in these areas (up to 65–88 RUB/kWh) entail annual subsidies from the regional budget in the amount of more than ₽800 million per year in order to compensate for shortfalls in revenue to power utilities. The use of renewable energy sources will save some diesel fuel for remote communities, reduce budget subsidies for electricity supply, and enhance reliability and energy security.

II. Potential of Renewable Energy Sources

The solar and wind power potential in the Irkutsk region is presented cartographically to enhance its visualization. The maps were rendered in the open source geographic information system QGIS [1]. QGIS is a project of the Open Source Geospatial Foundation (OSGeo). It supports

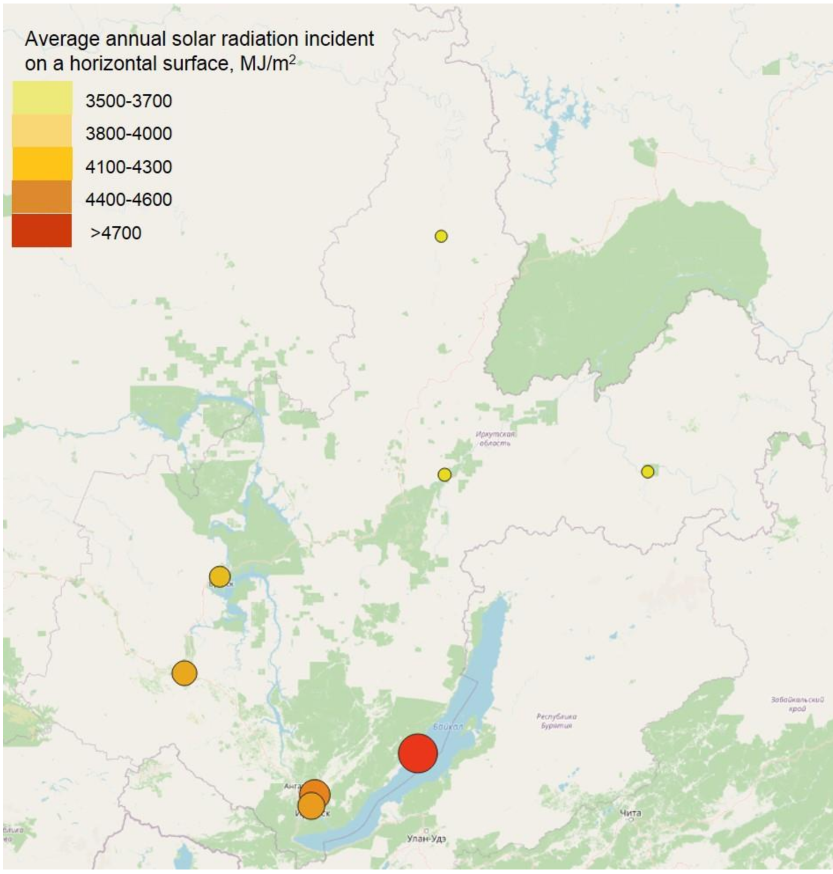


Fig. 1. Distribution of the solar power potential across the area of the region.

multiple vector and raster formats and databases, and has a wide range of capabilities.

Solar power potential

The basic parameter for assessing the type of the solar power potential distribution over the year is the total solar radiation incident on a horizontal surface.

The total average annual solar radiation incident on a horizontal surface within the area of the region is rather uneven: it ranges from 3 500 MJ/m^2 in the north to more than 4 500 MJ/m^2 in the south of the region [2]. The

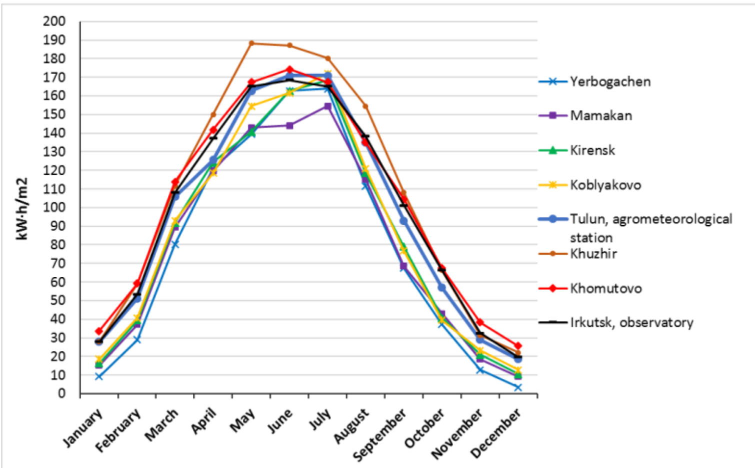


Fig. 2. Distribution of solar power potential over the year [3].

sunshine duration also varies with latitude: from slightly less than 1 500 h/year in the northern areas to more than 2 000 h/year in the southern areas (Fig. 1).

Our analysis of reference data [2, 3] allows us to draw the following conclusions:

- The distribution of solar energy potential parameters during the year has a pronounced spring-summer peak and virtually does not depend on the latitude of the settlements located both in the northern areas of the region (Yerbogachen, Mamakan, and Kirensk) and in the southern areas (Tulun, Khomutovo, and Irkutsk), as well as in the Lake Baikal basin (Khuzhir) (Fig. 2);
- The maxima of the basic parameter according to the available data for the area of the region, despite covering an extended latitude range, vary within a narrow margin from 155 to 190 kWh/m^2 per month;
- The best conditions for utilization of the solar power potential are observed in the water area of Lake Baikal: in particular, the highest values both in summer and winter were recorded in the settlement of Khuzhir (Olkhon Island).

Relatively high density of solar radiation creates opportunities for the use of solar power plants (SPP) in the central and southern areas of the region, on the coast of Lake Baikal and Olkhon Island. The implementation of the SPPs in the region has attested to their efficiency, resulting in a 40% saving of diesel fuel annually and a subsequent reduction in subsidies.

Wind power potential

The Irkutsk region, while occupying a large area, has a low wind power potential. The potential is mainly measured by the long-term average wind speed. The average annual wind speeds at the weather vane height of hydrometeorological stations (10-12 m) do not exceed 1-2 m/s in most of the area [2, 4]. In the northern areas and

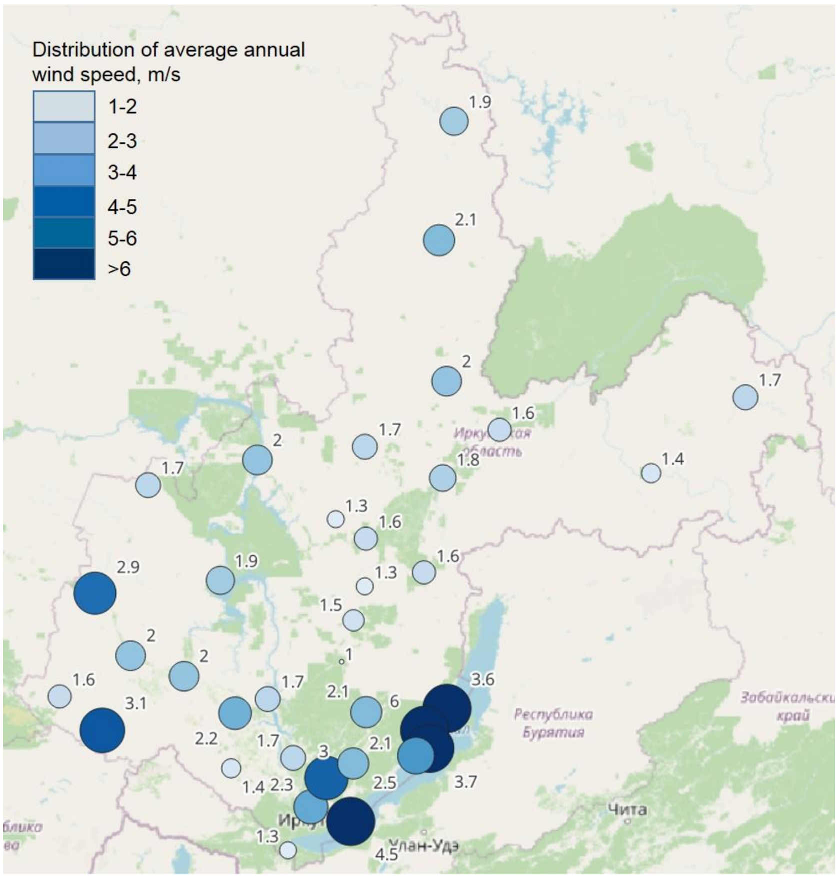
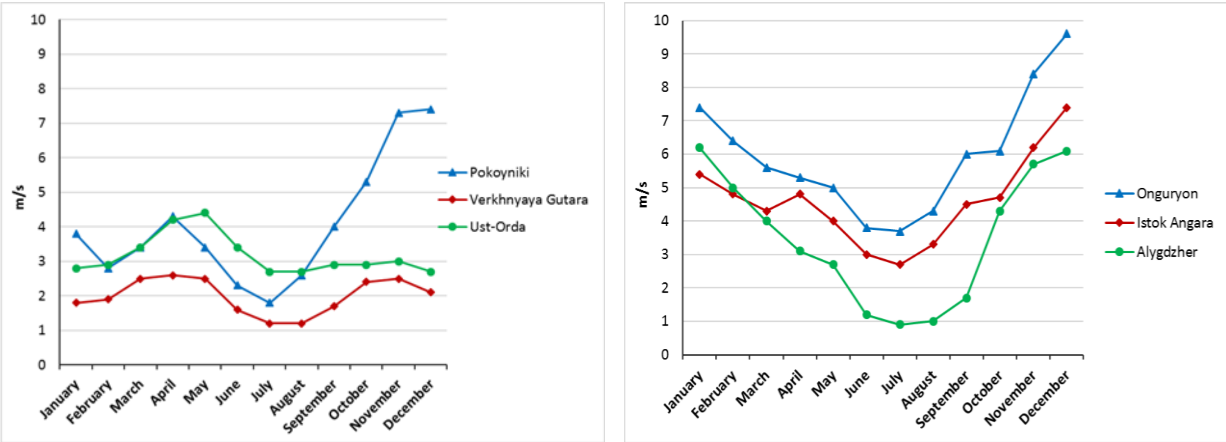


Fig. 3. Distribution of average multi-year wind speed over the area of the region.



a) Spring and fall peak b) Winter peak

Fig. 4. Distribution of average monthly wind speeds over the year [4].

small local zones, the value is slightly higher – 2-3 m/s. The exception is the coast of Lake Baikal and the westernmost areas of the region with an average annual wind speed of 3-5 m/s reaching 6 m/s and higher at certain locations (Fig. 3).

Relief and climate characteristics of the Irkutsk region have a decisive influence on the intra-annual distribution of wind power potential. During the coldest time of the year, when the anticyclone is at its strongest and encompasses Eastern Siberia, fair weather with some clouds and weak winds prevails. Cyclone activity increases during warm months, however, the wind speeds in the area prove insignificant.

Wind power is highly intermittent throughout the year, therefore the variation in its potential by month is an important indicator. The analysis of the intra-annual distribution of wind speeds has identified two well-defined groups.

The first group includes the majority of locations where the average annual speeds do not exceed 1.5-2.5 m/s. The change in average monthly values during the year is insignificant for these locations (Fig. 4a).

The second group includes locations with the highest average monthly winter wind speeds during the year (Fig. 4b).

The distribution of wind potential values that has a winter peak is deemed the most suitable for the use of wind power for power supply to off-grid consumers.

The area of the region is considered unsuitable for wind power deployment. Exceptions are some locations in the Olkhonsky District, where the average annual wind speeds are about 6 m/s.

Local use of wind turbines is possible in certain areas, these are mainly in the valleys of rivers flowing into Lake Baikal and on Olkhon Island, where small capacity wind turbines are already in operation. To that end, it is necessary to survey the location of the proposed placement of wind turbines to clarify the parameters of the wind

TABLE 1. Summary of the State of Power Systems of Remote Settlements of the Region

Settlement	Population (as of 2021), persons	DPS capacity, kW	Diesel fuel price, thousand RUB /ton
Karam	269	300	79.9
Alygdzher	513	1 130	96.15
Konoshanovo	45	100	107.9
Vershina Tutury	191	160	185.2
Pashnya	16	60	77.58
Ust'-Kirenga	53	60	77.58
Arshan	244	1 440	69.9
Klyuchi	86	180	79.1
Onguryon	983	400	97.9

TABLE 2. PV Cell Specifications

Cell type	HVL-570/HJT	HVL-390/HJT
Power, kW	0.57	0.39
Efficiency, %	22.05	19.5
PV cell area, m^2	2.56	2.00
PV cell cost, thousand RUB/kW	39.98	49.97

Source: Hevel URL: https://www.hevelsolar.com/catalog/solnechnye-moduli/

power potential. The survey should be aided by wind measuring systems and last for a certain period of time (1–2 years).

III. Calculation of Feasible Capacity and Underlying Assumptions

In order to decide on the feasible capacity of solar power plants, we examined nine off-grid settlements in the Irkutsk region, where neither the connection to the power system nor the use of local fuels is envisioned. Characteristics of settlements and specifications of their power supply are given in Table 1.

The feasible capacity of solar power plants was calculated for two types of photovoltaic cells (PVC) produced in Russia by the Hevel Group (Table 2).

The climate record book [2] served as the source of the data on climate and environmental conditions needed for estimating the solar power potential of the investigated localities. Due to the limited number of meteorological stations capable of actinometric measurements, we made up for the lack of data needed for calculations for the indicated localities by substituting the missing data with the data of the localities nearest to them and having similar geographical features (Tulun, Kirensk, and Khuzhir).

The SPP capacity calculation relied on the fast technique for estimating the feasible renewable power capacity in hybrid energy systems as detailed elsewhere [5]. The technique combines annual profiles of consumption and possible power generation from SPP when building up the capacity of plants to determine the useful output, which ensures full utilization of the SPP output [6, 7]. This determines the minimum feasible SPP capacity. The choice of the feasible SPP capacity depends on the ratio of capital outlays, which are a function of the total capacity of the plants, to the cost of the fuel saved at DPS. Higher SPP

TABLE 3. Findings of Feasible SPP Capacity Calculations for Settlements in the Irkutsk Region

Settlement	Feasible number of PV cells	SPP capacity, kW	SPP cost, million RUB
Karam	405–588	231–229	18.5–23
Alygdzher	858–1 281	489–499	39–50
Konoshanovo	61–88	35–34	3–3.5
Vershina Tutury	105–150	60–59	5–6
Pashnya	43–63	24.5–25	2–2.5
Ust'-Kirenga	113–165	64	5–6,5
Arshan	736–1 098	419–428	33.5–43
Klyuchi	91–130	52–51	4–5
Onguryon	269–388	153–151	12–15
TOTAL	2 681–3 951	1 527.5–1 540	122–154.5

TABLE 4. Technical and Economic Findings of Feasible SPP Capacity Calculations for Settlements in the Irkutsk Region

Settlement	Useful electricity generation, thousand kWh	Fuel savings, tons	Value of the fuel saved, million RUB	CUF, %
Karam	349–350	72–73	5.8	17.3–17.5
Alygdzher	722–742	149–153	14–15	16.9–17
Konoshanovo	53–52.5	11	1.2	17.3–17.5
Vershina Tutury	90–89	19–18	3.4	17.2–17.4
Pashnya	31–32	6.5	0.5	14.6–14.7
Ust'-Kirenga	82–83	17	1.3	14.6–14.7
Arshan	623–639	129–132	9	17–17.1
Klyuchi	77.5–77	16	1.3	17.1–17.3
Onguryon	261–260.5	54	5,3	19.5–19.7
TOTAL	2 288.5–2 325	473.5–480.5	41.8–42.8	–

capacity tend to involve larger capital outlays but also increases the useful energy output, and, accordingly, the amount and value of the fuel saved. It is the ratio of these values that serves as the criterion for deciding on the feasible SPP capacity.

IV. Results and Conclusions

Tables 3 and 4 sum up the results of calculations of the feasible SPP capacity for two types of PVCs based on the assumed input data (the first figure corresponds to the HVL-570/HJT PVC data, the second one - to the HVL-390/HJT PVC).

The total SPP capacity of nine remote off-grid settlements in the Irkutsk region is estimated at 1.5 MW. The annual fuel savings resulting from the use of these SPPs will amount to 470–480 tons/year and reduction in budget subsidies will be slightly less than RUB43 million/year.

V. Conclusion

The area of the region has significant solar power potential. The most favorable conditions for its use are observed within the water area of Lake Baikal. In contrast, available wind power potential makes prospects for its deployment in the region very limited. It is possible to add small capacities of wind turbines locally, mainly in the area of Lake Baikal and on Olkhon Island. This requires a dedicated survey of the location for the proposed wind turbine placement.

Nine settlements in the region are recommended for the use of solar power plants. The total feasible SPP capacity is more than 1.5 MW. Diesel fuel savings during the operation of SPPs are estimated at slightly less than 500 tons/year.

The key benefit that comes with the use of renewables to serve remote communities is reduction in budget subsidies for electricity supply and enhancement of reliability and energy security of consumers.

Acknowledgment

The research was carried as part of the State Assignment project FWEU-2021-0004 on "Comprehensive Studies of Priorities for Spatial Development of the Energy Industry of the Asian regions of Russia Informed by Technological Trends in the Sector of the Country and Energy Cooperation with the countries of North-East Asia."

References

[1] QGIS A free and open source geographic information system. [Online]. Available: https://www.qgis.org/ru/site/about/. (accessed 03.03.2023).

[2] Applied scientific handbook on the climate of the USSR. Series 3, parts 1-6, issue 22. The Irkutsk region and the western part of the Buryat ASSR. Leningrad, Russia: Gidrometeoizdat. 1991, 609 p. (In Russian)

[3] Handbook on the climate of the USSR. Iss. 22. The Irkutsk region and the western part of the Buryat ASSR. Part 1. Solar radiation, radiation balance, and sunshine. Leningrad, Russia: Gidrometeoizdat, 1966, 72 p. (In Russian)

[4] Handbook on the climate of the USSR. Iss. 22. The Irkutsk region and the western part of the Buryat ASSR. Part 3. Wind. Leningrad, Russia: Gidrometeoizdat, 1967, 232 p. (In Russian)

[5] A fast technique for feasibility studies of the optimal capacity of photovoltaic power plants as part of hybrid power complexes, by I. Yu. Ivanova, T. F. Tuguzova, N. A. Khalgaeva, (2022, May 13) Certificate of State Registration of Computer Program No. 2022618724. Right holder: Federal Publicly Funded Institution of Science Melentiev Energy Systems Institute, SB RAS.

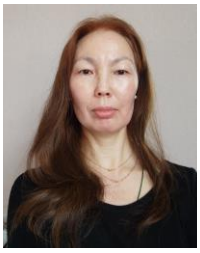
[6] I. Yu. Ivanova, T. F. Tuguzova, N. A. Khalgaeva, "Optimal sizing of renewable energy source capacity for off-grid consumers," Izvestiya RAN. Energetika, no. 3, pp. 22–28, 2014. (In Russian)

[7] B. G. Saneev, I. Yu. Ivanova, T. F. Tuguzova, N. A. Khalgaeva, "Impact of natural factors and costs on optimal capacity sizing of wind power plants as a part of the wind-and-diesel power complex in the East of the Russian Federation," Alternative Energy and Ecology (ISJAEE), no. 19–20, pp. 21–28, 2016. DOI: 10.15518/isjaee.2016.19-20.021-028. (In Russian)

Irina Yu. Ivanova, Ph.D. in Economics, is Head of the Energy Supply to Off-Grid Consumers Subdepartment at the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences. Her research interests are foundations, methods, and models for developing regional energy programs; evidence-based approach to the efficient use of renewables for energy supply to off-grid consumers in the eastern regions of Russia

Tatiana F. Tuguzova, Ph.D. in Engineering, is a Senior Researcher of the Energy Supply to Off-Grid Consumers Subdepatment at the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences. Her research interests include feasibility studies of the use of renewables for serving energy to off-grid consumers and

modeling of the joint use of renewables and fossil fuels. She is an active contributor to international and national conferences and workshops.



Nadezhda A. Khalgaeva is a Research Fellow of the Energy Supply to Off-Grid Consumers Subdepatment at the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences. Her research interests are evidence-based methods of the efficient use of renewables for energy supply to off-grid consumers in the eastern regions of Russia.

Modeling the Development of Energy Systems of Remote Areas in the Context of the Energy Transition

Y.D. Severina[1,*], V.A. Shakirov[1], L.N. Takaishvili[1]

[1] Melentiev Energy Systems Institute, SB RAS, Irkutsk, Russia

***Abstract* — This study focuses on the relevance of modeling the long-term development of energy systems in the context of the energy transition. The comparative analysis of software products for the modeling of energy systems and complexes is presented. Open source software such as SpineOpt, PyPsa, Switch, TEMOA, and TIMES are discussed in more detail. Based on this comparative analysis, SpineOpt is selected for further use as it is most feature-rich. The use of SpineOpt is considered in modeling the long-term development of the energy system of Novikovo located on the Tonin-Aniva peninsula in the Sakhalin region. An overview of the energy system, outline of plausible development options, and chosen key technologies are provided. The time frame of modeling extends to 2050 with multiple scenarios of development of the area considered. The scenarios differed in the constraints imposed on CO_2 emissions and new capacity additions of renewables. For each scenario, the model produced the optimal dynamics of evolution of the electricity generation mix, along with estimates of costs, greenhouse gas emissions, and hydrogen and germanium production volumes. Total CO_2 emissions during the modeled timespan, which extended to 2050, were about 946 thousand tons under the most stringent constraints, and 2 458 thousand tons under moderate ones. At the same time, capital expenditures for the construction of energy facilities amounted to $51.6 million and $45.8 million, respectively. The solutions resulting from modeling enable identifying the most promising areas for development and technologies to be adopted.**

***Index Terms* — Energy transition, decarbonization, modeling, energy system, renewable energy sources, long-term development.**

I. Introduction

Increased consumption of hydrocarbons, intensive growth of the energy, industrial, and transport sectors increases greenhouse gas emissions, which may lead to global warming. Therefore, there is a need for the energy transition that aims to create low-carbon energy systems that either use no fossil fuels at all or use them while leveraging carbon capture and storage technologies. In the future, this could lead to decarbonization of the energy sector, thereby addressing the large-scale and complex issue of global climate change [1, 2].

The use of renewables to generate electricity and heat, in contrast to the burning of fossil fuels, reduces emissions of pollutants and greenhouse gases into the atmosphere. Therefore, renewable energy sources (RES) play a major role in reducing the human-induced impact on the ecosystem [3].

The key part of the energy transition is combating climate change that has become much worse over the past few years and could further cause considerable damage to the global economy. In this regard, 197 countries around

* Corresponding author.
E-mail: yan.sewerina2910@yandex.ru

http://dx.doi.org/10.25729/esr.2024.04.0005

Received December 5, 2024. Acc. December 13, 2024. Available online December 28, 2024.

the world adopted the Paris Agreement in 2015. The agreement aims at significantly reducing global greenhouse gas emissions and limiting the average temperature increase to 1.5°C, thereby ensuring the transition to a low-carbon economy [4].

Modeling expansion and operation of energy systems in the context of the energy transition is key to analyzing and predicting the changes that occur in the energy industry in the long-term [5].

A salient feature of the current stage of development planning of energy systems is an incessant increase in the dimensionality of the problems being solved and the level of granularity of the mathematical treatment of technologies and the time step of modeling [6–8]. The use of modeling to solve energy sector problems provides ample opportunities, such as analyzing the effect of various factors on the structure and operation of energy systems, making the electricity and heat consumption forecast, as well as evaluating the performance of different development strategies to improve the stability of operation and reliability of energy supply to consumers [9, 10].

Long-term expansion planning of energy systems in remote areas needs to be informed by the current trends in the energy transition and numerous factors and conditions specific to such areas [11, 12].

This article reviews software products developed for energy systems modeling. The long-term development of Novikovo, a remote area of the Sakhalin region power grid, is used as an example to demonstrate the capabilities of SpineOpt, one of the most promising modeling tools. Scenarios of energy system development have been formed and optimal solutions of technological development have been received taking into account the constraints on greenhouse gas emissions.

II. Overview of Software Products

There are a large number of software products for modeling energy systems, which were reviewed in [13-15]. Based on the analysis found in the reviews, SpineOpt, PyPsa, Switch, TEMOA, and TIMES were considered in more detail because they are open source software available for scrutiny and empowering users to extend the functionality of the product.

These software products were compared according to several criteria listed in Table 1.

A. Data Structure

The Data Structure section presents criteria related to the organization and management of data, as well as the storage of the results obtained. The data structure in PyPSA is based on a specific set of core components that are linked to each other and customized by selecting the values of their predefined properties. The list of available elements includes generators, loads, power transmission lines, transformers, storage, etc. PyPSA is implemented in Pyomo, a Python-based open source package [16].

TEMOA builds a linear model using certain components and the processes related to them. The modeling framework includes three main blocks: “Resources”, “Conversion”, and “Consumption”. An energy system is described in mathematical terms as a model of coupled processes where energy carriers (e.g., coal, oil, etc.) are converted into heat or electricity to meet demand. This software product, like PyPSA, is implemented in Pyomo, a Python-based open source package [17].

Switch uses separate modules to model different scenarios, energy sources, transmission lines, etc. After the input data are analyzed, Switch generates a spatio-temporal model of the energy system with various constraints and conditions. Unlike the other products compared here, Switch only allows creating models of electric power systems. The software is implemented in Pyomo, a Python-based open source package [18].

TIMES allows modeling the long-term development of energy systems, and also enables a technical and economic analysis of the model. The data structure in TIMES supports specifying an energy system of any scale and with multiple economic sectors. However, the software relies on a proprietary solver (GAMS), which imposes some limitations on its use [19].

SpineOpt is open source software, and its structure is similar to that of other products, except that it is extended by a wide range of functions to solve diverse problems dealt with in the energy industry. The model data structure is generated as a database in the Spine Toolbox environment. SpineOpt is implemented in Julia with the use of the JuMP modeling language for mathematical optimization [13, 15].

B. Specification of the Temporal Dimension of the Model

Time-dependent modeling capability is necessary to capture the dynamics of energy system model changes over a given period of time. There are short-term simulation models that aim to obtain a short-term forecast of the consumption and loading of energy facilities to serve the load profile. Long-term models seek to solve problems related to projecting consumption or making optimal investment decisions over an extended time horizon, often spanning several decades.

The software tools PyPsa, TEMOA, TIMES, and Switch enable modeling horizon to be specified, but the horizon itself cannot be further divided into specific time intervals [16–18]. SpineOpt stands apart from the competition in that it supports specifying different temporal resolution depending on the conditions related to specific geographical areas, industries, and technologies. This allows specifying object parameters with individual temporal relationships at the level of a single node or energy facility. Depending on the problem to be solved, the time horizon covered by a model can vary from a few seconds to several decades. At the same time, SpineOpt supports specifying a time step value, i.e., the time horizon can be divided into seconds, minutes, hours, days, months, or years. This feature of SpineOpt enables solving various problems of short-term or long-term studies of energy systems [13].

C. Modeling under uncertainty

In order to account for uncertainties in the modeling process, a stochastic approach is employed based on the generation of different scenarios of how events unfold. All software products presented in Table 1, except PyPSA and Switch, can handle stochastic conditions and parameters [16, 17].

TEMOA does not deal with stochastic parameters or conditions as such but can explore a variety of solutions by employing a heuristic technique of "modeling to generate alternatives" (MGA) [17].

TIMES supports specifying a multi-stage stochastic model of an energy system with probability distribution of uncertain parameters on an event tree [11].

SpineOpt supports modeling of alternative scenarios and multi-stage stochastic models. Possible changes in the input data during the modeling process can be introduced through individual scenarios that contain all the specified values or conditions for any parameter. This approach produces a single result for each scenario and is often used for modeling a variety of complex problems in the energy industry. For example, this feature of the software is used when setting stochastic parameters of thermal or electrical loads, availability factors of solar and wind power, or water inflow to a reservoir. In this way, SpineOpt supports consistent addition of scenarios to different objects of the model. Therefore, SpineOpt allows a combination of alternative scenarios to be considered under uncertainty in the model input values, which yields more accurate results. Moreover, the stochastic structure of SpineOpt enables independent modeling of stochastic input data for different regions or sectors [13, 14].

D. Solving Large-Scale Problems

This section presents criteria related to solving large-scale problem. SpineOpt and TIMES are capable of solving this kind of problems. The solution process relies on decomposition, where a large problem (e.g., the combined problem of system operation and planning) is broken down into an equivalent set of smaller problems in order to control the computational process and reduce its complexity [5, 11].

The availability of the "rolling planning" feature is also essential for solving such problems. "Rolling planning" is a planning technique that treats the nearest time period in more detail, whereas more distant time periods are considered in broad lines. This feature is supported by SpineOpt and TIMES, which allows a single task of long duration to be split into a series of overlapping tasks of shorter duration to solve them sequentially using a rolling window. In SpineOpt, the duration of a rolling window can be any integer value with a duration ranging from seconds to several years [13].

E. Operational Detail

This section discusses software features that are necessary for solving the problems of expansion and operation of energy systems and complexes. One such criterion is "Support for modeling of energy systems with multiple energy sources". As mentioned in the previous section, the energy transition makes the use of renewables particularly relevant. Therefore, modeling of alternative and conventional energy sources informed by their specific features is essential for the software tool in solving this kind of problems. All software products that are listed in Table 1, except Switch, ship with this feature.

TABLE 1. Comparison of Software Products for Energy Systems Modeling

Criterion / Software product	PyPSA	TEMOA	TIMES	Switch	SpineOpt
Data structure					
1. Relationship between blocks / sectors of the model	✓	✓	✓	–	✓
2. Convenience and flexibility of the interface	✓	–	✓	✓	✓
Specification of the temporal dimension of the model					
1. Division of the modeling process into specific time periods / intervals	–	–	–	–	✓
2. Support for user-defined modeling horizons	✓	✓	✓	✓	✓
Modeling under uncertainty					
1. Stochastic modeling	–	✓	✓	–	✓
2. Modeling of multiple scenarios of system development	–	–	–	–	✓
Solving large-scale problems					
1. Rolling planning	–	–	✓	–	✓
2. Availability of the decomposition algorithm	–	✓	–	–	✓
Operational detail					
1. Reserve modelling	–	✓	✓	✓	✓
2. Support for production and consumption constraints	✓	✓	✓	✓	✓
3. Scheduling the start-up and shut-down of units	✓	✓	✓	✓	✓
4. Support for models of energy systems with multiple energy sources	✓	✓	✓	–	✓
Software development and technical support					
1. Free and open source software	✓	✓	–	✓	✓
2. Documentation and tutorials	✓	✓	✓	✓	✓
3. Data management tools	–	✓	✓	–	✓

Furthermore, setting limits on energy production and consumption is required for studying operating conditions of energy systems and ensuring their energy balance. All software products listed in Table 1 have this feature.

Another essential feature is scheduling startups and shutdowns of individual units. This property applies when a new energy facility is added to the system, or an old facility is taken out of operation for maintenance or decommissioned. All software products listed in Table 1 have this feature.

Modeling of energy systems usually covers an extended period of time, over which there may be an increase in electrical and thermal loads or disruptions in energy supply to consumers. Therefore, the software tool chosen for studying such models must be able to model the reserve. All software products listed in Table 1 have this feature [13, 15].

F. Software Development and Technical Support

Almost all of the software tools listed in Table 1 are free of charge and open-source products and are available for download with a full array of features. The exception is TIMES, as this product uses proprietary code, so some features may not be available.

Each software is also provided to some extent with documentation and tutorials covering all available functions. Furthermore, official websites of some software products link to specialized webinars. For example, SpineOpt developers hold conferences where they discuss solutions to specific problems in the energy sector implemented in this program [20].

Based on the information in Table 1, SpineOpt has been chosen for further research because of its properties such as versatility and feature availability. The software enables stochastic programming and rolling planning, modeling of different energy systems with and without renewables, and simultaneous analysis of multiple scenarios. Such capabilities are suitable for solving problems related to the study of long-term development of energy systems and complexes. Also, unlike TIMES, SpineOpt can use free optimization solvers such as HiGHS.

III. Input Data and Research Methodology

The study of development of local energy system development in the Sakhalin region was carried out using SpineOpt. The research methodology is outlined in Fig. 1. At Step 1 data on the modeled object was collected: this includes wind speed and solar radiation data, electric and thermal load profiles, technical and economic performance of energy generation and transmission technologies. Solar radiation data were prepared in 'System model advisor' [21]. Wind speed data were generated using the NASA POWER database [22] and the Wind-MCA software tool [23]. At Step 2, SpineOpt was used to build a model informed by the features and constraints specific to the area. At Step 3, data were input for all blocks of models and modeling parameters and technical and economic parameters of technologies were determined. Step 4 was modeling under several assumed development scenarios. At the last step the received results were analyzed.

A. General Information About the Energy System of the Sakhalin Region

The software product SpineOpt was used to study the areas for possible development of the energy system of Novikovo located on the Tonin-Aniva peninsula in the Sakhalin region. The Sakhalin region's power sector is unique in that it is technologically isolated from the UES of Russia and the UES of the East. The Sakhalin region's power system is divided into separate stand-alone power system districts:

– the Central district of the power system, which serves electricity to the southern and central parts;

– the Northern district of the power system, which supplies power to the municipal entity of the Okha urban district of the Sakhalin region;

– decentralized (off-grid) districts of the power system that are located on the Kuril Islands and in remote settlements of a number of municipalities of the Sakhalin region

The main sources of electricity and heat in the Sakhalin region are thermal power plants. In the Central district of the power system, the key generating facilities are the Yuzhno-Sakhalinskaya combined heat and power plant (CHPP) CHPP-1 that runs mostly on natural gas, and the Sakhalinskaya condensing power plant (CPP) CPP-2 that uses coal as its main fuel. The main source in the “Northern district of the power system” is the Okha CHPP, which runs on natural gas to generate power. The off-grid districts of the power system generate electricity at diesel power plants and distribute it within the boundaries of settlements, as they are not connected to major power system districts of the region.

One such off-grid district of the power system is Novikovo, which is located in the southwestern part of Sakhalin island. This district of the power system is located on the Tonin-Aniva peninsula and includes the settlement of Novikovo, Pikhtovoye, Beregovoye, and Muravyevo.

The main source of electricity in the area is the Novikovo wind/diesel power plant (WDPP Novikovo), with an installed capacity of 4.666 MW. The power plant utilizes two Vestas V25 wind turbines with a rated capacity of 2x225 kW. The electric network is made up of 6(10) kV power transmission lines that are 7.31 km long. One substation with a 1 MVA transformer is connected to the line. The power system district also has 7.54 km of 0.22–0.4 kV low voltage transmission lines constructed there. In 2020, electricity consumption amounted to 1.603 million kWh with useful output of 1.49 million kWh (of which industrial consumers consumed 0.05 million kWh,

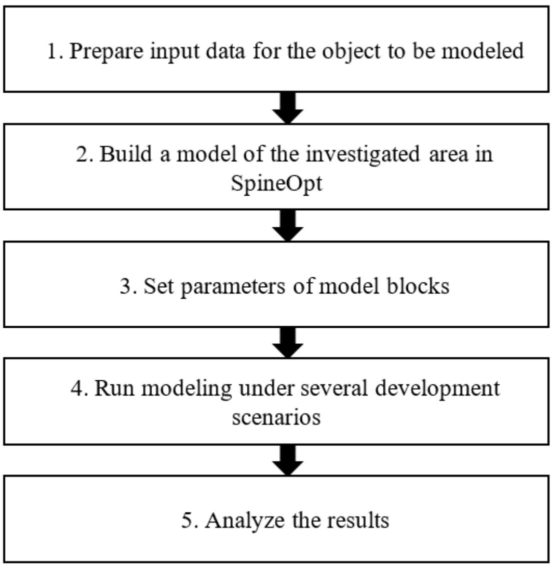


Fig.1. Flow diagram of key steps of the study.

households – 0.97 million kWh, others – 0.48 million kWh), and consumption for auxiliary needs was 0.059 million kWh. This implies that there are consumers with different load patterns in the area.

Since the power system district of Novikovo is not connected to the grid, it is planned to connect the Novikovo WDPP to the Central district of the power system in the future, in accordance with the Sakhalin region's Grid layout and expansion plan of the power system.

The Novikovskoye coal deposit (formerly the Novikovsky open-pit coal mine), which was commissioned in 1967, is located on the Tonin-Aniva peninsula. This open-pit mine produced germanium-bearing metallurgical coal and mudrocks, as well as thermal coal. Various sources note that the Novikovsky open-pit coal mine provided up to 80% of the germanium produced in the USSR. Since 2007, the deposit has been discontinued and all residual reserves have been re-classified as non-licensed reserves [24, 25].

Germanium is an essential metal widely used in space research, military technology, radio engineering, electrical engineering, etc. In recent years, there has been an increase in germanium demand and prices, and the range of its applications is expanding. Germanium recovery is possible during combustion of coal with capture of the germanium-bearing fly ash [26]. Another option could be coal gasification with germanium recovery from the fly ash. At the same time, coal gasification opens the way for obtaining various products from syngas: hydrogen, methanol, and others. The use of coal for thermal power generation is possible both on the basis of conventional steam turbine plants and with the use of combined cycle gas turbines with integrated coal gasification (IGCT) [27].

The use of coal entails consideration carbon capture and storage technologies. In addition, the area has a high wind and solar power potential, which warrants the inclusion of RES generation in the analysis.

Due to the diversity of options available for the development of the Tonin-Aniva peninsula energy system, SpineOpt proves to be a suitable tool for its modeling.

B. Modeling of the Tonino-Aniva Peninsula Energy System in SpineOpt

Figure 2 shows the model for studying the areas of possible development of the Tonin-Aniva peninsula energy system in SpineOpt. The model of the system spans a time horizon extending from 2025 to 2050.

At its initial state, the energy system includes the existing Novikovo WDPP (“DieselPP” and “WindFarm”

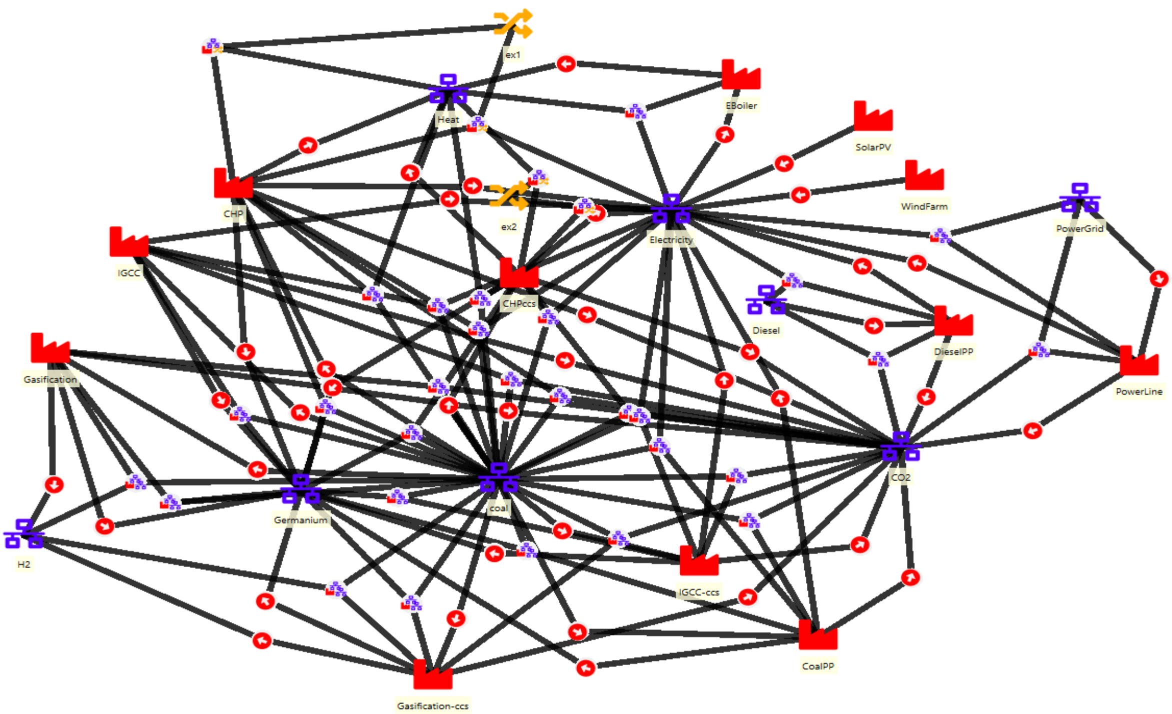


Fig.2. A SpineOpt model of Tonino-Aniva peninsula energy system development.

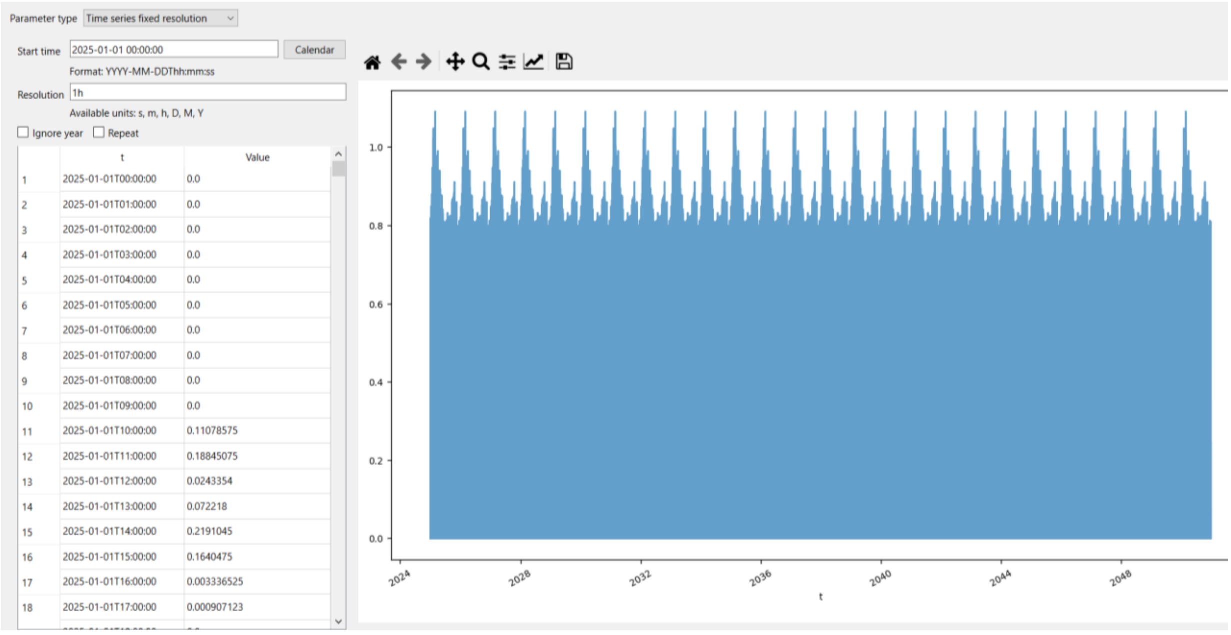


Fig. 3. Solar radiation data as a time series for the "SolarPV" block.

blocks), which is the main power source. The "DieselPP" diesel power plant runs on diesel fuel from the "Diesel" node to generate electricity.

The model covers such possible strands of development as germanium recovery ("Germanium" node) and the use of coal for thermal power generation at a CHP plant with or without CO_2 capture ("CHP" and "CHPcss" blocks), or to run a coal-fired power plant ("CoalPP" block) to serve future electricity and heat loads ("Electricity" and "Heat" blocks). These plants use the coal from the "Coal" node for power generation.

The use of coal paves the way to its gasification by means of IGCT ("ICGT" block) or other technologies ("Gasification" block). The product of gasification is syngas, which can be used for hydrogen production ("H2" node). We also consider the possibility of supplying power to consumers from a solar PV power plant (SolarPV block).

In addition, the model provides for hook-up of the off-grid power system of Novikovo to the Central district of the power system ("PowerLine" and "PowerGrid" blocks). The presence of the "CO2" node enables setting constraints on greenhouse gas emissions.

As noted earlier, the first step involved the collection of wind speed and solar radiation data for the investigated area. SpineOpt allows setting these parameters in the form of a multi-year time series with hourly resolution, which is shown in Fig. 3.

Depending on the specified conditions (prices, energy demand) and constraints (greenhouse gas emissions, investments, available technology), SpineOpt can generate optimal energy system configurations and development scenarios for a given period of time.

The modeling was carried out under three possible scenarios of development: 1) strict limits on CO_2 emissions and new capacity additions of renewables, 2) moderate limits on CO_2 emissions and unconstrained new capacity additions of renewables, and 3) moderate limits on CO_2 emissions and new capacity additions of renewables. Running models for each of the scenarios provided information on the energy system generation mix by 2050, annual CO_2 emissions, hydrogen production, and germanium production, as well as some economic performance indicators.

IV. Results and Discussion

Table 2 shows the optimal mix of generation capacity of the energy system by 2050 for three scenarios.

Table 3 presents the values of some economic indicators calculated for the three scenarios, as well as information on hydrogen production, germanium production, and CO_2 emissions for the considered timespan.

As a result of the modeling of the first scenario, the existing WDPP became a part of the energy system to serve the electrical loads. A coal-fired power plant and a solar PV power plant were commissioned in 2025 for the same purpose. From 2030 onwards, consumers were connected to a district heating system, so a CHP plant without CO_2 capture was built. The same year also saw an increase in electricity consumption, as a consequence of which another coal plant was commissioned to serve the demand. Since this option sets strict limits on greenhouse gas emissions, SpineOpt mostly commissioned sources with CO_2 capture. In 2035, the projected increase in heat and electricity consumption led to commissioning of a CHP plant with CO_2 capture (CHPcss block) and construction of a power transmission line for connection to the grid. Another CHP plant with CO_2 capture was commissioned in 2040 due to further growth in electricity and heat loads. Coal gasification technology with CO_2 capture ("Gasification with css" block) was adopted in 2035 and 2040. Germanium production and CO_2 emissions were 217.86 tons and 945.73 thousand tons, respectively.

The second scenario uses the wind farm as the main source of the energy system as the restrictions on new capacity additions of renewables have been lifted. In this case, SpineOpt eliminated the diesel power plant but retained the coal plant ("CoalPP" block) and CHPP without CO_2 capture ("CHP" block). This is because coal is cheaper than diesel fuel. The only renewable energy sources were wind turbines, and the solar PV plant was removed from the system. This is due to the fact that the investigated area has a high wind power potential. The system also adopted coal gasification technology without CO_2 capture ("Gasification" block) as the scenario sets moderate emission limits. Due to high coal consumption, germanium production also increased to 350.4 tons. For the same reason, the total value of greenhouse gas emissions amounted to 2 032.06 thousand tons, which is higher than the same value in the previous scenario.

TABLE 2. Generation Capacity Mix by 2050 for Three Scenarios

Scenario 1: Strict limits on CO_2 emissions and new capacity additions of renewables			Scenario 2: Moderate CO_2 emission limits			Scenario 3: Moderate limits on CO_2 emissions and new capacity additions of renewables		
Energy facility	Qty, pcs.	Power, MW	Energy facility	Qty, pcs.	Power, MW	Energy facility	Qty, pcs.	Power, MW
CHP	1	1	CHP	3	3	CHP	3	3
CHPcss	2	2	CHPcss	0	0	CHPcss	0	0
CoalPP	3	3	CoalPP	10	10	CoalPP	12	12
DieselPP	5	5	DieselPP	0	0	DieselPP	5	5
PowerLine	1	1	PowerLine	0	0	PowerLine	0	0
SolarPV	5	5	SolarPV	0	0	SolarPV	1	1
WindFarm	7	1.75	WindFarm	45	11.25	WindFarm	5	1.25
Gasificationcss	5	5	Gasification	5	5	Gasification	5	5

TABLE 3. Results of Modeling for Three Scenarios

Parameter/Scenario	Scenario 1	Scenario 2	Scenario 3
Fuel cost	26.87 mln USD	42.04 mln USD	50.84 mln USD
Investment costs	51.61 mln USD	55.96 mln USD	45.81 mln USD
Total costs	148 mln USD	121.6 mln USD	121.85 mln USD
Hydrogen production	350 400 MWh	350 400 MWh	341 640 MWh
Germanium production	217.86 t	350.4 t	423.72 t
CO_2 emissions	945.73 thous. t	2 032.06 thous. t	2 457.53 thous. t

The second scenario envisions higher penetration of renewables into the energy system, which increases the risks related to system stability. Therefore, the third scenario sets moderate limits on CO_2 emissions, but also imposes constraints on new capacity additions of renewables. Under the above assumptions, the main sources were a coal-fired plant, CHP without CO_2 capture, and diesel power plant. Wind turbines and a solar PV power plant were also included in the system. Germanium production amounted to 423.72 tons, which was higher than the corresponding value in the second scenario. In this case, consumers were mainly supplied from conventional energy sources, so the total CO_2 emissions amounted to 2 457 530 tons, which is higher than the values obtained for the previous two scenarios.

Thus, the developed SpineOpt model of the Tonin-Aniva peninsula energy system can be used to study various long-term development options under various conditions and constraints.

V. Conclusion

The study addressed a set of issues related to modeling the long-term evolution of energy systems in the context of the energy transition, subject to various conditions and constraints. The comparative analysis of software products for energy system modeling is able to single out SpineOpt as the most versatile and feature-rich solution. A model of the Tonin-Aniva peninsula energy system built in SpineOpt can be applied to study different options of its long-term development. Using SpineOpt model the analysis of the energy system development was carried out under three scenarios: 1) strict limits on CO_2 emission limits and new capacity additions of renewables, 2) moderate CO_2 emission limits and unconstrained new capacity additions of renewables, and 3) moderate limits on CO_2 emissions and new capacity additions of renewables. The resulting solutions make it possible to identify promising directions for the technological development of the energy system.

VI. Acknowledgements

The research was carried out under the State Assignment (FWEU-2021-0004) of the Program for Basic Research of the Russian Federation for 2021–2035 and made use of the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Education and Science of the Russian Federation, project No. 13.CKP.21.0038).

References

[1] A. Q. Al-Shetwi, I. Z. Abidin, K. A. Mahafzah, M. A. Hannan, “Feasibility of future transition to 100% renewable energy: Recent progress, policies, challenges, and perspectives,” Journal of Cleaner Production, vol. 478, p. 143942, Nov. 2024. DOI: 10.1016/j.jclepro.2024.143942.

[2] P. K. Adom, “Global energy efficiency transition tendencies: Development phenomenon or not?”, Energy Strategy Reviews, vol. 55, p. 101524, Sep. 2024. DOI: 10.1016/j.esr.2024.101524.

[3] Y. Shang, S. Sang, A. K. Tiwari, S. Khan, X. Zhao, “Impacts of renewable energy on climate risk: A global perspective for energy transition in a climate adaptation framework,” Applied Energy, vol. 362, p. 122994, May 2024. DOI: 10.1016/j.apenergy.2024.122994.

[4] N. Doan, H. Doan, C. P. Nguyen, B. Q. Nguyen, “From Kyoto to Paris and beyond: A deep dive into the green shift,” Renewable Energy, vol. 228, p. 120675, Jul. 2024. DOI: 10.1016/j.renene.2024.120675.

[5] V. Del Duca, C. Ponsiglione, S. Primario, S. Strazzullo, “Towards Economic, Environmental, and Societal Sustainable World: Reviewing the Interplay of Methodologies, Variables, and Impacts in Energy Transition Models,” Journal of Cleaner Production, vol. 479, p. 144074, Oct. 2024. DOI: 10.1016/j.jclepro.2024.144074.

[6] N. Moksnes, M. Howells, W. Usher, “Increasing spatial and temporal resolution in energy system optimisation model – The case of Kenya,” Energy Strategy Reviews, vol. 51, p. 101263, Jan. 2024. DOI: 10.1016/j.esr.2023.101263.

[7] O. Omoyele et al., “Increasing the resolution of solar and wind time series for energy system modeling: A review,” Renewable and Sustainable Energy Reviews, vol. 189, p. 113792, Jan. 2024. DOI: 10.1016/j.rser.2023.113792.

[8] S. D. Manuel, T. Floris, W. Kira, S. Jos, F. André, “High technical and temporal resolution integrated energy system modelling of industrial decarbonisation,” Advances in Applied Energy, vol. 7, p. 100105, Sep. 2022. DOI: 10.1016/j.adapen.2022.100105.

[9] M. Hoffmann et al., “A review of mixed-integer linear formulations for framework-based energy system models,” Advances in Applied Energy, vol. 16, p. 100190, Dec. 2024. DOI: 10.1016/j.adapen.2024.100190.

[10] S. Feng, H. Ren, W. Zhou, “A review of uncertain factors and analytic methods in long-term energy system optimization models,” Global Energy Interconnection, vol. 6, no. 4, pp. 450–466, Aug. 2023. DOI: 10.1016/j.gloei.2023.08.006.

[11] Y. Liu, S. Yu, Y. Zhu, D. Wang, J. Liu, "Modeling, planning, application and management of energy systems for isolated areas: A review," Renewable and Sustainable Energy Reviews, vol. 82, pp. 460–470, Feb. 2018. DOI: 10.1016/j.rser.2017.09.063.

[12] S. Kwon, W. Won, J. Kim, "A superstructure model of an isolated power supply system using renewable energy: Development and application to Jeju Island, Korea," Renewable Energy, vol. 97, pp. 177–188, Nov. 2016. DOI: 10.1016/j.renene.2016.05.074.

[13] M. Ihlemann et al., "SpineOpt: A flexible open-source energy system modelling framework," Energy Strategy Reviews, vol. 43, p. 100902, Sep. 2022. DOI: 10.1016/j.esr.2022.100902.

[14] L. Laveneziana, M. Prussi, D. Chiaramonti, "Critical review of energy planning models for the sustainable development at company level," Energy Strategy Reviews, vol. 49, p. 101136, Sep. 2023. DOI: 10.1016/j.esr.2023.101136.

[15] J. Kiviluoma et al., "Spine Toolbox: A flexible open-source workflow management system with scenario and data management," SoftwareX, vol. 17, p. 100967, Jan. 2022. DOI: 10.1016/j.softx.2021.100967.

[16] T. Brown, J. Hörsch, D. Schlachtberger, "PyPSA: Python for Power System Analysis," Journal of Open Research Software, vol. 6, no. 1, p. 4, Jan. 2018. DOI: 10.5334/jors.188.

[17] K. Hunter, S. Sreepathi, J. F. DeCarolis, "Modeling for insight using Tools for Energy Model Optimization and Analysis (Temoa)," Energy Economics, vol. 40, pp. 339–349, Nov. 2013. DOI: 10.1016/j.eneco.2013.07.014.

[18] J. Johnston, R. Henriquez-Auba, B. Maluenda, M. Fripp, "Switch 2.0: A modern platform for planning high-renewable power systems," SoftwareX, vol. 10, p. 100251, Jul. 2019. DOI: 10.1016/j.softx.2019.100251.

[19] R. Loulou, G. Goldstein, A. Kanudia, A. Lettila, U. Remme, Documentation for the TIMES model part I, 2016, 151 p.

[20] SpineOpt.jl. Tutorials / Webinars [Online] Available: https://spine-tools.github.io/SpineOpt.jl/latest/tutorial/webinars/.

[21] M. Chennaif, M. Maaouane, H. Zahboune, M. Elhafyani, S. Zouggar, "Tri-objective techno-economic sizing optimization of Off-grid and On-grid renewable energy systems using Electric system Cascade Extended analysis and system Advisor Model," Applied Energy, vol. 305, p. 117844, Jan. 2022. DOI: 10.1016/j.apenergy.2021.117844.

[22] Z. Zeng, P. Stackhouse, J.-H. (Jeannie) Kim, R. T. Muehleisen, "Development of typical solar years and typical wind years for efficient assessment of renewable energy systems across the U.S.," Applied Energy, vol. 377, part D, p. 124698, Jan. 2025. DOI: 10.1016/j.apenergy.2024.124698.

[23] V. G. Kurbatsky, V. A. Shakirov, "Methodology and software for assessing the wind energy potential of the northeast of Russia," Proceedings of Irkutsk State Technical University, vol. 24, no 1, pp. 145–163, 2020. DOI: 10.21285/1814-3520-2020-1-145-163. (In Russian)

[24] "Novikovskoye deposit of germanium-bearing coal (Novikovskiy area) / Germanium. Lignite," Nedradv.ru. [Online]. Available: https://nedradv.ru/nedradv/ru/find_place?obj=887a9597925efa925a2151143f0b27fa. (In Russian)

[25] A. V. Tarasov, Subsoil of the Sakhalin region, O. A. Zayats, Ed. Yuzhno-Sakhalinsk, Russia: Publishing House "Sakhalin" – Priamurskiye Vedomosti" LLC, 2013, 120 p. (In Russian)

[26] P. B. Avdeev, A. A. Kuzhikov, G. L. Kuklina, "Prospects for the use of germanium-bearing coal of the Tarbagataisky lignite deposit in Transbaikalia," Mining information and analytical bulletin (scientific and technical journal), no. 4, pp. 26–31, 2015. (In Russian)

[27] S. P. Filippov, A. V. Keiko, "Coal gasification: at a crossroads. Technological factors," Thermal Engineering, no. 3, pp. 45–58, 2021. (In Russian)

Yana Severina is a first-year PhD student majoring in "2.4.5 Power Systems and Complexes" at the Melentiev Energy Systems Institute, SB RAS, Irkutsk. Educational background: Irkutsk National Research Technical University, Master's degree in 13.04.02 "Electric Power Engineering and Electrical Engineering" ("Intelligent Power Supply Systems" Program). Research interests: renewable energy sources, energy systems modeling. Contacts: 130 Lermontov st., 664033, Irkutsk, Russia. E-mail: yan.sewerina2910@yandex.ru

Vladislav Shakirov graduated from Bratsk State University in 2004. He received Ph.D. in 2007. Shakirov V.A. is a senior researcher at the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia. His research interests include renewable energy, multi-criteria optimization and decision making methods, energy systems expansion planning. Contacts: 130 Lermontov st., 664033, Irkutsk, Russia. E-mail: shakirov@isem.irk.ru

Liudmila Takaishvili received a Ph.D. in engineering from the Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences in 1991. Currently, she is a senior researcher at the Melentiev Energy Systems Institute SB RAS. Her research areas include the studies on the coal industry development prospects and the development of software and information support for these studies. Contacts: 130 Lermontov st., 664033, Irkutsk, Russia. E-mail: lucy@isem.irk.ru

An Outlook for Alternative Fuel Demand in Road Transport: The Case of the Irkutsk Region

D.V. Maksakova[1,*], S.P. Popov[1]

[1] Melentiev Energy Systems Institute, SB RAS, Irkutsk, Russia

***Abstract* — The paper presents an approach to making projections of demand for alternative fuels in road transport with a focus on natural gas, electricity, and hydrogen. The proposed approach is based on chaining multiple simulation models (both econometric and deterministic) that capture the changes in the number of vehicles on the roads, sales structure, and energy efficiency. The models are tailored to available statistical data on the vehicle fleet in regions of Russia. We explore the main features of road transport in the Irkutsk region and project the demand for alternative fuels by the transport sector under the innovation-driven scenario of regional economic development. Despite recent vehicle purchases in the sector of municipal passenger transport and the increased motorization rate, today's vehicle fleet is in need of modernization. The key takeaway from this study is that the growth of population will favor the market for vehicles running on alternative fuels; however, the market size depends on vehicle affordability, gas supply to the region, and government support.**

***Index Terms* — alternative energy sources, road transport, energy demand outlook, Irkutsk region.**

I. Introduction

Road transport is essential for meeting the demand for passenger transit and freight transport, as well as the development of a number of economic sectors, such as machinery, steelmaking, electrical engineering, and oil refining industries.

The importance of road transport for the energy and oil industries can hardly be overestimated. According to the International Energy Agency, consumption of petroleum products by motor vehicles in 2021 was 1.9 billion toe, or 49% of global final consumption of petroleum products [1]. The trends in the consumption of petroleum products by the transport sector in individual regions of the world are divergent. While in developing countries the demand for petroleum products is increasing following higher motorization rates, developed countries face the stagnation and decline due to the following factors:

1) improved energy efficiency;
2) the already attained high motorization rates;
3) slower economic growth and lower freight volumes;
4) structural shifts: the use of fuels alternative to petroleum products (natural gas, electricity, biofuels, and hydrogen).

While the effect of the first three factors on energy consumption in the transport sector has been studied well enough and lends itself to prediction by econometric methods, the assessment of changes in the makeup of energy consumption is a research problem in its own right, which often calls for a tailor-made approach [2]–[5]. The methods and models used to predict structural changes depend on the object of the study, as the rate and scale of the transition to energy sources alternative to petroleum products can vary significantly subject to their unique economic and social features and the government policies that accommodate them, both at the national and regional levels. Projecting energy consumption of alternative fuels at the initial stage of commercialization of the respective technologies may pose additional challenges when historical data on changes in the makeup of energy

* Corresponding author.
E-mail: maksakova@isem.irk.ru

http://dx.doi.org/10.25729/esr.2024.04.0006

Received November 20, 2024, Acc. November 29, 2024. Available online December 28, 2024.

consumption have not been accumulated. Making projections gets even more difficult due to inconsistent statistical reporting at the regional level on the overall makeup of the vehicle fleet and its energy consumption, which warrants the need to combine statistical methods with expert judgment techniques [6].

Projections of energy consumption by the transport sector in Russia as a whole are published by a number of research institutions [7]–[9]. At the same time, regional trends may differ from them as they reflect the level of economic development and the features of the energy sector specific to individual constituent entities of the Russian Federation. All of the above exacerbates the incentive for the methods of motor fuel demand estimation to better cater to regional needs.

This study details an approach to estimating the demand for alternative fuels and electricity based on a system of econometric and deterministic models. Our approach is designed so as to align with the quality of statistical data available on the regions of the Russian Federation. We use this approach to make a projection of the demand for alternative fuels under the innovation-driven scenario of economic development of the Irkutsk region.

II. Methodology

Projections of energy demand for alternative fuels and electricity by road transport are important for 1) drawing up a projected energy balance, 2) evaluating changes in demand for petroleum products, 3) assessing promising developments in energy industries (gas, electricity, hydrogen). For example, electrification of road transport can meaningfully influence the level of electricity consumption, demand for generation capacity, and daily load profiles [10].

The studies carried out at the Melentiev Energy Systems Institute to provide an evidence-based rationale and projections for key trends in consumption of alternative fuels by road transport in the Irkutsk region employ an approach that embraces the lack of statistical data available on individual regions of the Russian Federation. The approach breaks down the process of making projections of energy consumption of alternative fuels and electricity by road transport into the following steps:

1. vehicle classification;
2. estimation of the vehicle fleet size (by vehicle type);
3. determination of the number of new vehicles;
4. calculation of the size of the vehicle fleet and the number of new vehicles running on alternative fuels and electricity;
5. estimation of consumption of alternative fuels and electricity.

1. Overall Makeup of the Vehicle Fleet

The frequency of vehicle use (mileage) and specific fuel consumption vary considerably depending on the intended

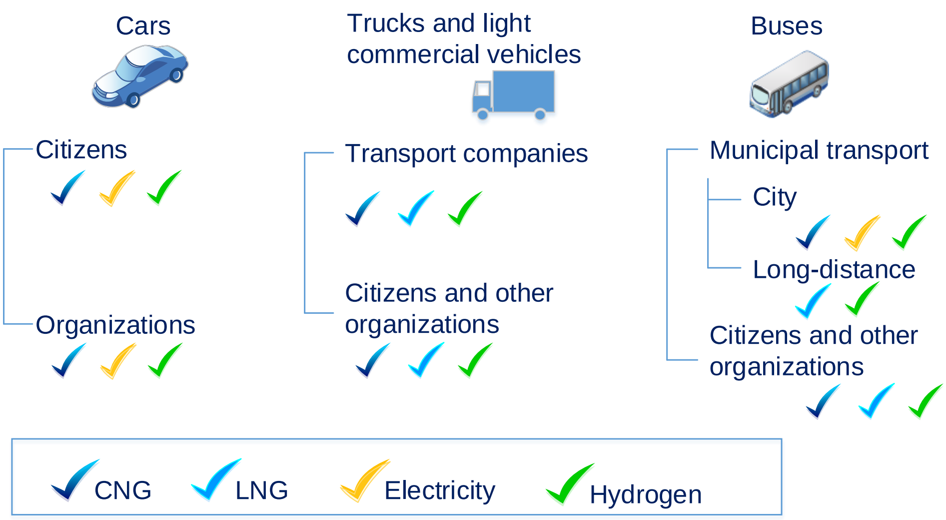


Fig. 1. Vehicle types.

1. Overall Makeup of the Vehicle Fleet

The frequency of vehicle use (mileage) and specific fuel consumption vary considerably depending on the intended use of the vehicle; therefore, energy consumption is projected separately for cars, trucks, and buses. For each vehicle type, we identify alternative fuels (compressed natural gas (CNG), liquefied natural gas (LNG), electricity, and hydrogen) that can replace petroleum products and be competitive with them in technological and economic terms (Fig. 1).

We assume that passenger cars and urban public transport can be converted to electricity. Electrification of freight transport is not foreseen due to the relatively long charging times compared to natural gas and hydrogen refueling, as it would otherwise lead to longer queues at charging stations. We assume that CNG can be used as a fuel for cars, light commercial vehicles, and buses, provided there is a developed refueling infrastructure and acceptable prices for consumers. The target niche for LNG-powered vehicles, which have a greater cruising range compared to CNG, is trucks and large-capacity passenger buses serving long-distance routes. In the long term, it is envisaged that hydrogen-fueled vehicles will be used first in pilot projects (mainly in the public transit segment and by large companies wishing to state their commitment to decarbonization goals) and then in the private vehicle segment.

2. Fleet Size

We rely on econometric (autoregressive and factor-analytical) and deterministic (per-unit) models to estimate the fleet size. Regularly published statistical indicators are used as the explanatory variable: Gross Regional Product (GRP), population, per-capita GRP, passenger traffic, freight traffic:

$$\textit{Number of vehicles}_{it} = f\,(\textit{factor}), \tag{1}$$

where i – vehicle type, t – year.

3. Calculation of the Number of New Vehicles

Next, we build a simulation model of the fleet size dynamics for each type of vehicles. The parameter is the target useful life, which determines the rate of fleet renewal:

$$\textit{Number of vehicles}_{it} = \textit{Number of vehicles}_{i,t-1} + \textit{New}_{it} - \textit{Decommissioned}_{it}, \tag{2}$$

$$\textit{Decommissioned}_{it} = \textit{New}_{i,t-\textit{useful life}}, \tag{3}$$

$\textit{New}_{it}$ – the number of vehicles entered into service in the year t;

$\textit{Decommissioned}_{it}$ – the number of vehicles taken out of service in the year t.

4. The Number of Vehicles Running on Alternative Fuels and Electricity

Similar to the previous step, we build a simulation model of the dynamics of new vehicles entering into service and running on the alternative fuel j. The number of vehicles running on alternative fuels is determined through their share in the sales of a given type of vehicles:

$$\textit{Number of vehicles}_{ijt} = \textit{Number of vehicles}_{ij,t-1} + \textit{New}_{ijt} - \textit{Decommissioned}_{ijt}, \tag{4}$$

$$\textit{New}_{ijt} = \textit{Share in sales}_{ijt} \text{ x } \textit{New}_{it}. \tag{5}$$

5. Energy Consumption of Alternative Fuels and Electricity

At the final stage, we build a deterministic model to estimate the consumption of the energy carrier j, the parameters of which are the consumption rate of the energy carrier, average annual mileage, and average number of vehicles:

$$\textit{Consumption}_{ijt} = \textit{Consumption rate}_{ijt} \text{ x } \textit{Mileage}_{i} \times \textit{Average number of vehicles}_{ijt}. \tag{6}$$

The dynamics of change in the consumption rate of an alternative energy carrier is defined by the energy efficiency index:

$$\textit{Consumption rate}_{ijt} = \textit{Consumption rate}_{ij,t-1} \times \textit{Energy efficiency}_{ijt}. \tag{7}$$

The alternative energy demand is then summarized by vehicle type. The result is projected consumption by road transport of the energy sources alternative to petroleum products:

$$\textit{Consumption}_{jt} = \Sigma_i \textit{Consumption}_{ijt}. \tag{8}$$

III. Motor Vehicles in the Irkutsk Region: Development Dynamics and Key Features

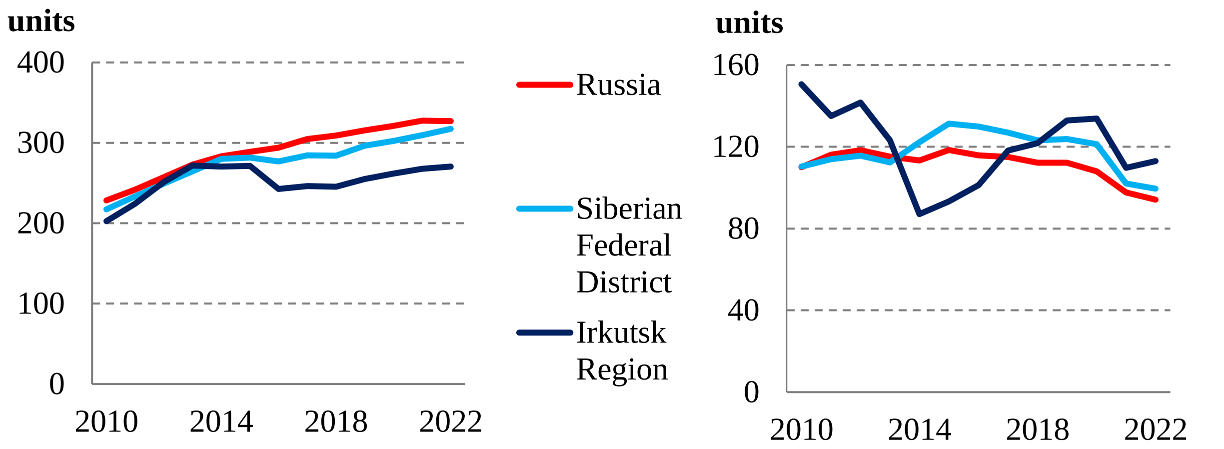
At the end of 2022, the fleet of motor vehicles in the Irkutsk region consisted of 662 000 passenger cars (of which 633 000 cars were owned by citizens), 129 000 trucks, and 19 000 buses (of which 2 600 buses are intended for scheduled passenger service).

The Irkutsk region seriously lags behind the Siberian Federal District and the Russian Federation as a whole in terms of the motorization rate. In 2022, the number of privately-owned passenger cars per 1,000 inhabitants in the

Irkutsk region amounted to 270 units, whereas in the Siberian Federal District it was 317 units, and in Russia – 326 units (Fig. 2). The average motorization rate in Russia, in turn, lags far behind the developed countries: in the USA, the number of passenger cars per thousand inhabitants was 774, in Australia – 569 [11], and in the EU – 564 [12].

Another issue is the aging of the vehicle fleet. The average age of passenger cars in the Irkutsk region is 17 years [13], in Russia as a whole – 15 years [14]. At the same time, the expected useful life of passenger cars is 3 to 10 years [15].

The Irkutsk region is ahead of Russia as a whole and the Siberian Federal District in terms of the average capacity of public transport per capita. In 2022, the Irkutsk region had 113 buses per 100 000 people, whereas the Siberian Federal District had 100 units, and Russia as a whole – 94 units (Fig. 2). At the same time, while in Russia and the Siberian Federal District in 2010–2022 the values of this metric correlated with each other and were approximately at the same level, the dynamics of per-capita public transport capacity in the Irkutsk region can be considered divergent. This may be related to bus purchase programs with the continuing trend of declining population in the region. The bus fleet needs to be renewed: the average age of buses in Irkutsk, which is the capital of the region,



a) passenger cars per 1 000 inhabitants b) transit buses per 100 000 inhabitants

Fig. 2. Motorization rate in the Irkutsk region.

Compiled based on data reported in [17].

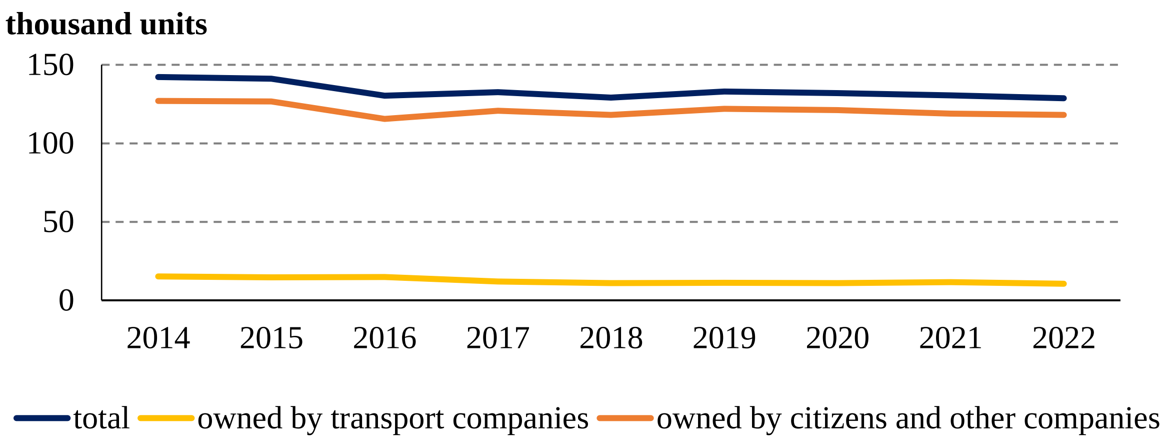


Fig. 3. The number of light commercial vehicles and trucks.

Compiled based on data reported in [17].

exceeds 11 years [16], while their expected useful life is 3 to 10 years [15].

The number of trucks in the Irkutsk region, both those used by transport companies and those owned by citizens or other organizations, has been maintained at about 130 thousand trucks for the last decade, with a slight downward trend (Fig. 3).

Thus, the main features of the road transport in the Irkutsk region, which may facilitate the growth in the number of motor vehicles and, consequently, the consumption of motor fuel, are a relatively low motorization rate of the population and a high average age of vehicles exceeding their expected useful life. At the same time, the rate of car fleet renewal will depend on the population welfare and car affordability, terms of car loans, availability of programs for subsidizing car purchases by the state. The impact of fleet growth on motor fuel consumption can be partially offset by enhancing the energy efficiency (i.e., lower fuel consumption rate per 100 km) of new cars. However, one should also take into account the possibility of an opposite effect: if the fuel consumption rate decreases, the mileage may increase.

IV. Projection of Alternative Fuel and Electricity Consumption by Road Transport in the Irkutsk Region for the Innovation-Driven Scenario of Economic Development

1. Scenario Assumptions

Currently, vehicles running on alternative fuels account for a very modest share of the vehicle fleet. In 2023, there were 2 087 electric vehicles on the roads of the Irkutsk region [18]. The development of the NGV market today is backed by the resources originating from the Bratsk GCF[19], more than 70 CNG-fueled buses run in Bratsk [20]. The Irkutsk Region Gasification Program for 2024–2033 provides for gasification of Kirensk, Zhigalovo, and 6 settlements of the Kazachinsko-Lensky district based on the gas from the Kovykta GCF, which will create new opportunities for expanding the market for NGV fuel. In addition, there is a potential for growth in NGV fuel consumption due to imports of LNG from other regions or the construction of a small-capacity LNG plant in the Irkutsk region, which is scheduled for 2026 [21].

In the Irkutsk region, regional transportation tax exemptions are effective for natural gas vehicles and electric vehicles [22]. Subsidies are provided for conversion of vehicles to CNG, purchase of buses and vehicles of road and utility services, purchase of compressed gas tank trucks [23]. However, despite the measures to encourage the conversion of motor vehicles to natural gas, the potential of NGV fuel utilization is curtailed by the underdeveloped refueling infrastructure: in the Irkutsk region, there are only three CNG fueling stations in Bratsk and one station in Tulun [19].

The innovation-driven scenario that underlies the projected detailed in this paper assumes that the following preconditions for the market penetration of alternative fuels in the transport sector will be met by 2030:

1) the region's economic growth potential will be effectively realized, which will lead to an increase in the welfare of the population and, as a consequence, the motorization rate;

2) by 2036, a gas trunkline from Russia to China will be built: it will run through the Irkutsk region, which will make it possible to switch public transit vehicles and then, as the refueling infrastructure develops, private vehicles to compressed natural gas in the regional capital and other cities;

3) the freight transport and long-distance bus transit

Table 1. Vehicles Powered by Alternative Fuels and Electricity in 2050, Percentage of Total Sales

Vehicle type		CNG	LNG	Electricity	Hydrogen
Cars	owned by citizens	12	–	20	0.5
	owned by organizations	12	–	15	5
Trucks	owned by transport companies	10	15	–	1
	owned by citizens and other organizations	10	15	–	–
Buses	regular buses	25	4	1.5	0.5
	other buses	25	4	–	0.5

TABLE 2. Per-Unit Fuel and Electricity Consumption per 100 km in 2023

Vehicle type		CNG	LNG	Electricity	Hydrogen
Cars		10 m^3	–	20 kWh	0.76 kg
Trucks	owned by transport companies	18 m^3	25 kg	–	9 kg
	owned by citizens and other organizations	15 m^3	25 kg	–	9 kg
Buses	regular buses	40 m^3	35 kg	114 kWh	6.1 kg
	other buses	23 m^3	35 kg	–	6.1 kg

Compiled based on data reported in [25]–[33].

segments will use LNG imported from other regions and, at a later stage, the one produced in the Irkutsk region;

4) the number of electric vehicles will continue to grow, supported by relatively low electricity prices, the development of charging infrastructure, and increased supply and expanded product range on the part of automobile factories located in the country;

5) by 2030, the Irkutsk region will launch a manufacturing of electric buses, and the products of the factory will serve as a basis for several pilot projects for the electrification of public transport equipped with advanced battery technology.

Our projections rely on the following assumptions. The GRP growth rate in 2024–2036 is assumed to be in accordance with the second option envisioned in the strategy for socio-economic development of the Irkutsk region [24], and the average GRP growth rate in 2037–2050 is taken to be 2%. Similarly, the population dynamics in 2024–2036 is assumed to be in line with the second option set out in the strategy [24], and the annual population growth rate in subsequent years is taken to be 0.07%.

Table 1 shows the key scenario assumption regarding sales of vehicles running on alternative fuels and electricity. It is expected that the fleet of electric and CNG vehicles will continue to grow, facilitated by the development of refueling infrastructure, gasification of large cities, and government support programs. Light commercial vehicles and commuter buses will be converted to CNG, while trucks and buses serving government agencies and tourists will be converted to LNG. After 2035, hydrogen car pilot projects will begin.

Table 2 shows the basic assumptions on the fuel consumption rate by different types of vehicles. It is assumed that as the energy efficiency of new vehicles increases, this figure will gradually decrease.

Due to the lack of statistical information on actual vehicle mileage, assumptions regarding this variable are based on the data reported in [34] and [35].

2. The Resulting Projection

Figure 4 shows the resulting projection of the consumption of electricity, natural gas, and hydrogen by the road transport under the innovation-driven scenario of economic development of the Irkutsk region.

The rate of NGV fuel use will be linked to gas transmission infrastructure development programs in the region. The largest increase in the consumption of NGV fuel will occur after 2030. It is expected that by that time, piped gas will be supplied to major cities in the Irkutsk region and the construction of the LNG plant will be completed. Until 2030, CNG will be consumed primarily by public transit buses. After 2030, the development of refueling infrastructure will also make the consumption by cars and trucks grow at an accelerated rate. The largest share of LNG consumption up to 2037 will come from buses providing long-distance bus services, and after 2037 – from privately-owned trucks. LNG energy consumption will stagnate between 2040 and 2045 because fleet renewal is not expected during this period (the number of new vehicles is a function of their useful life and the projected fleet size). By 2050, compressed natural gas consumption will be 103 million cubic meters and LNG consumption will be 55 000 tons.

Electricity consumption will have a steady upward trend over the entire time frame covered by the projection; however, the growth rates will vary. Until 2030, the growth will be insignificant; in 2030–2035, electricity consumption in the transport sector will grow at a more robust rate due to the increase in motorization rate and welfare of the population, as well as the use of electric buses. By 2040, the growth rate of electricity consumption will slow down, mainly due to energy efficiency

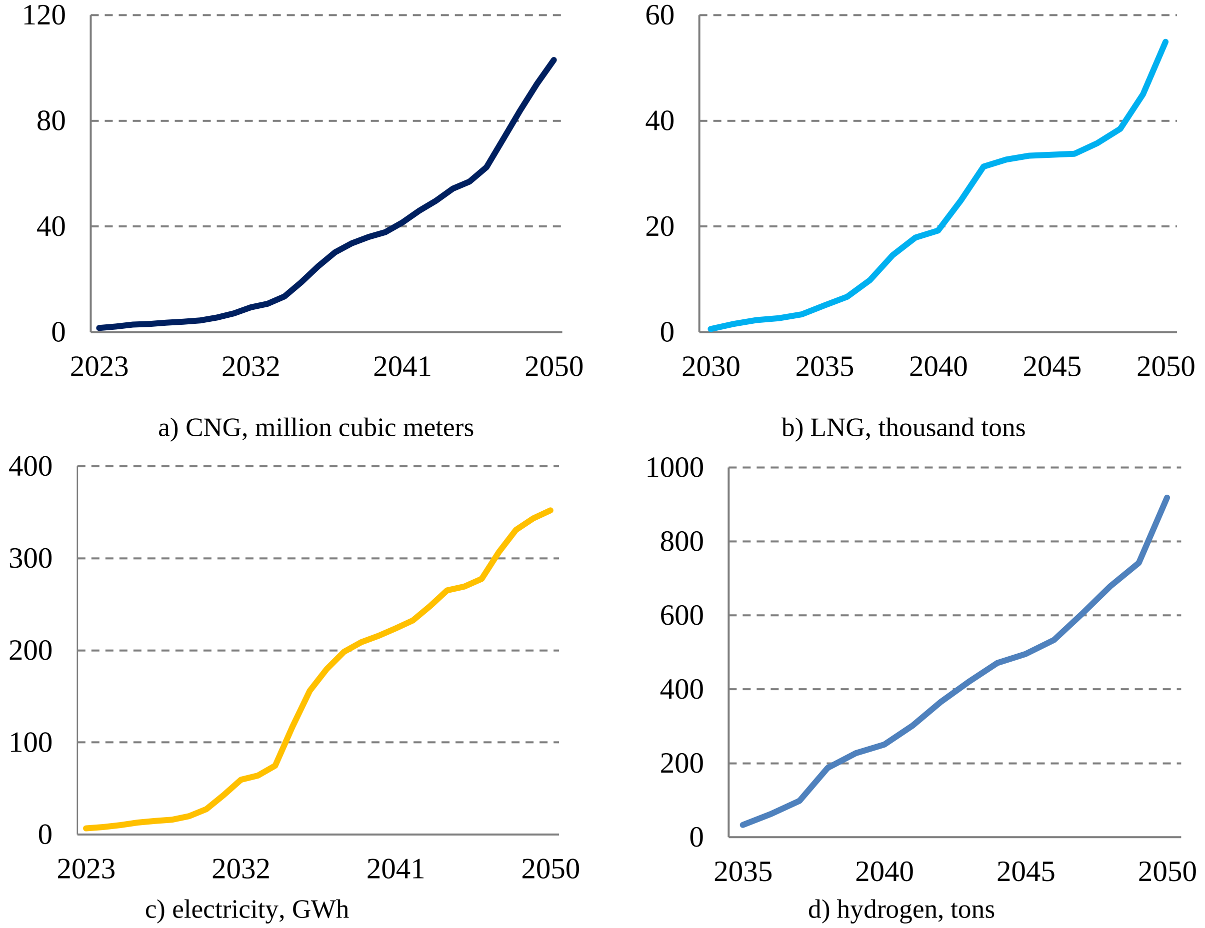


Fig. 4. Projected natural gas, electricity, and hydrogen consumption in road transport in the Irkutsk region*.

*Estimated data for 2023 and 2024.

improvements in new cars. However, sales of electric vehicles will continue to grow throughout the projection timespan. As a result, road transport electricity consumption will reach 352 GWh in 2050.

According to the assumed scenario, pilot projects for hydrogen use in transport will be being after 2035. These measures will result in 918 tons of hydrogen consumption by the transport sector in 2050.

Note that while the resulting projections are usually represented as continuous functions, the approach advocated in this study allows plotting the projected energy consumption as collections of contiguous line segments. This is achieved by the use of models simulating the vehicle number to capture the uneven dynamics of fleet renewal related to the end-of-life of vehicles.

Due to the lack of statistical data, the projection does not take into account energy consumption by utility vehicles: dump trucks, machines for road construction, etc. In addition, it should be noted that the number of vehicles is projected based on the number of vehicles registered in the Irkutsk region, which does not always match the place of actual refueling. This issue is particularly important when it comes to trucks and buses that may be used for cross-regional transportation. This emphasizes the need to keep valid statistical records of motor fuel and electricity consumption in transport in order to further calibrate the proposed predictive models based on the analysis of actual statistical data.

V. Conclusion

This study contributes a projection of the consumption of natural gas, electricity, and hydrogen by road transport under the innovation-driven scenario of economic development of the Irkutsk region. The main challenges faced in forecasting motor fuel consumption are related to the lack of necessary statistical information and panel data. In this regard, making projections forces us to adopt a number of assumptions based on expert judgment informed by the goals of socio-environmental development and environmental policy, occasional surveys and analytical studies conducted by consulting firms, and averaged per-unit data. The resulting projected values may vary depending on the underlying assumptions. That being said, they can serve as benchmarks when forming a strategy for the development of energy and energy infrastructure and making investment decisions.

Our projections of the demand for NGV fuel, hydrogen, and electricity in the road transport segment in the Irkutsk Region enable us to draw the following conclusions:

1. The low motorization rate of the Irkutsk region's population, old age of the existing vehicles encourage the growth in the number of vehicles running on motor fuel and electricity. Government programs for fleet renewal that provide for legislative restrictions on the use of obsolete vehicles could be one of the driving forces behind the development of the domestic automotive industry.
2. The pace and scale of gasification, successful completion of LNG plant construction projects, and development of the refueling infrastructure are the main factors that determine the amount of NGV fuel used by public and private motor vehicles.
3. The low purchasing power of the population limits the pace of electrification of transport. That being said, the development of the domestic automotive industry and the availability of programs for the purchase of electric vehicles supported by the state should contribute in the long term to the renewal of the car fleet by electric vehicles. The areas not covered by gasification can pursue the option of using electric buses.

Acknowledgment

The research was carried out in partial fulfillment of requirements for State Assignment Project (no. FWEU-2021-0004) and benefited from resources of the Shared Research Facilities Center “The High-Temperature Circuit” (Ministry of Science and Higher Education of the Russian Federation, project no. 13.CKP.21.0038). The authors would like to thank Marina Ozerova for translating the paper into English.

References

[1] “World Energy Balances Highlights,” IEA, Paris, Sep. 2024. [Online] Available: https://www.iea.org/data-and-statistics/data-product/world-energy-balances-highlights. Accessed on Oct. 9, 2024.

[2] L. V. Eder, V. Yu. Nemov, “Forecasting energy consumption in passenger road transport,” Studies on Russian Economic Development, no.4, pp. 83–93, 2017. (In Russian).

[3] E. V. Grushevenko, D. A. Grushevenko, V. A. Kulagin, “Long-Term impact of technological development on European road transportation sector’s fuel mix: focus on electric vehicles”, in 2016 Electric Power Quality and Supply Reliability (PQ), Tallinn, Estonia, 2016, pp. 165–170. DOI: 10.1109/PQ.2016.7724107.

[4] D. Grushevenko, N. Kapustin, “Modelling of energy consumption in the transport sector,” AIP Conf. Proc., no. 2552, Article ID 080015, 2023. DOI: 10.1063/5.0111525.

[5] “ITF Fleet Model overview,” OECD. [Online] Available: https://www.itf-oecd.org/sites/default/files/itf_fleet_model.pdf. Accessed on: Oct. 9, 2024.

[6] Yu. V. Sinyak, “Projected demand for motor fuels by road transport and final energy consumption of petroleum products: the case of the Tula region),” Scientific Works: Institute of Economic Forecasting of the Russian Academy of Sciences, 2017, pp. 218–233. (In Russian)

[7] O.V. Mazurova, “Long-term assessment of energy demand in russian passenger transport in the context of low-carbon transformation,” Studies on Russian Economic Development, vol. 35., no. 3, pp. 415–422, 2024. DOI: 10.1134/S1075700724030109.

[8] Russia 2035: Toward a New Quality of National Economy. Scientific report, A. A. Shirov, Ed. Moscow, Russia: Artique Print, 2024, 264 p. (In Russian)

[9] Forecast for the development of energy in the world and Russia 2024, A. A. Makarov, V. A. Kulagin, D. A. Grushevenko, A. A. Galkina, Eds. Moscow, Russia: ERI RAS, 2024, 208 p. (In Russian)

[10] F. V. Veselov, A. I. Solyanik, R. O. Alikin, “The effect of electrification in the road transport sector on electricity consumption and daily load profiles in the UES of Russia,” Izvestiya RAN. Energetika, no. 1, pp. 57–71, 2023. DOI: 10.31857/S0002331023010077. (In Russian)

[11] “Passenger road vehicle fleet and rate per thousand inhabitants at 31 December by vehicle category,” UNECE Statistical Database. [Online]. Available: https://w3.unece.org/PXWeb2015/pxweb/en/STAT/STAT__40-TRTRANS__03-TRRoadFleet/01_en_TRRoadTypVehR_r.px/table/tableViewLayout1/. Accessed on: Oct. 9, 2024.

[12] "Passenger cars – per thousand inhabitants," EUROSTAT. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/road_eqs_carhab/default/table?lang=en&category=road.road_eqs. Accessed on: Oct. 9, 2024.

[13] "The average age of a passenger car in the Irkutsk region is 17 years", SIA, Apr. 20, 2022. [Online]. Available: https://sia.ru/?section=484&action=show_news&id=432234. Accessed on: Oct. 9, 2024. (In Russian)

[14] M. Vershinin, "The average age of cars in Russia is almost 15 years", Kommersant, Jun. 13, 2023. [Online]. Available: https://www.kommersant.ru/doc/6042758. Accessed on: Oct. 9, 2024. (In Russian)

[15] Decree of the Government of the Russian Federation (2002, Jan. 01). No. 1, On the Classification of fixed assets included in depreciation groups (as amended on Nov. 18, 2022). (In Russian)

[16] "Not even in the top 50. Irkutsk comes at the bottom of the ranking of cities in terms of the quality of public transit," Ircity.ru, Feb. 6, 2024. [Online]. Available: https://ircity.ru/text/transport/2024/02/06/73198892/#:~:text=Средний%20возраст%20автобусов%20и%20маршруток,е%20место%20из%2020%20возможных. Accessed on: Oct. 9, 2024. (In Russian)

[17] "Official statistics," Unified cross-departmental information and statistical system. [Online]. Available: https://www.fedstat.ru/. Accessed on: Oct. 9, 2024. (In Russian)

[18] A. Timerkhanov, "Moscow accounts for a quarter of all electric vehicles in Russia," AVTOSTAT, Mar. 1, 2024. [Online]. Available: https://www.autostat.ru/news/57007/. Accessed on: Oct. 9, 2024. (In Russian)

[19] "The feasibility of building a liquefied natural gas plant and creating a network of gas fueling stations in the Irkutsk region is being explored," Oblastnaya, May 5, 2023. [Online]. Available: https://www.ogirk.ru/2023/05/05/v-irkutskoj-oblasti-izuchat-vozmozhnost-stroitelstva-v-regione-zavoda-po-proizvodstvu-szhizhennogo-prirodnogo-gaza-i-sozdanija-seti-gazozapravochnyh-stancij/. Accessed on: Oct. 9, 2024. (In Russian)

[20] "Seven new natural gas buses have arrived in Bratsk," Oblastnaya, Feb. 22, 2023. [Online]. Available: https://www.ogirk.ru/2023/02/22/sem-novyh-avtobusov-na-golubom-toplive-pribyli-v-bratsk/. Accessed on: Oct. 9, 2024. (In Russian)

[21] Resolution of the Government of the Irkutsk region (2023, Oct. 24). No. 932-pp, On Approval of the Regional Gas Supply Program for the Public Utilities Sector, Industrial and Other Organizations of the Irkutsk Region for 2024–2033. (In Russian)

[22] The Law of the Irkutsk region (2007, Jul. 4). No. 53-oz, On the transportation tax (as amended on Nov. 23, 2020). [Online]. Available: https://docs.cntd.ru/document/819009758. Accessed on: Oct. 9, 2024. (In Russian)

[23] "An agreement on expanding the use of natural gas as a motor fuel was signed between the Government of the Irkutsk Region and Gazprom PJSC," Irkobl.ru, Jun. 16, 2023. [Online]. Available: https://irkobl.ru/news/2962370/. Accessed on: Oct. 9, 2024. (In Russian)

[24] The Law of the Irkutsk region (2022, Jan. 10). No. 15-OZ, On the approval of the strategy for socio-economic development of the Irkutsk region to 2036. (In Russian)

[25] "Do not hesitate to refuel," Kommersant, Apr. 21, 2021. [Online]. Available: https://www.kommersant.ru/doc/4782193. Accessed on: Oct. 9, 2024. (In Russian)

[26] "KAMAZ-5490 NEO 2 – a natural gas (methane) technology." [Online]. Available: https://kamaz.spbmb.ru/info/articles/kamaz-5490/kamaz-5490-neo-2-tekhnika-na-prirodnom-gaze-metan/. Accessed on: Oct. 9, 2024. (In Russian)

[27] V. Chekhuta, "Can LNG become an alternative to diesel fuel? (Part 2)," Gruzovik press, no. 10, 2019. [Online]. Available: http://www.gruzovikpress.ru/article/24310-mojet-li-spg-stat-alternativoy-dizelnomu-toplivu-ch-2/. Accessed on: Oct. 9, 2024. (In Russian)

[28] "Toyota MIRAI. MIRAI means "future". [Online]. Available: https://h2.live/en/fuelcell-cars/toyota-mirai/. Accessed on: Oct. 9, 2024.

[29] "Hydrogen buses on the Veluwe." [Online]. Available: https://www.h2nodes.eu/images/docs/20200416_status_verslag_2BP_Hydrogen_buses_on_the_Veluwe_Eng_.pdf Accessed on: Oct. 9, 2024.

[30] H. Basma, F. Rodríguez, "Fuel Cell Electric Tractor-Trailers: Technology Overview and Fuel Economy," Jul. 18, 2022 [Online]. Available: https://theicct.org/publication/fuel-cell-tractor-trailer-tech-fuel-jul22/#:~:text=Depending%20on%20the%20size%20of,and%209.2%20kg%2F100%20km. Accessed on: Oct. 9, 2024.

[31] Catalog of gas engine equipment, Saint Petersburg, Russia: Gazprom Gas Motor Fuel LLC, 2015, 191 p. (In Russian)

[32] A. Krasnov, "When You Can't Stock Enough Electric Current. Why does a Popular Electric Car in Russia Refuse to Charge at an EV Charging Point at Full Speed," Feb. 8, 2024 [Online]. Available: https://76.ru/text/auto/2024/02/08/73197356/. Accessed on: Oct. 9, 2024. (In Russian)

[33] E. M. Chikishev, D. V. Kapskiy, S. S. Semchenkov, "Assessment of Transport, Natural and Climatic Factors Influence on the Level of Electric Buses Energy Consumption in Urban Environment," Science and Technique, vol. 22, no. 1, pp. 48–59, 2023. DOI: 10.21122/2227-1031-2023-22-1-48-59. (In Russian)

[34] Regulation of the Bank of Russia (2021, Mar. 4). No. 755-P, On a unified methodology for calculating restoration costs of damaged vehicles. (In Russian)

[35] E. L. Makhnin, I. N. Novoseletsky, S. V. Fedotov, et al, Methodological guidelines for conducting automotive forensic examinations and studies of wheeled vehicles to determine the amount of damage, calculate repair costs, and perform an evaluation, S. A. Smirnova, V. G. Grigoryan, Sci. Dirs. Moscow, Russia: Ministry of Justice of the Russian Federation, Center for Forensic Examination, 2018, 326 p. (In Russian)

Darya Maksakova joined the Melentiev ESI SB RAS in 2016, after receiving the Bachelor's degree in International Economics from Baikal State University, Russia. In 2018, she received her Master's degree in Finance from the same university. She is currently a junior researcher at the Melentiev ESI SB RAS. Her research interests include energy economics and energy modeling tools.

Sergei Popov is a senior researcher at the Melentiev ESI, SB RAS. He is responsible for analysis of the East Asian and Asia-Pacific energy markets. He joined the Melentiev ESI in 1982 and received his PhD in Energy Systems Modeling from the Melentiev ESI, SB RAS in 1993. In 2004–2011, he worked at the Asia Pacific Energy Research Center, Japan. His research interests include energy systems modeling, development of regional energy policies, and issues of international energy cooperation.

Expansion of the Prosumer's Heating System in the Context of the Transition to Carbon-Free Energy

V.A. Stennikov[1], V.B. Tashlykova[1,*], E.A. Barakhtenko[1], D.V. Sokolov[1]

[1] Melentiev Energy Systems Institute, SB RAS, Irkutsk, Russia

***Abstract* — The paper discusses the key points to be considered when selecting an additional heat source as part of an intelligent integrated energy system. Modeling prosumers poses a number of challenges related to the implementation of their functional properties, especially when the prosumers manage their distributed energy resources. The transition to carbon-free energy in the heating sector implies the use of renewables, alternative heat sources, and electric heating. It is known that peak times of heat and electricity consumption mostly coincide, thus putting high stress on the energy system. If electric heating is the only heat source, even a short-term power outage halts the heating. Therefore, an additional source of heat is needed that will reduce the loads served by the power system and yield sizable annual cost savings. To that end, it is important to analyze the effects of various suitable sources that do not emit pollutants during operation. For this purpose, we consider possible configurations of heat sources and analyze them with respect to their energy efficiency and economic feasibility. This study presents a mathematical model of the prosumer. The model takes into account the constraints on heat generation from renewable sources, incorporates thermal energy storage into the arrangement of heat sources, adheres to the energy balance constraints, and finds the optimal option of heat network configuration. Mixed integer programming is utilized to formulate and solve the problem of the prosumer's heat network expansion in the context of the transition to carbon-free energy. As a result of the optimization, an additional source is selected to complement the main source, which notably reduces heating costs.**

***Index Terms* — Prosumer, intelligent integrated energy system, distributed energy, mixed integer programming.**

* Corresponding author.
E-mail: vsb@isem.irk.ru

http://dx.doi.org/10.25729/esr.2024.04.0007

Received November 20, 2024. Acc. November 29, 2024. Available online December 28, 2024.

I. Introduction

Modern heating systems in Russia require a new expansion paradigm to achieve economic viability [1]. The design of energy systems should strive for higher efficiency of energy generation, controllability, and efficiency of their operation [2]; lower energy transmission loss; and higher penetration of renewable energy [3]. These goals are difficult to achieve without major capital outlays: the use of renewables of large capacity also entails the need for a flexible source to flatten intermittent renewable generation, thereby increasing the capital required. In this case, the most plausible solution is to use distributed generation at the consumer's end [4], which will lower energy transmission loss, increase the penetration of renewables in the energy system, enhance the efficiency of energy generation, and reduce dependence on current energy tariffs, which tend to go up [5]. Naturally, the above benefits for the energy system can be attained only if the choice of the prosumer's source is optimal both from the economic and energy standpoints. This is because the assumed energy supply strategy implies the use of each source under the most efficient and economical conditions to serve the energy demand of the prosumer.

Thus, provided a wide selection of available distributed energy plants equipped with intelligent control, the optimal mix of generation equipment at the prosumer's end contributes to reducing emissions from energy generation and the transition to low-carbon/no-carbon energy.

II. PROSUMERS

Prosumers are consumers capable of load shifting, i.e., managing their energy consumption profile, making independent decisions with respect to choosing how the energy is supplied to them, while balancing their energy needs and their willingness to cut energy costs.

The term 'regulating consumer' (essentially a prosumer) was coined by S.A. Kukel-Krajewski back in 1932 to refer to an industrial enterprise whose production schedule allowed utilizing the excess capacity of power plants for a short period of time [6].

A body of research published in various countries covered various aspects of prosumer activities, including demand response by electricity consumers of the public utilities sector [7–9] and management of private electricity sources (microgrids [10] or virtual power plants [11]) as part of the smart grid architecture [12–14]. Demand response will remain an important part of the power system even in a decentralized power system with prosumers as energy suppliers [7].

There are also models that address the effect of distributed generation on energy supply systems at various levels. For example, a general model presented in [15] allows considering different source configurations as interconnected at the city level.

The definition and properties of prosumers in electric power systems are discussed in [16, 17], which led to the emergence of the concept of the intelligent electric power system with an active-adaptive grid [18]. Study [19] presents a vision statement for the "Concept of the intelligent energy system of Russia," noting the importance of consumer involvement in the process of energy system expansion.

Several papers [20–22] focus on the advancement of intelligent heating systems. In [20], the use of low-temperature heat sources is considered as a potential solution to the problems related to the adoption of distributed generation.

The emergence of prosumers acting as heat producers makes it important to control thermal and hydraulic states in the heating system [21]. The study [22] highlights the key aspects of breaking down the prosumer's demand into its heat and electricity components in an integrated power system.

A proper representation of different heating configurations requires the model of the prosumer's heating to cover both their heat sources and a thermal energy storage system. At the same time, the district heating is omitted from the consideration, which imposes corresponding constraints on what is possible for the active consumer with respect to their heating system.

Prosumer capabilities

It is not only industrial enterprises with energy-intensive production [1], but also consumers in the public utilities sector that can manage their energy consumption. As follows from the definition, consumers become prosumers if they manage their energy consumption profile in situations where such consumers are served by centralized energy supply systems at time-of-use tariffs. Such a supply strategy can reduce supply costs for the same amount of energy supplied, but without shifting part of the demand from peak times, which correspond to the maximum tariff, to off-peak times. Prosumers are capable of influencing not only how energy is supplied to them, but also what is supplied to other consumers, as they can feed their excess output back to the centralized energy system and benefit from such deliveries.

Prosumers can perform the following functions [23]:

- Managing their energy consumption to match their demand for energy and optimizing their energy costs, accordingly;

- Identifying conditions for applying to purchase/sell resources/energy, provided their generating capacities are fully utilized.

Thus, prosumers are full-fledged energy management participants, making decisions on how energy is supplied to them and whether to feed their excess output to centralized energy supply systems by optimizing their energy supply costs, considering outdoor air temperatures during the given period, tariffs for primary energy resources, and capital outlays incurred by the generating units at issue.

Given that the infrastructure for the operation of prosumers within energy systems is actively evolving, it becomes highly relevant to research the optimal type and mix of generating equipment for energy systems at different levels.

III. Mathematical Statement of the Problem of the Prosumer's Heating System Expansion Planning

The goal is to find the optimal type and capacity of energy generating equipment that allows serving thermal energy to the prosumer in each hour of the time period under consideration while taking into account the changes in the prosumer's demand for thermal energy. This also includes the strategy for serving thermal energy, such that it ensures the lowest possible costs of heating, i.e. output at each source. The input data are performance indicators and process constraints of the considered generating units, primary energy tariffs, and weather conditions (outdoor air temperature, solar radiation intensity) during the considered time span that affect the prosumer's demand for thermal energy and heat generation performance.

The objective is to minimize the function of total heating costs incurred by the prosumer, which has the following form:

$$f\left(e_t, h_t, D_t, Q_{st,t}\right) = C_{i,t}^{e/e}\left(e_t\right) + \\ + \sum_{i=1}^{I}\sum_{t=1}^{T} \alpha_i \left(a \cdot C_i\left(h_i, Q_{st,t}\right) + C_{i,t}^{maint}\left(h_i, Q_{st,t}\right)\right) \to \min, \quad (1)$$

where e_t is electricity used for thermal energy generation in the period *t*; h_t is thermal energy produced by the prosumer's heat source; D_t is the prosumer's demand for thermal energy; $Q_{st,t}$ is the level of thermal energy in the storage; $C_{i,t}^{e/e}$ is electricity purchase costs for option *i*; α_i is the coefficient corresponding to the choice of the heat source *i*; *a* is the discount factor; C_i is capital outlays for the *i*-th option of the heat source configuration; $C_{i,t}^{maint}$ is maintenance costs of the *i*-th option of the heat source configuration; *I* is the set of heat sources, *T* is the number of time periods under consideration.

The constraints to be met when solving the problem are as follows:

$$h_{min} \le h_{i,t} \le h_{max};\ 0 \le e_t \le e_t^{max}; \quad (2)$$

$$0 \le Q_t \le Q_t^{max};\ h_t - D_t + Q_{st,t} \le Q^{max}, \quad (3)$$

where h_{min}, h_{max} are the lower and upper limits of heat output from source *I*, respectively; e_t^{max} is the maximum possible electricity consumption; Q_t^{max} is the maximum capacity of the thermal energy storage.

Energy balance equation is

$$\sum_{i=1}^{I} \alpha_i \cdot h_{i,t} + Q_t^{st(+)} - Q_t^{st(-)} = D_t^h, \quad (4)$$

where $Q_t^{st(+)}$ is heat supplied from the storage; $Q_t^{st(-)}$ is heat stored in the storage.

IV. Configurations of the Prosumer's Heating System

A period of 1 year was assumed as the time horizon in solving the problem of the prosumer's heating system design. This made it possible to cover the most common situations arising under different loads and temperatures.

None of the considered heat sources use carbon-based fuels or emit pollutants into the environment during their operation, which aligns well with the objective stated in this study. The list of heat sources is as follows: a flow-through heater (FTH), a heat pump (HP), an electric boiler (EB), and a heating and hot water system made up of 10 solar collectors with a heat exchanger (SC). However, the HP and SC output is limited due to process constraints. The efficiency of the HP depends on the outdoor air temperature, so its operation is inherently limited. The SC output depends on the solar radiation intensity. It is therefore impractical to consider the option of either the HP or SC alone, because what is needed is a heat source that operates independently of solar radiation intensity and outdoor air temperature. Consequently, we consider the EB as the main source of thermal energy. Table 1 lists key parameters of the plants considered in the study.

In order to take into account the constraints on the SC and HP output, we introduce several options of heating system configurations: FTH, EB, EB and HP; EB and SC; EB and SC with HP. In what follows, we analyze heating strategies together with their corresponding operational and production costs of heat energy sources to draw

Table 1. Key Parameters of the Options

Symbol	Power, кW	Capital expenditures, thousand ₽	Operating temperature range, °C
FTH	36	300	[-40…+30]
EB	36	360	[-40…+30]
HP	32	448	[-20…+30]
SC	30	383	[-30…+30]

TABLE 2. Technical and Economic Performance of the Options

Configuration	FTH	EB	EB and HP	EB and SC	EB, HP, and SC
Cost of heat generated, ₽/kWh	3.46	2.04	1.67	1.46	1.27
Present value of capital expenditures, thousand ₽	38	43	97	89	143
Annual total heating costs, thousand ₽	535	315.6	258.8	195.1	197.7
Operating costs, thousand ₽	497	272.3	112.8	106.1	54.7
Electricity consumed for heat generation, thousand kWh	154	96.1	76.6	74.1	22.6
Supply from the storage, thousand kWh per year	–	95.8	78.8	96.3	97.9
Reduction in electricity consumption for heat generation, thousand kWh	–	58.5	78	80.5	131.4
Estimated savings, thousand ₽	–	219.4	276.2	339.9	337.3
Payback period of additional capital outlays, years	–	1.1	0.54	0.37	1.34

conclusions about the applicability of the above plants in the prosumer's heating system considered in this study.

Table 2 shows the reduction in electricity consumption, estimated savings, and payback period of additional capital outlays, which were calculated with the FTH option as the baseline.

The optimization yielded the configuration of the prosumer's heating system, comprising electric boiler and solar collector. The electric boiler is to be used during periods when there is no generation by solar collectors, whereas the storage unit supplies thermal energy during peak tariff periods.

V. RESULTS

The FTH option served as the baseline for calculating economic feasibility of all options of heat sources configurations. This was due to the following reasons: the FTH option requires the least amount of capital outlays, it has no limitations on heat output, and can operate within a wide temperature range. However, electric heating is the only source of heat this option provides, the loads to be served by the power supply system are at their maximum and, consequently, the costs of purchasing electricity are also high: the operating costs that come with this option are the greatest among all others. The advantage of having the lowest present value of capital outlays is offset by high operating costs.

In the electric boiler option, electricity consumption went down during peak hours and operating costs were lowered as compared to the FTH option. Although the EB capacity was not sufficient to meet the majority of the prosumer's demand, the amount of thermal energy stored was enough to reduce peak consumption and halve operating costs. The payback period for the additional capital outlays was 1 year and 1 month.

The option of combining the EB with the HP assumes relatively low utilization of the EB for heating, limiting it to the periods of minimum temperatures, i.e., when the outdoor air temperature is lower than the temperature specified in Table 1. It is important to note that this option lowers operating costs (compared to the EB option): the joint operation of the HP with the thermal energy storage resulted in significant savings. However, the additional source in this option also adds to the loads to be served by the power system.

The most economically feasible option is to install the EB with the SC in the prosumer's heating system. The generation of thermal energy in vacuum-tube collectors and its storage significantly reduced electricity consumption during peak-load periods throughout the investigated time span. This was true both in the first quarter with the relatively low heat output from the SC, and in the third quarter with the high solar radiation intensity (there were periods when it was necessary to turn off the SC due to the lack of demand for heat, free storage capacity, or the possibility of supplying excess energy to the heat network). This option proves optimal, which is confirmed by the lowest total costs among all options.

The option that assumes simultaneous installation of the EB, HP, and SC has the lowest operating costs among all other options, but the present value of capital expenditures is the greatest. At the same time, the EB was used during the period of the lowest temperatures and highest loads, as it was needed only when the SC output was low and outdoor air temperature was below the minimum temperature required for the HP operation.

VI. Conclusion

Sustainable development of energy systems and the transition to carbon-free energy depend largely on the use of various types of renewable energy sources. This is a challenging task to deal with because it requires choosing multiple energy sources, which means higher capital outlays. Therefore, determining the optimal mix and type of generating equipment is essential to attain the goal of the maximum reduction in air pollutant emissions in existing energy systems.

Acknowledgment

The study was carried out at the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, under the State Assignment Project (No. FWEU-2021-0002) for the program of basic research of the Russian Federation for 2021–2030.

References

[1] A. S. Nekrasov, Yu. V. Sinyak, S. A. Voronina, V. V. Semikashev, “The state of the heating sector in Russia,” Studies on Russian Economic Development, no. 1, pp. 30–43, 2011. (In Russian)

[2] N. I. Voropai, S. I. Palamarchuk, S.V. Podkovalnikov, “The state and outstanding issues of the power sector of Russia,” Studies on Russian Economic Development, no. 5, pp. 49–69, 2001. (In Russian)

[3] N. I. Voropai, “Smart Grid: myths, reality, prospects,” Energy Policy, no. 2, pp. 9–15, 2010. (In Russian)

[4] JSC SO UES, “Active Energy Complex: How to integrate distributed energy into the UES and reduce consumers' costs,” Electric Power. Transmission and Distribution, no. 2(59), pp. 26–29, 2020. (In Russian)

[5] V. A. Kryukov, “Heat and the market,” ECO, no. 3(537), pp. 4–7, 2019. (In Russian)

[6] S. A. Kukel'-Kraevsky, The Unified Electric Power System of the European part of the USSR: a working hypothesis and technical and economic model for electrification planning. Moscow, USSR: G. M. Khrzhizhanovsky Power Engineering Institute, Academy of Sciences Publishing House, 1938. (In Russian)

[7] M. Lotfi, C. Monteiro, M. Shafie-khah, M. Shafie-khah, J. Catalao, “Evolution of Demand Response: A Historical Analysis of Legislation and Research Trends,” in 2018 Twentieth International Middle East Power Systems Conference (MEPCON), Cairo, Egypt, 2018, pp. 968–973. DOI: 10.1109/MEPCON.2018.8635264. Available: https://www.researchgate.net/publication/330950426_Evolution_of_Demand_Response_A_Historical_Analysis_of_Legislation_and_Research_Trends.

[8] P. Siano, “Demand response and smart grids – A survey,” Renewable and Sustainable Energy Reviews, vol. 30, pp. 461–478, 2014. DOI: 10.1016/j.rser.2013.10.022.

[9] S. Nan, M. Zhou, G. Li, “Optimal residential community demand response scheduling in smart grid,” Applied Energy, vol. 210, 2018, pp. 1280–1289. DOI: 10.1016/j.apenergy.2017.06.066.

[10] Chr. Green, Sr. Garimella, “Residential microgrid optimization using grey-box and black-box modeling methods,” Energy and Buildings, vol. 235, p. 110705, 2021. DOI: 10.1016/j.enbuild.2020.110705.

[11] D. J. Vergados, I. Mamounakis, P. Markis, E. Varvarigos, “Prosumer clustering into virtual microgrid for cost reduction in renewable energy trading markets,” Sustainable Energy, Grids and Networks, vol. 7, pp. 90–103, 2016. DOI: 10.1016/j.segan.2016.06.002.

[12] X. Fang, S. Misra, G. Xue and D. Yang, “Smart Grid – The New and Improved Power Grid: A Survey,” IEEE Communications Surveys & Tutorials, vol. 14, no. 4, pp. 944–980, 2012. DOI: 10.1109/SURV.2011.101911.00087.

[13] L. Tightiz, L. Minh Dang, S. Padmanaban, K. Hur, “Metaverse-driven smart grid architecture,” Energy Reports, vol. 12, pp. 2014–2025, 2024. DOI: 10.1016/j.egyr.2024.08.027.

[14] S. E. Bibri, J. Krogstie, “Environmentally data-driven smart sustainable cities: applied innovative solutions for energy efficiency, pollution reduction, and urban metabolism,” Energy Informatics, no. 3, vol. 29, 2020, DOI: 10.1186/s42162-020-00130-8.

[15] S. Samsatli, N. J. Samsatli, “A multi-objective MILP model for the design and operation of future integrated multi-vector energy networks capturing detailed spatio-temporal dependencies,” Applied Energy, vol. 220, pp. 893–920, 2018. DOI: 10.1016/j.apenergy.2017.09.055.

[16] B. B. Kobets, I. O. Volkova, “Prospects and opportunities for the evolution of the SMART GRID concept in the Russian power sector,” in Innovative development of the electric power industry based on the Smart Grid concept, Moscow, Russia: Energiya Publishing and Analytical Center, 2010, pp. 154–197. (In Russian)

[17] I. O. Volkova, M. V. Gubko, E. A. Salnikova, “Prosumers: the problem of optimizing electricity consumption and in-house generation,” Control Sciences, no. 6, pp. 52–61, 2013. (In Russian)

[18] V. E. Fortov, A. A. Makarov, Vision Statement for the Intelligent Electric Power System of Russia with the Active-Adaptive Grid. Moscow, Russia: NTTs FSK EES, 2012. (In Russian)

[19] I. O. Volkova, "Smart energy in Russia: assessment of the available development potential," ECO, no. 12 (510), pp. 90–100, 2016. (In Russian)

[20] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund, B. V. Mathiesen, "4th Generation District Heating (4GDH) integrating smart thermal grids into future sustainable energy systems," Energy, vol. 68, pp. 1–11, 2014. DOI: 10.1016/j.energy.2014.02.089.

[21] V. K. Averyanov, Yu. V. Yuferev, A. A. Melezhik, A. C. Gorshkov, "The heating of cities in the context of the emergence of prosumers of intelligent energy systems," Academia. Architecture and Construction, no. 1, pp. 78–87, 2018. DOI: 10.22337/2077-9038-2018-1-78-87. (In Russian)

[22] N. I. Voropai, V. A. Stennikov, E. A. Barakhtenko, O. N. Voitov, "A heat and electricity demand response procedure for an integrated energy system with prosumers," Izvestiya RAN. Energetika, no. 4, pp. 11–23, 2020. DOI: 10.31857/S0002331020040081. (In Russian)

[23] V. A. Stennikov, E. A. Barakhtenko, D. V. Sokolov, V. B. Shelekhova, "Active involvement of the consumer in the management of their energy supply," Power engineering: research, equipment, technology, no. 11–12, pp. 88–100, 2017. (In Russian)

Valery A. Stennikov Interim Director of the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences (RAS), Irkutsk), Academician of the Russian Academy of Sciences, Prof. Doctor of Engineering, Honored Scientist of the Russian Federation, a leading expert in the field of theoretical foundations, modeling, analysis, optimization, and systems research of pipeline systems of the energy sector.

Veronica B. Tashlykova, junior researcher. She graduated with a specialist's degree from the Institute of Power Engineering at Irkutsk State Technical University in 2015, and received the Master's degree in 2017. Her research interests include modeling of prosumer-based energy systems, district heating systems, and building of models for energy facilities.

Evgeny A. Barakhtenko received the Ph.D. degree in Engineering from Irkutsk State Technical University in 2011. He is the Scientific Secretary of the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences. His research interests include models, methods and software for the expansion planning of pipeline systems and intelligent integrated energy systems.

Dmitry V. Sokolov received the Ph.D. degree in Engineering from the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, in 2013. He is a Senior Researcher at the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences. His research interests include optimization methods, development of fast algorithms, and software engineering.

Feasibility of Connecting Consumers in Isolated Communities to the Irkutsk Power System

I.Yu. Ivanova[1,*], V.A.Shakirov[1], R.A. Ivanov[1]

[1] Melentiev Energy Systems Institute, SB RAS, Irkutsk, Russia

***Abstract* — The study summarizes key data on public power supply to isolated off-grid communities in the Irkutsk region. We compile a list of candidate settlements that qualify for grid extension and indicate the substations that in all likelihood will be used to feed them. This includes a multi-factor analysis of economic performance of power supply to such settlements. We report the findings of a technical and financial feasibility study of connecting remote communities to the power grid. The feasibility is assessed based on consolidated costs of the construction of power grid facilities. The study identifies the settlements where it is most economically viable to link them to the power grid. Additionally, we assess the feasibility of connecting two large off-grid industrial consumers in the mining industry to the power system. The successful completion of these projects is a prerequisite for connecting two communities in Tofalariya to the grid.**

***Index Terms* — Diesel power, economic electricity rates, fuel cost, power transmission line, substation, capital expenditures, payback period.**

I. Introduction

The Irkutsk region has 64 off-grid communities with a population of 9.1 thousand people, which are supplied with electricity from 60 stand-alone municipal diesel power plants (DPP). The total DPP capacity is 17.8 MW, and the electricity generation is 32.7 million kWh. Annual diesel fuel consumption is estimated at 8.6 thousand tons. The key issue in serving power to this category of consumers is the underdeveloped transport infrastructure and a complex logistics flow of fuel delivery. As a consequence, the price of diesel fuel in the most remote communities reaches 150 thousand rubles/ton, and economic electricity rates are as high as 65–88 rubles/kWh [1]. In order to maintain residential electricity rates at an acceptable level and to compensate electric utilities for the shortfall in revenues, the latter are entitled to annual subsidies from the regional budget, which are currently estimated at more than 800 million rubles/year.

Improved economic performance and reliability of power supply to some remote and isolated communities can be ensured by their connection to the power grid. The grid layouts and programs for the expansion planning of power facilities in the Irkutsk region [2, 3] considered the feasibility of modernization of diesel power plants or connection to the power grid of some communities where such solutions perform reasonably well in economic terms. The expansion of power supply systems in some locations is part of the investment programs of electric utilities. For some of them (Alygdzher, Podvoloshino, Oktyabrsky, Ust'-Kirenga, and Pashnya) preliminary design or feasibility studies have been completed. These projects are currently at various stages of completion and are largely dependent on the construction of interconnected power grid facilities. The purpose of this study is to bring the previously reported economic performance estimates up to date with the current economic conditions.

II. Assumed Conditions and Research Methods

We perform a technical and economic analysis of the key data on power supply to isolated communities in the

* Corresponding author.
E-mail: nord@isem.irk.ru

http://dx.doi.org/10.25729/esr.2024.04.0008

Received December 6, 2024. Acc. December 10, 2024. Available online December 28, 2024.

TABLE 1. Key Data on Electricity Supply to Isolated Communities

District	Settlement	Population (as of January 1, 2021), persons	Diesel fuel price, thousand rub/t	Economic electricity rate, rub/kWh	Share of population that consumes electricity, %
Usol'sky	Oktyabrsky	183	79.90	38.20	96.7
	Maninsk	10			
Kirensky	Ust'-Kirenga	58	77.58	32.04	100.0
	Pashnya	12			
Katangsky	Podvoloshino	356	112.13	45.27	92.3
Cheremkhovsky	Moto-Bodary*	40	–	–	–
Nizhneudinsky	Alygdzher	517	96.15	27.41	83.0
Kazachinsko-Lensky	Karam	305	79.90	45.26	91.1
Bratsky	Karakhun	546	96.80	25.20	83.4
	Ozyorny	592		22.99	90.2
Ust'-Udinsky	Klyuchi	93	79.10	36.94	92.7
	Anosovo	495			
Tulunsky	Arshan	274	69.90	36.10	98.6

Note: there is presently no electricity supply in the village of Moto-Bodary

region to account for the current costs and the health of the power grid infrastructure. To that end, we select 13 communities where conditions are favorable or relatively favorable for connection to the power grid. The data and findings of our previous studies serve as input data for the present study. The list of settlements includes those located at a distance of no more than 150 km from the points of possible connection to the Irkutsk power system. Table 1 presents the key data on power supply to the selected settlements.

For each settlement, we determine its potential main substation, voltage rating, and length of possible transmission lines, as well as specifications of required transformer substations. Then we estimate future possible ranges of electrical loads of the settlement. Our study of technical and financial feasibility of connecting remote communities to the power grid relies on consolidated costs of the construction of power grid facilities [4–6]. The calculation of capital expenditures uses region-specific price adjustment coefficients (with the prices in the first zone of the Russian Federation being the reference value) and the coefficients that adjust for difficult working conditions. The simple payback period of investment costs serves as the decision criterion.

III. RESULTS AND DISCUSSION

The main factors affecting the feasibility of connection to the power grid are projected electrical loads, remoteness from the power grid, and the voltage of the grid. The options of connecting communities that are more than 100 km away or require building a substation with a voltage as high as 110–220 kV prove barely feasible (Table 2).

Our feasibility study allowed us to shortlist settlements most suitable for connection to the power grid and having a payback period of less than 10 years. The candidate settlements are the village of Podvoloshino in the Katangsky district and Oktyabrsky and Maninsk in the Usolsky district.

The project to connect Podvoloshino to the substation of the oil pumping station No. 8 of the Eastern Siberia–Pacific Ocean oil pipeline, which is part of the investment program of the regional state unitary energy enterprise Oblkommunenergo, is currently nearing its completion. Activities to connect the settlements of Oktyabrsky and Maninsk to the substation in the settlement of Razdol'ye were included in the investment program of Irkutskaya elektrosetevaya kompaniya (IESK) JSC for 2015-2019 but have not been completed yet.

The investment program of IESK JSC features another project that envisions the connection of Ust'-Kirenga and

Pashnya villages in the Kirensky district to the Makarovo substation as per the Grid layout and program for expansion planning of power facilities in the Irkutsk region in 2023–2027 [3]. Based on our comparative calculations we argue that the project is not feasible. We arrived at a similar conclusion based on the results of the studies presented in Table 2. The payback period for construction costs of power grid facilities is 31–36 years, depending on the assumed electric loads of settlements.

The calculation results indicate that it is possible to connect the Ozyorny settlement and, at a later stage, the Karakhun settlement in the Bratsky district to the power grid (Fig. 1). Cost payback periods are 4–6 and 12–14 years, respectively.

In addition, we assessed the feasibility of connecting to the power grid emerging enterprises involved in the development of the Gurbey ore gold deposit and Zashikhinskoye rare metals deposit, both located in the off-grid area in remote parts of the Nizhneudinsky district of the region (Fig. 2). The Grid layouf and program for expansion planning of power facilities in the Irkutsk region in 2023–2027 [3] envisioned a comprehensive expansion of the 110 kV grid in the Nizhneudinsky district in 2027 in line with then-current plans of the owners. It assumed the construction of the 110/10 kV Alygdzher substation (2×4 MVA) at the request of the Nizhneudinsky District Administration, 110/6 Gurbeyskaya substation at the request of Tekhservis LLC (1×16 MVA), and 110/6 Zashikhinskaya substation at the request of Tekhnoinvest Al'yans CJSC.

As it stands now, the requests for utility hook-up referred to in [3] have been canceled. The Grid layout and

TABLE 2. Estimates of the Payback Period for Costs Incurred for Connection to the Power Grid

Settlement	Electrical load, kW		Main substation	Distance to the main substation, km	Connection method	CapEx, mln rub.	Payback period, years
	projected	maximum					
Oktyabrsky Maninsk	118	136	SS in Razdol'ye	25	10 kV TL, 10/0.4 SS	75.3	6.4–7.3
Moto-Bodary	34.5	46	SS in Tunguska	25	10 kV TL, 10/0.4 SS	76	25–33
Alygdzher	498	573	SS from 220 OHL to Zashikhinsky MBP	12	220/10 SS, 10 kv TL, 10/0.4 SS	659.9*	9.8–11.3 14.2–16.4**
Arshan	243	324	SS from 220 OHL to Zashikhinsky MBP	137	35 kV TL 35/10 SS, 35/0.4 SS	883.6**	40–53.7
Anosovo, Klyuchi	414	552	SS in Novaya Uda	120	35 kV TL 35/10 SS, 10/0.4 SS	790	21.8–29
Karam	282	324	SS in Ul'kan	160	35 kV TL 35/10 SS, 10/0.4 SS	1,010.6	39–54
Ozyorny	669	892	SS in Bol'she-okinsky	40	35 kV TL 35/10 SS, 10/0.4 SS	459.3	4.2–5.7
Karakhun	608	699	SS in Priboyny	118	35 kV TL 35/10 SS, 10/0.4 SS	779***	12–13.8
Ust'-Kirenga Pashnya	158	182	110 kV SS in Makarovo	30	110/10 SS, 10 kV TL, 10/0.4 SS	364.1	31–36
Podvoloshino	419	558	SS at OPS No. 8	0.3	10 kV TL, 10/0.4 SS	3.4	0.1

Notes: * cost estimates assume that the Tulun-Zashikhinskoye 220 kV transmission line construction project is completed;
** estimates assume the construction of 220/35/10 substations in Alygdzher to enable connection of remote consumers to the 35 kV grid;
*** cost estimates assume the construction and connection to the 35/10 kV Ozyorny substation by a transmission line.

Fig. 1. Connection of the Ozyorny and Karakhun settlements in the Bratsky district.

Fig. 2. Location of Tofalariya settlements relative to the deposits Gurbey and Zashikhinskoye.

program for expansion planning of power systems in Russia 2024–2029 [7] does not envision the expansion of the power grid in the Nizhneudinsky district. The payback period for connection costs of these relatively large emerging enterprises is 2–3 years under the assumed baseline conditions. In this regard, it is advisable to provide for future connection of the mining and beneficiation plant at the Gurbey deposit to the Irkutsk power system via the

TABLE 3. Key Data of the Projects to Connect Consumers in Isolated Communities to the Power Grid

Variable	Podvoloshino Oktyabrsky Maninsk	Ozyorny Karakhun	Verkhnyaya Gutara Alygdzher
Length of transmission lines, km	25.3	158	66
Capacity of decommissioned DPPs, MW	0.9	2.3	1.6
Reduction of fuel consumption, thousand tons/year	0.47	1.1	0.4
Reduction of budget subsidies, mln rubles/year	50	81	44

193 km long Nizhneudinsk-Gurbey power transmission line. This transmission line can be considered in the future as a basis for connection to the power system of the village of Verkhnyaya Gutara (41 km) (see Fig. 2). In the future, it makes sense to connect the mining and beneficiation plant at the Zashikhinsky deposit to the power system via the 240 km long Tulun-Zashikhinsky power transmission line or to the substation at the Gurbey deposit (120 km), given the rugged relief of the deposit area. This is also a prerequisite for connecting the Alygdzher settlement to the power grid.

IV. CONCLUSION

Our feasibility study identified five isolated communities where the connection to the power grid proves an economically viable option. Three of them (in the Katangsky and Usol'sky districts) are priority projects included in investment programs of utility companies but have not yet been completed. Drawing upon the calculation results, we recommend two more projects in the Bratsky district with payback periods of 4–6 and 12–14 years, respectively. The successful completion of priority projects requires the construction of 25 km of power transmission lines, while 0.9 MW DPPs will be decommissioned and relegated to the status of backup sources (Table 3). In the case of completing the projects in the Bratsky district, the length of the required transmission lines will be 158 km and the capacity of decommissioned DPPs will be 2.3 MW.

ACKNOWLEDGMENT

The research was carried in partial fulfillment of the State Assignment project FWEU-2021-0004 on “Comprehensive studies of priorities of spatial development of the energy industry of the Asian regions of Russia as informed by the trends in technological developments of the sector of the country and energy cooperation with the countries of North-East Asia”.

REFERENCES

[1] Minutes of the meetings of the Management Board of the Tariff Service of the Irkutsk Region (2024, Oct. 18, 2024, Oct. 25, 2024, Dec. 23, 202425.12.2024). [Online] Available: https://irkobl.ru/sites/sti/index.php?type=special. Accessed on: Oct. 02, 2024. (In Russian)

[2] Decree of the Governor of the Irkutsk region (2018, Aug. 21) No. 161-ug, Grid layout and program for expansion planning of power facilities in the Irkutsk region in 2019–2023. [Online]. Available: http://publication.pravo.gov.ru/document/3800201808290002?index=6. Accessed on: Oct. 02, 2024. (In Russian)

[3] Decree of the Governor of the Irkutsk Region (2022, Apr. 28). No. 71-ug, Grid layout and program for expansion planning of power facilities in the Irkutsk region in 2023–2027. [Online]. Available: http://publication.pravo.gov.ru/Document/View/3800202204290009. Accessed on: Oct. 02, 2024. (In Russian)

[4] Consolidated costs of power transmission lines and substations with voltage of 35–750 kV. Moscow, Russia: Institut Energoset'proekt JSC, 2013. (In Russian)

[5] Order of the Ministry of Construction of the Russian Federation (2024, Mar. 7). No. 166/pr, On Approval of Consolidated Construction Price Standards. Consolidated Construction Price Standards. NTsS 81-02-12-2024. Compilation No. 12. Outdoor Electrical Networks. [Online]. Available: https://minstroyrf.gov.ru/trades/tsenoobrazovanie/ukrupnennye-normativy-tseny-stroitelstva/. Accessed on: Oct. 02, 2024. (In Russian)

[6] Order of the Russian Ministry of Construction (2024, Feb. 16). No. 122/pr, On Approval of Consolidated Construction Price Standards. Consolidated Construction Price Standards. NTsS 81-02-21-2024. Compilation No. 21. Energy facilities (excluding infrastructural facilities). [Online]. Available: https://minstroyrf.gov.ru/trades/tsenoobrazovanie/ukrupnennye-normativy-tseny-stroitelstva/. Accessed on: Oct. 02, 2024. (In Russian)

[7] Order of the Ministry of Energy of Russia (2023, Nov. 30). No. 1095, Grid layout and program for expansion planning of power systems in Russia in 2024–2029. [Online]. Available: https://www.so-ups.ru/future-planning/sipr-ees/. Accessed on: Oct. 02, 2024. (In Russian)

Irina Yu. Ivanova PhD in Economics, Head of the Energy Supply to Off-Grid Consumers Subdepartment, Melentiev Energy Systems Institute (ESI) SB RAS, Irkutsk. She graduated from the Cybernetics Department of Irkutsk Polytechnic Institute with a double major in Computer-Aided Control and Large Energy Systems. Her research areas include small-scale energy, policy of energy supply to consumers in the northern and remote areas, and modeling of economic activities of stand-alone energy sources. Contacts: 130 Lermontov st., 664033, Irkutsk, Russia Tel.: (3952) 500646 ad. 345. E-mail: nord@isem.irk.ru.

Vladislav A. Shakirov PhD in Engineering, Senior Researcher at the Energy Sector of Siberia and the Russian Far East Subdepartment. Melentiev Energy Systems Institute (ESI) SB RAS, Irkutsk. He graduated from Bratsk State University with a major in Electric Power Systems and Networks. His research areas include renewable potential assessment, hybrid renewable energy systems, and multi-attribute decision making. Contacts: 130 Lermontov st., 664033, Irkutsk, Russia Tel.: (3952) 500646 ad. 376. E-mail: shakirov@isem.irk.ru.

Roman A. Ivanov PhD in Engineering, Researcher at the Energy Supply to Off-Grid Consumers Subdepartment, Melentiev Energy Systems Institute (ESI) SB RAS, Irkutsk. He graduated from the Cybernetics Department of Irkutsk State Technical University with a major in Computing Machines, Complexes, Systems and Networks. His research areas include information technology in the energy sector, data visualization and analytics, and development of software for decision-making in energy. Contacts: 130 Lermontov st., 664033, Irkutsk, Russia Tel.: (3952) 500646 ad. 346. E-mail: crowndriver@gmail.com

Prerequisites and Prospects for Hydrogen Energy Development in the Baikal Region

O.A. Baldynov[1,*], S.P. Popov[1]

[1] Melentiev Energy Systems Institute, SB RAS, Irkutsk, Russia

***Abstract* — A series of legislative documents has been adopted in the Russian Federation with the objective of promoting the development of hydrogen energy. The Irkutsk Region is one of the regions in which the establishment of a large-scale production facility for green hydrogen is planned. According to the Russian Atlas of Low-Carbon and Carbon-Free Hydrogen and Ammonia Production Projects, published by the Ministry of Industry and Trade, the total hydrogen production in Irkutsk Oblast is projected to reach 21,800 tons per year. The principal avenues for utilization are expected to be the domestic market and export to countries in the Asia-Pacific region. The high cost of hydrogen transportation will render export a suboptimal economic strategy in the medium to long term. Export of hydrogen may be feasible through the establishment of a hydrogen green certification system, which would allow for trade of hydrogen without its physical relocation. In this case, the utilization of hydrogen within the region is necessary. The objective of the study is to ascertain the optimal applications of hydrogen and the advancement of hydrogen technologies.**

***Index Terms* — Hydrogen infrastructure projects, hydrogen technologies, Baikal region.**

* Corresponding author.
E-mail: oabaldynov@isem.irk.ru

http://dx.doi.org/10.25729/esr.2024.04.0009

Received December 10, 2024. Accepted December 17, 2024. Available online December 28, 2024.

I. INTRODUCTION

In the 2020–2021, the Russian Federation adopted a number of framework documents that approved the creation of the hydrogen energy industry as one of the areas of development of the energy sector of the country in 2020-2050 [1–5]. The information published in these documents indicates that the creation of the hydrogen energy industry is export-oriented and seeks establishing facilities for the production, storage, and transport of hydrogen and hydrogen compounds. The documents highlight the aspiration of the Russian Federation to become a leading global producer and exporter of hydrogen [1–5].

The transport of hydrogen over long-distances (1 000 km and more), however, is likely to remain inefficient for both domestic deliveries and exports. This is caused by the loss of energy throughout the production, storage, and transport of hydrogen, as well as the necessity to utilize costly equipment due to the low density of this energy carrier and the considerable effect exerted by hydrogen on metals (hydrogen embrittlement). In the long run (2050–2100), provided the advancement of hydrogen technologies and their decreased cost, it will be feasible to export hydrogen from the Irkutsk region to China and other countries of the Asia–Pacific (APEC). In the near-term future, hydrogen in Russia and abroad will be produced in the most economical manner subject to the conditions specific to a given area and the production will be concentrated in close proximity to end users.

II. PREREQUISITES AND PROSPECTS FOR HYDROGEN ENERGY DEVELOPMENT IN THE BAIKAL REGION

In 2021, the Ministry of Industry and Trade of the Russian Federation published the “Atlas of Russian projects for the production of low-carbon and carbon-free hydrogen and ammonia,” which included 33 projects [6]. The implementation of five projects for the production of environmentally friendly hydrogen, with a total capacity of 21 800 tons per year, is envisaged in the Baikal region between 2024 and 2025. These projects target both the domestic market and exports to the APEC countries as hydrogen destinations. (Fig. 1).

The choice of the Irkutsk region as the place for the creation of the hydrogen infrastructure is due to the possibility of leveraging hydropower facilities (Bratsk, Ust-Ilimsk, Irkutsk, and Mamakan hydropower plants) and the availability of fresh water reserves.

The process of electrolysis, which is employed in the production of hydrogen, is contingent upon the treatment of water: the production of 1 kg of hydrogen takes a minimum of 9 liters of distilled water, but the total water consumption required for the production process is 16–35 liters per kilogram, and the value of this parameter depends on the specific type of electrolyser employed. The presence of large freshwater reserves in the region is a competitive advantage due to low energy consumption for water treatment compared to seawater. The use of seawater requires the construction of desalination plants, which adds to the final cost of hydrogen production [7].

The production of “green” hydrogen in the Irkutsk region powered by the electricity generated by hydroelectric power plants in the foreseeable future extending to 2050 can prove economically viable if a system of “green” hydrogen certificates is in place. Similar to renewable energy certificates, hydrogen certificates

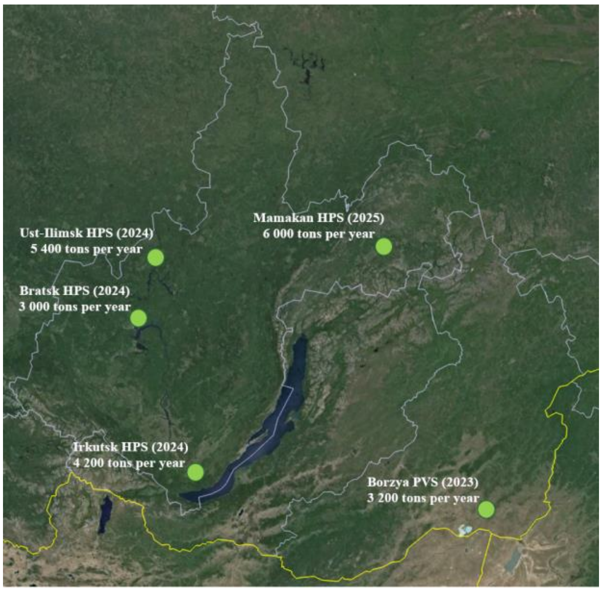


Fig. 1. Planned hydrogen projects in Baikal region.

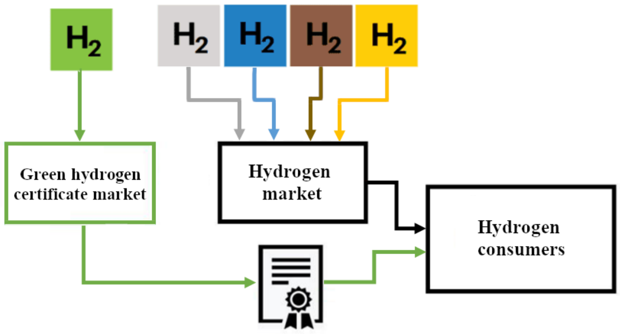


Fig. 2. Flowchart of the green hydrogen certificates market.

would serve to guarantee the carbon-free origin of the fuel (Fig. 2) [8]. By purchasing such a certificate, the purchaser would be able to consume hydrogen as 'green' hydrogen produced with carbon monoxide emissions.

The cost of such certificates must compensate for the production costs discrepancy between the “green” hydrogen (including the transaction costs of the “green” hydrogen certificates trading system) and the hydrogen consumed by the end user, which is produced with carbon monoxide emissions. This mechanism will facilitate the trading of produced hydrogen in domestic and international markets without the need for its physical movement. In this case, the construction of large-scale hydrogen production facilities in the Irkutsk region will have to be backed by its consumption within the region.

Hydrogen can be used as a feedstock in the oil refining and petrochemical industries [9]. The utilization of “green” hydrogen in the Irkutsk region facilitates the low-carbon refining of oil and petroleum products at the Angarsk refinery for hydrotreating and hydrocracking of oil to produce petroleum products. Additionally, hydrogen can be used in the region for the manufacturing of non-energy products in the chemical, food, and construction industries (Table 1).

Currently, the largest consumer of hydrogen is the Angarsk petrochemical company, where hydrogen is used as a raw material for oil refining [11]. Its production is

TABLE 1. Non-energy uses of hydrogen [9, 10]

Economic sector	Direction of hydrogen using
Chemical industry	production of chemicals (ammonia, methanol, hydrochloric acid, etc.), mineral fertilizers
Food industry	hydrogenation of oils and fats to produce solid fats (margarine)
Construction	welding of refractory metals

TABLE 2. Forecast of Hydrogen Consumption and Production for its Non-Energy Use in the Irkutsk Region

Types of hydrogen	2022	2030	2035	2050
Hydrogen consuming, kt	70	80	90	100
Hydrogen production, kt:				
“grey”	70	30		
“turquoise”		50	80	80
“green”			10	20

carried out by reforming, but the implementation of projects for the electrolysis production of “green” hydrogen based on electricity generated by hydroelectric power plants in the Irkutsk region will reduce greenhouse gas emissions at the stage of production of motor fuels and chemical products by replacing “gray” hydrogen with “green” (Table 2). At the same time, the total volume of hydrogen production is estimated as insufficient to meet the needs of the Angarsk petrochemical company [12].

At present, the hydrogen required for various manufacturing processes is produced by steam-gas reforming of natural gas, but the use of “green” hydrogen allows reducing carbon dioxide emissions. Reducing carbon dioxide emissions in the production of industrial goods aligns well with the global trend to track carbon footprints, which may lead to changes in the trade of energy-intensive goods. In particular, the European Union has already introduced the Carbon Border Adjustment Mechanism (CBAM). During the transition period from 2023 to 2025, CBAM measures aim to control imports of five commodity groups: steel, aluminum, cement, fertilizers, and electricity. It is noted that the number of targeted products may be expanded in the future [13]. The introduction of similar measures is being discussed in North American and East Asian countries, which may compromise the competitiveness of Russian goods.

Possible applications of hydrogen in the Baikal region also include fuel supply of the transport sector. The advent of hydrogen vehicles equipped with fuel cells (fuel cell electric vehicles, or FCEV) represents a further evolution of electric vehicles. The key benefit of FCEV is their high fuel (compressed or liquefied hydrogen) efficiency. The efficiency of modern internal combustion engines of vehicles is 35%, whereas the efficiency of fuel cells is 45% or more [14]. Hydrogen vehicles set themselves apart from the competition in that they do not produce pollutant emissions, have a shorter refueling time and reduced weight and size of fuel storage systems if compared to electric batteries, as well as a longer range and a diminished impact of low temperatures on fuel consumption [15, 16]. Various types of vehicles can be converted to run on hydrogen: road vehicles, rail vehicles, ships, and aircraft. Given the existing fleet of electrified public transport (trams and trolleybuses) in the Irkutsk region, it would be reasonable for the region to convert public transit and long-range buses, as well as utility vehicles and trucks with internal combustion engines, to hydrogen use.

Another potential avenue for the use of hydrogen in the transport sector is hydrogen-powered airships. Currently, research is underway to design helium-filled airships, while studies are also being conducted to assess the feasibility of utilizing hydrogen as an alternative [16, 17]. The flammable nature of hydrogen, in contrast to helium, presents a significant safety concern that limits its use as a lifting gas. On the other hand, the scarce global helium reserves and the considerably lower cost of hydrogen may favor the use of hydrogen or helium-hydrogen airships in remote locations [18]. In the Irkutsk region, their deployment will facilitate year-round delivery of certain cargoes, including energy carriers, to the otherwise inaccessible districts.

To ensure a reliable fuel supply for passenger and utility vehicles, it is essential to build a hydrogen infrastructure, comprising storage and distribution systems and refueling stations. The establishment of this infrastructure will inevitably result in an increased utilization of hydrogen by vehicles, which will subsequently lead to a notable reduction in carbon monoxide emissions by the region's transport sector.

The mass production and consumption of hydrogen in the region requires the advancement of Russian-made technology, including electrolysers, fuel cells, hydrogen storage and distribution systems. Once the necessary technological infrastructure is in place, it will be possible to address the pressing issue of developing environmentally friendly hydrogen energy supply systems in isolated and remote conservation areas. Self-contained integrated systems of the carbon-free production of hydrogen can be built to supply energy to small consumers (up to several megawatts) in such locations. Renewables, small and medium-capacity nuclear power plants, or a combination of both can serve as their energy source. The production of ‘green’ hydrogen will provide environmentally neutral motor fuel for vehicles, allow for the accumulation of renewable energy, and reduce cargo traffic to settlements and mining sites located in remote areas.

Despite the existing benefits from the use of hydrogen in the energy and transport sectors, industry (oil refining) is likely to remain the main consumer in the Irkutsk region for a long period of time due to the high cost of creating a hydrogen infrastructure (Fig. 3).

III. CONCLUSION

The existing hydropower capacity in the Baikal region and the availability of fresh water reserves may prove instrumental in setting up carbon-free hydrogen production. The implementation of hydrogen projects, complemented by a system of trading of “green” hydrogen certificates at the national and international levels, will lead to monetization of electricity generated by the region's hydroelectric power plants in the near future. Given the high cost and technological challenges involved, hydrogen exports will rely on the green certificates trading mechanism, avoiding long-distance transport. This will have to be backed by hydrogen consumption inside the region.

The hydrogen produced in the region can be used for low-carbon refining of petroleum products and manufacturing of non-energy products. The availability of the Russian-made technology will facilitate the use of hydrogen as a fuel in the transport sector, as well as the formation of energy supply systems in isolated and remote areas of the Baikal region. Hydrogen energy deployment in the region will require substantial capital outlays, the training of highly skilled personnel, and development of knowledge-intensive industries and domestic hydrogen technologies.

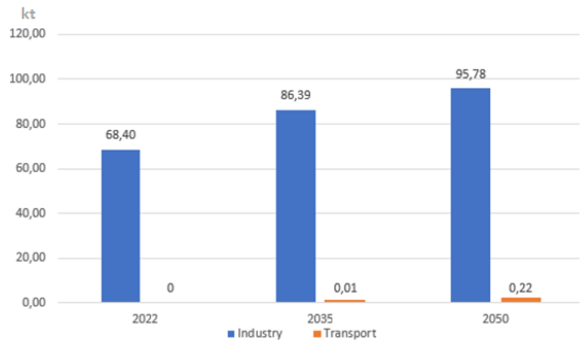


Fig. 3. The structure of hydrogen consumption in the Irkutsk region.

ACKNOWLEDGEMENTS

The research was carried out in partial fulfillment of requirements for the State Assignment (FWEU-2021-0004) of the Program for Basic Research of the Russian Federation for 2021–2035 and benefited from the use of resources of the High-Temperature Circuit Shared Research Facility (Ministry of Education and Science of the Russian Federation, project No. 13.CKP.21.0038).

REFERENCES

[1] Decree of the Government of the Russian Federation (2020, Jun. 09). No. 1523-r, On the Energy Strategy of the Russian Federation for the period until 2035. [Online]. Available: http://publication.pravo.gov.ru/Document/View/0001202006110003. Accessed on: Dec. 17, 2024. (In Russian)

[2] Decree of the Government of the Russian Federation (2021, Aug. 05). No. 2162-r, On approval of the Concept for the development of hydrogen energy in the Russian Federation. [Online]. Available: http://publication.pravo.gov.ru/Document/View/0001202108100014. Accessed on: Dec. 17, 2024. (In Russian)

[3] Decree of the Government of the Russian Federation (2020, Oct. 12). No. 2634-r, On approval of the action plan “Development of hydrogen energy in the Russian Federation until 2024.” [Online]. Available: http://static.government.ru/media/files/7b9bstNfV640nCkkAzCRJ9N8k7uhW8mY.pdf. Accessed on: Dec. 17, 2024. (In Russian)

[4] Decree of the Government of the Russian Federation (2021, Oct. 29). No. 3052-r, On approval of the Strategy for the socio-economic development of the Russian Federation with low greenhouse gas emissions until 2050. [Online]. Available: http://static.government.ru/media/files/ADKkCzp3fWO32e2yA0BhtIpyzWfHaiUa.pdf. Accessed on: Dec. 17, 2024. (In Russian)

[5] Decree of the Government of the Russian Federation (2021, Nov. 27). No. 3363-r, On approval of the Transport Strategy of the Russian Federation until 2030 with a forecast for the period until 2035. [Online]. Available: https://mintrans.gov.ru/documents/2/11577. Accessed on: Dec. 17, 2024. (In Russian)

[6] Atlas of Russian projects for the production of low-carbon and carbon-free hydrogen and ammonia. Moscow, Russia Federation, 2021 [Online]. Available: https://minpromtorg.gov.ru/docs/663f0df0-8439-4152-a8ea-2c4d0d36ffe4. Accessed on: Dec. 17, 2024. (In Russian)

[7] Water for hydrogen production. Irena, Abu Dhabi, United Arab Emirates, 2023. [Online]. Available: https://www.irena.org/Publications/2023/Dec/Water-for-hydrogen-production. Accessed on: Dec. 17, 2024.

[8] F. Gale, D. Goodwin, H. Lovell, H. Murphy-Gregory, K. Beasy, M. Schoen, "Renewable hydrogen standards, certifications, and labels: A state-of-the-art review from a sustainability systems governance perspective," International Journal of Hydrogen Energy, vol. 59, p. 654–667, 2024.

[9] Global Hydrogen Review 2023. Paris, France, 2023. [Online]. Available: https://iea.blob.core.windows.net/assets/ecdfc3bb-d212-4a4c-9ff7-6ce5b1e19cef/GlobalHydrogenReview2023.pdf. Accessed on: Dec. 17, 2024.

[10] K. Zhang, L. He, L. Jiang, S. Jiang, R. Yu, H. C. Lau, C. Xie, Z. Chen, "The role of hydrogen in the energy transition of the oil and gas industry," Energy Reviews, vol. 3, no. 4, p. 100090, 2024. DOI: 10.1016/j.enrev.2024.100090.

[11] "Unique equipment is being installed at the hydrogen production plant of the Angarsk petrochemical company," Irkutsk, Russia, 2014 [Online]. http://www.gazetahot.ru/novosti/biznes/81866-na-ustanovke-proizvodstva-vodoroda-oao-anhk-montiruyut-unikalnoe-oborudovanie.html. Accessed on: Dec. 17, 2024. (In Russian)

[12] "The Angarsk petrochemical company will carry out commissioning at the hydrogen production plant by the end of 2016," Rupec.ru, Aug. 05, 2015. [Online]. Available: https://rupec.ru/news/31825/. Accessed on: Dec. 17, 2024. (In Russian)

[13] "Carbon Border Adjustment Mechanism." [Online]. Available: https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en. Accessed on: Dec. 17, 2024.

[14] O. Nikiforov, "EU and Japan to boost fuel cells vehicles", ng.ru, Apr. 04, 2020. [Online]. Available: https://www.ng.ru/energy/2020-04-13/13_7842_transport.html. Accessed on: Dec. 17, 2024. (In Russian)

[15] Global EV Outlook 2024: Moving towards increased affordability. International Energy Agency, 2024, 174 p. [Online]. Available: https://iea.blob.core.windows.net/assets/a9e3544b-0b12-4e15-b407-65f5c8ce1b5f/GlobalEVOutlook2024.pdf. Accessed on: Dec. 17, 2024.

[16] "Technical note fuel cell electric buses cold weather operation Canada." [Online]. Available: https://www.ballard.com/docs/default-source/motive-modules-documents/technical-note---bus-cold-weather-operation---final.pdf?sfvrsn=4&sfvrsn=4. Accessed on: Dec. 17, 2024.

[17] L. Zhang, M. Lv, J. Meng, H. Du, "Conceptual design and analysis of hybrid airships with renewable energy," Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, vol. 232, no. 11, pp. 2144–2159, 2018. DOI: 10.1177/0954410017711726.

[18] J. D. Hunt, E. Byers, A.-L. Balogun, W. L. Filho, A. V. Colling, A. Nascimento, Y. Wada, "Using the jet stream for sustainable airship and balloon transportation of cargo and hydrogen," Energy Conversion and Management: X, vol. 3, p. 100016, 2019. DOI: 10.1016/j.ecmx.2019.100016.

Oleg Baldynov received the bachelor's degree in finance in 2015 and the master's degree in innovation management in 2017 from Irkutsk National Research Technical University. From 2017 to 2021, he was a Ph.D. student at the Melentiev Energy Systems Institute, SB RAS. His research interests include renewable energy sources, hydrogen energy, and energy transport.

Sergei Popov is a senior researcher at the Melentiev Energy Systems Institute, SB RAS. He is responsible for the analysis of the East Asian and Asia-Pacific energy markets. He joined the Melentiev Energy Systems Institute in 1982 and received the Ph.D. in Energy Systems Modeling from the Melentiev Energy Systems Institute, SB RAS in 1993. In 2004-2011, he worked at the Asia Pacific Energy Research Center, Japan. His research interests include energy systems modeling, development of energy policies, and issues of international energy cooperation.

Optimal Sizing of Hybrid AC/DC Distributed Generation Systems with On-Site Renewables for Off-Grid Power Supply to Remote Areas

N.R. Rakhmanov[1], H.B. Guliyev[2,*], F.Sh. Ibrahimov[2], and Z.A. Mammadov[1]

[1] Azerbaijan Scientific Research and Design-and-Surveying Institute of Energy, Baku, Azerbaijan
[2] Azerbaijan Technical University, Baku, Azerbaijan

***Abstract* — This study proposes a self-contained hybrid power system with DC and AC voltage buses connected to renewable and conventional energy sources to supply power to remote areas. The conventional sources are meant to serve as a backup for renewables to meet the demand during power shortages in the system. This research focuses on integrating an optimal structure of an off-grid system consisting of PV and WT generators with a battery energy storage system (BESS) and a diesel generator set (DGS) to ensure high reliability of power supply to a remote area. We contribute a machine learning algorithm (TLBO) for optimal sizing of the installed capacity of the PV-WT-BESS-DGS hybrid system components. The algorithm relies on the original multi-objective function to determine the most advantageous values of unit capacities for PV and WT plants, as well as the number of batteries and diesel generators, to meet the demand in the hybrid system under different scenarios of PV and WT power shortage.**

The optimization problem is solved considering the variability of meteorological conditions as manifested in the random and uncertain intermittency of PV and WT generation as well as in the stochastic nature of the electricity consumption process. To enhance the efficiency of its solution, this study seeks to cluster these processes and identify common scenarios for the data set of hourly measurements of PV and WT generation and loads during the year. We use k-means clustering to determine the number of clusters for PV, WT, and loads for representative geographical areas. The study reports the results of the analysis of optimal configurations for a hybrid AC/DC system made up of PV, WT, BESS, and DPS in these areas.

***Index Terms* — Distributed generation, microgrids, hybrid systems, PV generators, wind turbines, battery energy storage, teaching learning-based optimization (TLBO), common scenarios of wind speed, solar radiation and electrical loads, AC/DC systems.**

I. Introduction

The great bulk of the research on the transformation of electric power systems deals with the development of distributed generation (DG).

In the last decade, DG has become an increasingly more attractive option because of the widespread use of renewable sources. DG configurations that integrate renewable sources such as PV and WT generators can fully serve the demand while operating off-grid. At the same time, due to the intermittency and uncertainty of PV and WT power generation in DG systems, power supply stability may be disturbed, and in case of excessive power generation, it may lead to power shedding [1–3]. Hybrid DG configurations with WT and PV generators, an integrated BESS, and a diesel generating set are considered reliable off-grid power supply systems for rural and remote areas [4, 5].

* Corresponding author.
E-mail: huseyngulu@mail.ru

http://dx.doi.org/10.25729/esr.2024.04.0010

Received December 6, 2024. Acc. December 17, 2024. Available online December 28, 2024.

A critical challenge for hybrid systems incorporating distributed generation and on-site renewables is optimal sizing of individual components, such as wind turbines, solar generators, and battery energy storage system. This sizing is essential to achieve optimal technical performance, ensuring compliance with reliability standards, and economic performance through minimization of total costs of power supply to consumers in a given area.

The unreliability of renewables can be overcome by increasing the size of the components (PV and WT generators), but this also increases the cost of the system. On the other hand, under-sizing of components can lead to power outages when the renewable power generation is less than the loads. Therefore, it is critical to optimally size renewable sources, thereby determining the exact number of their components [6]. A hybrid PV-WT-BESS-DGS microgrid has been designed and successfully utilized to supply electricity to three remote hamlets [7]. Studies [6, 7] and several other works related to optimal sizing of hybrid systems with renewable sources rely on the HOMER software for solving the problem. The software has some practical limitations, as it is mainly intended for economic valuation of hybrid system component selection and does not consider the impact of meteorological changes on system reliability. In recent years, various metaheuristics-based algorithms have been developed for multi-objective optimization, including genetic algorithms, which have been widely adopted [8, 9].

This paper solves the problem of optimal sizing of components of an off-grid PV-WT-BESS system with the aid of the improved TLBO algorithm (JAYA). Unlike existing algorithms designed to determine the optimal parameters of the hybrid system, the TLBO algorithm used in this paper allows considering variability of meteorological conditions. To capture the stochastic variability of wind speed, solar radiation, and electricity consumption, we performed their spatial and temporal analysis and identified common scenarios for optimal sizing of renewable sources in the proposed microgrid setup. The scenarios generated by our model approximate the original scenarios and reduce the number of data for efficient combination of hybrid system components.

The proposed optimization approach was applied to a case study of representative geographical areas in Azerbaijan.

II. The Statement of the Problem of Optimal Sizing of the Hybrid AC/DC (PV-WT-BESS-DGS) System to Ensure System Reliability From the Technical Standpoint

1. Configuration of the hybrid AC/DC distributed generation system “PV – WT – BESS – DGS”

This paper presents a standardized hybrid dual-bus AC/DC distributed generation system with on-site renewables. The following are connected to the AC subsystem: wind turbines, loads consisting of AC and DC consumers, and a DGS that serves as an emergency source. The DC subsystem has a wind turbine, a battery energy storage, and DC and AC loads connected to it.

The AC and DC subsystems are interconnected by a bi-directional inverter. Depending on power generation from sources in the AC and DC subsystems, there can be various load conditions in each of the subsystems and in the entire hybrid system: balanced, surplus, and shortage. Under the balanced conditions, the total power generated from PV in the DC subsystem and WT in the AC subsystem equals the total power of consumers in these subsystems. When the total power output in the DC and AC subsystems exceeds the total consumption and total power in the battery storage system, the excess power is discarded. In the event of a power generation shortage in the AC and DC subsystems, when the overall load exceeds the available supply and the battery capacity is insufficient to compensate for this shortage, the corresponding part of the load is shed.

2. Reliability criteria for off-grid AC/DC systems

Maintaining the reliability of off-grid AC/DC systems is essential when selecting the performance specifications as this directly impacts the continuous power supply dependent on renewable energy generation. These specifications are formalized by the following indices [10]:

1. Probability of power outage:

$$\Delta \tilde{P}_{load} = \frac{\sum_{t=1}^{T} \Delta P_{load}(t)}{\sum_{t=1}^{T} (P_{loadDC}(t) + P_{loadAC}(t))}, \qquad (1)$$

where $\Delta P_{load}(t)$ – the amount of the disconnected power of the total load in the AC/DC system; t – the duration of the shortage T = 8 760 h.

2. Proportion of generation shed $P_{gen}(t)$: when the sum of the generation from AC and DC subsystems exceeds the total load, and the BESS reaches its maximum storage

capacity, the excess generation must be disconnected:

$$\Delta\tilde{P}_{gen} = \frac{\sum_{t=1}^{T} \Delta P_{gen}(t)}{\sum_{t=1}^{T} (P_{DC}(t)+P_{AC}(t))}. \quad (2)$$

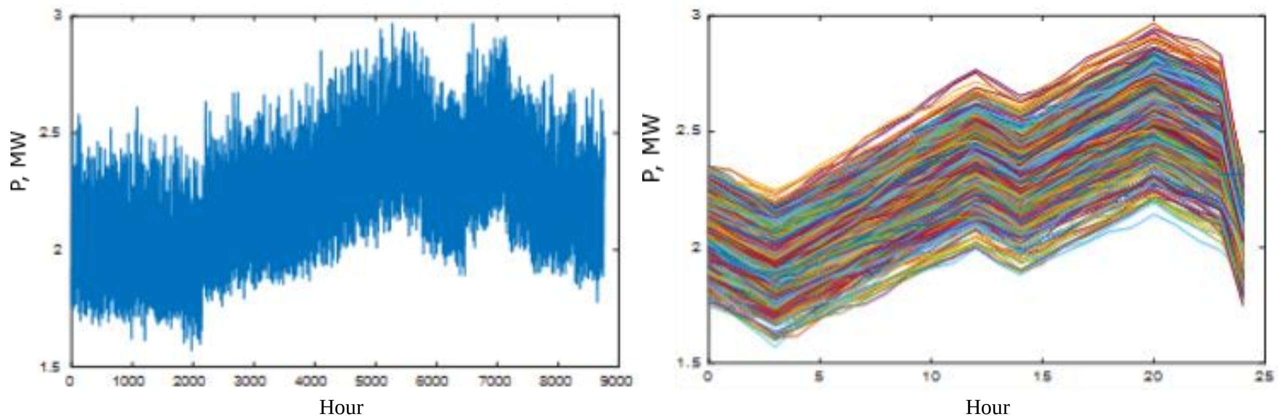
We have designed a flowchart of calculation of optimal values of reliability indices (1) and (2) for off-grid hybrid AC/DS systems.

III. The Use of *K*-Means Clustering for Generating Common Scenarios of Random Variations in Solar Radiation, Wind Speed, and Electricity Consumption for Representative Geographical Areas of Azerbaijan

The intermittent nature of power generation from solar PV and wind turbines makes their integration into the electric power system challenging. There are different approaches to decompose a data set of random variable changes into a combination of multiple recurrent changes. This study uses *k*-means clustering to generate common scenarios of solar radiation, wind speed, and loads. The resulting common clusters significantly reduce the number of investigated scenarios that would otherwise have to be generated from a large set of input data. *K*-means clustering is performed as follows:

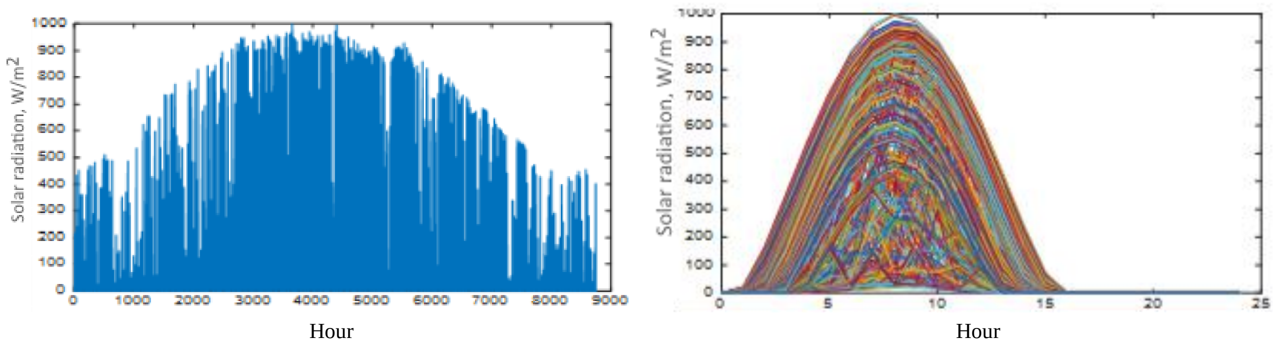
1. Input an array of time series data for solar radiation (W/m^2), wind speed (m/s), and loads (W) for 1 year.
2. Perform individual clustering of stochastic processes of loads, solar radiation, and wind speed on the basis of hourly measurements for the entire year; the basic unit of clustering is one day (24 hours).
3. Based on the known relationship (spatial correlation) between loads and solar radiation, perform their joint clustering.
4. Identify common solar radiation/load scenarios according to the centroids of the solar radiation/load clusters (based on the joint load/solar radiation data set).
5. Use each type of solar radiation/load scenarios and common scenarios for wind data (based on the centroids of wind speed clusters) to establish relationships between solar radiation/load and wind speed.

Aided by the computer implementation of the above steps, we determined the optimal number of clusters for



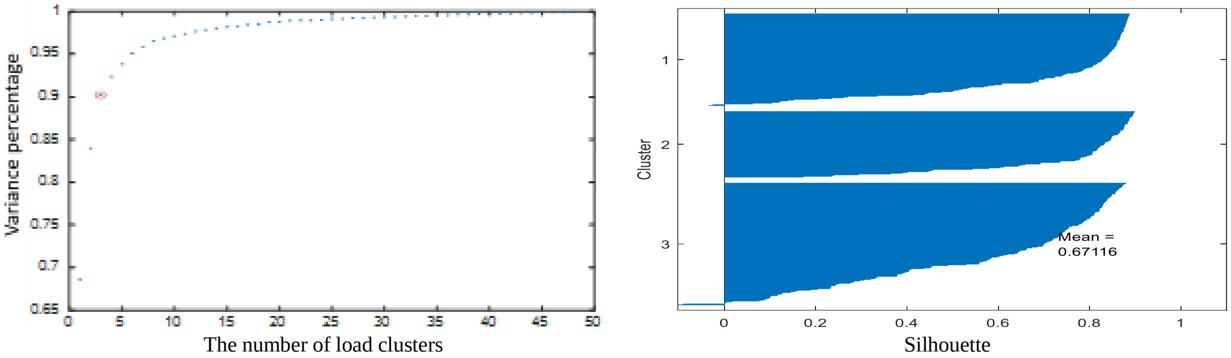
a) *b)*

Fig. 1. Profile of load changes by hour throughout the year (a) and day (b).



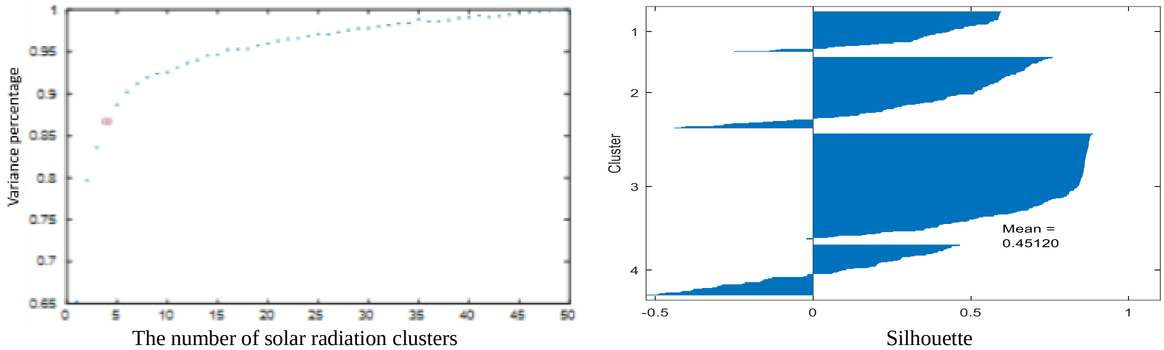
a) *b)*

Fig. 2. Profile of solar radiation changes by hour throughout the year (a) and day (b).



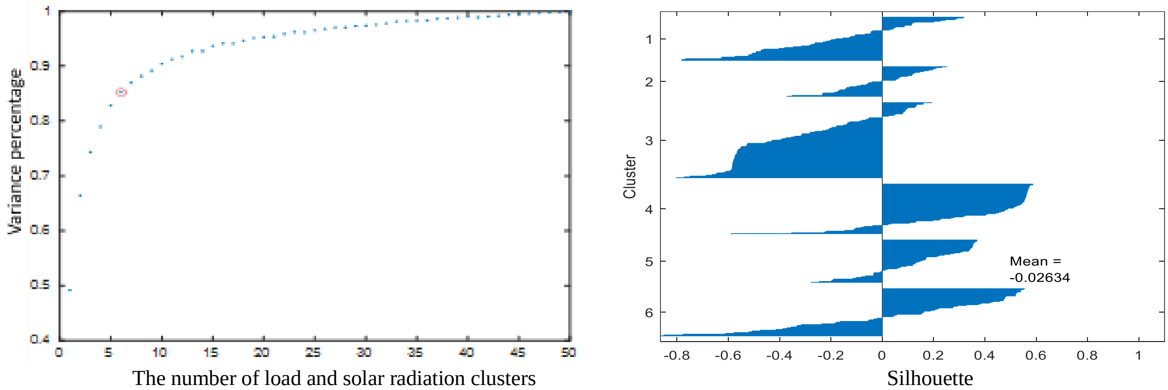
a) *b*)

Fig. 3. Optimal numbers of clusters for annual load variability (a) and corresponding silhouettes (b).



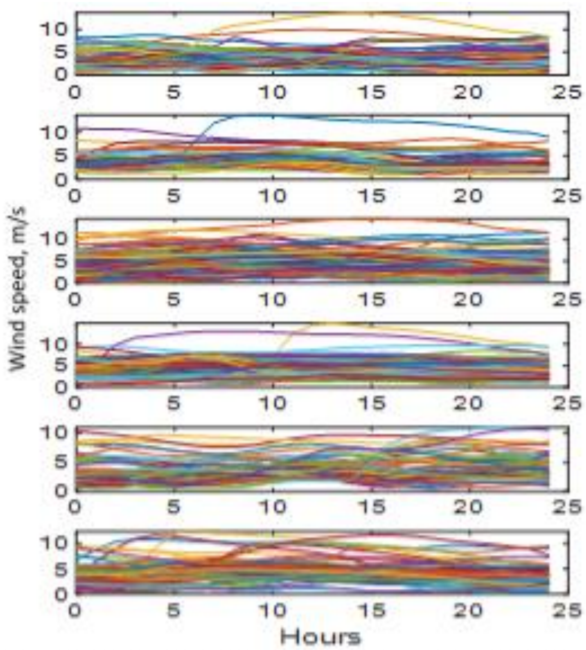
a) *b*)

Fig. 4. Optimal number of clusters for annual solar radiation variability (a) and corresponding silhouettes (b).

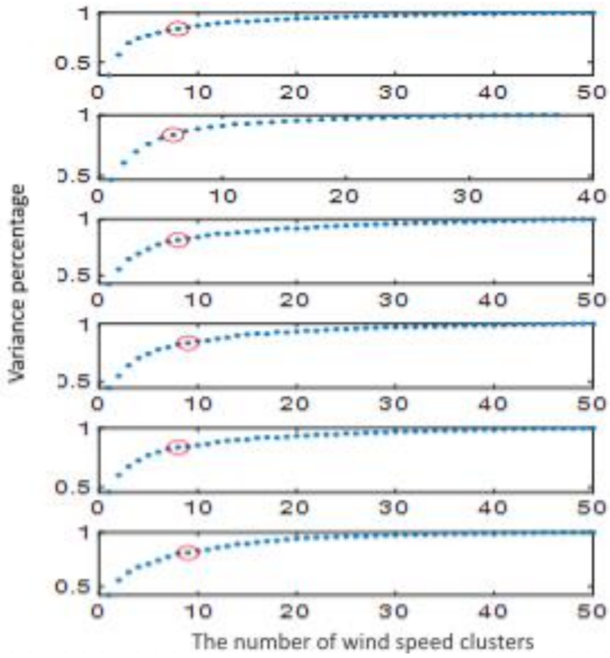


a) *b*)

Fig. 5. Optimal number of clusters for a set of solar radiation/load variability data (a) and their silhouettes (b) throughout the year.



a) Changes in wind speed in accordance with solar radiation/load



b) The number of clusters in accordance with daily changes in wind speed

Fig. 6. Optimal number of solar radiation/load variability clusters according to wind speed variability.

radiation/electrical load and wind speed for mountainous areas of Azerbaijan.

IV. Clustering Analysis of Variability in Solar Radiation, Loads, and Wind Speed for Meteorological Conditions of Mountainous Areas in Azerbaijan

The clustering analysis and identification of representative clusters relied on hourly measurements of solar radiation, loads, and wind speed obtained for a remote area of the Kalbajar district of the East Zangezur economic region of Azerbaijan. The measurements covered a time span of one year. Figures 1(a, b), 2(a, b), and 3(a, b) show images of these processes for one-year and one-day time spans, respectively.

The comparative analysis of solar radiation and load dynamics for both the one-year and one-day time spans has revealed that they exhibit a more recurrent pattern compared to the speed fluctuations. Based on these considerations, we also analyzed the clusters of the joint dynamics of loads and solar radiation to find common scenarios.

The optimal numbers of clusters for load, solar radiation, and wind speed data for a period of 1 year for the Kalbajar district were determined with the aid of the algorithm reported in [10]. Figures 4 to 6 illustrate the trend in the percentage ratio of the variance in clustering results related to the dynamics of loads and solar radiation, along with the corresponding silhouettes of the clusters.

Thus, as seen in Fig. 1–6, the optimal number of scenarios for the load data is 3, for solar radiation data – 4, together for solar radiation and load data – 6. There are 6 scenarios for combined load, solar radiation, and wind speed data, consisting of the following number of clusters: 6, 7, 8, 9, 8, and 9. In total, 282 scenarios were obtained. The identified numbers of scenarios serve as the initial base for the mix of RES connected to the AC and DS subsystems of the hybrid system.

Optimal control of power generation in AC and DC subsystems depends on the spatial and temporal operating conditions of the hybrid system, which is treated as a multi-objective problem.

V. The Multi-Criteria Function of Optimal Sizing of an Off-Grid Hybrid AC/DC System with Integrated PV and WT Generators

An essential part of configuring an off-grid hybrid system with on-site renewables is to ensure the reliability of its operation under uncertain and changing meteorological data on solar radiation and wind speed, as well as the random process of power consumption by electrical loads [11]. The power output in the AC subsystem is expected to cover in full the load P^e_{AC} connected to the subsystem and transmit up to 30% of the output, in the event of its excess, to the DC subsystem.

The output of PV generators in the DC subsystem is assumed to be sufficient to meet its connected load and, in the case of its excess, to transmit the surplus power to the AC subsystem. In the event of excess generation $P^W(t)$ over period t, reliability in the system can technically be maintained by pursuing the objective:

$$F_1(N^W, N^{PV}, N^{bat}, N^{DG}) = \sum[P^W(t) - P^{PV}_{DC-AC}(t) - P^L_{AC}(t)] \Rightarrow min,$$

where N^W, N^{PV}, N^{bat}, N^{DG} – the number of wind turbines, solar cells, battery storage units, and diesel generators, respectively; $P^{PV}_{DC-AC}(t)$, $P^L_{AC}(t)$, $P^W(t)$ – power flows between AC and DC buses, loads connected to the AC bus and wind turbine generation power at time t, respectively.

Accordingly, when wind power is insufficient, the objective of optimal power management in the hybrid AC/DC system is described by the function:

$$F_2(N^W, N^{PV}, N^{bat}, N^{DG}) = \sum[P^W(t) + P^{PV}_{DC-AC}(t) + P^{DG}(t) + P^L_{AC}(t)] \Rightarrow min.$$

The optimization of power management in the event of excess or shortage of the power generated from PV (DC subsystem) can be expressed through the following objectives.

Power excess:

$$F_3(N^W, N^{PV}, N^{bat}, N^{DG}) = \sum^{\Sigma}[P^W(t) - P^{PV}_{DC-AC}(t) - P^{bat}(t) - P^L_{DC}(t)] \Rightarrow min.$$

Power shortage:

$$F_4(N^W, N^{PV}, N^{bat}, N^{DG}) = \sum^{\Sigma}[P^{PV}(t) + P^W_{DC-AC}(t) + P^{bat}(t) - P^L_{DC}(t)] \Rightarrow min.$$

Inverter output power:

$$P_{inv}(t) = \frac{P^L(t)}{\eta_{inv}},$$

where η_{inv} – the inverter efficiency factor.

Possible scenarios of hybrid system operation (PV + WT):

1) $\sum P_G$ exceeds the power required to serve the load (inverter input power). In this case, the excess energy is stored in the battery storage, and the power remaining after the battery is charged to full capacity is not used, i.e., is shed.

2) $\sum P_G$ is less than the power required to serve the load. The power shortage is compensated by the storage unit.

3) In the case the equality $\sum P_G = P_{inv}$ holds, the power (capacity) P_{bat} remains unchanged.

Table 1 shows the results of the calculations that assume that the amount of the disconnected load (F = min DL) at $100 < N^{bat} < 20\ 000$, $100 < N^{PV} < 60\ 000$, $100 < N^W < 5\ 000$, $C_{bat} = 40\ 000\ Wah$, $P^{PV} = 125\ W$, and $P^W = 5\ 000\ W$ is the objective function.

The optimal solution is presented in the first row of Table 1. Other options were also considered.

VI. Conclusion

1. The present paper proposes a technique for optimally sizing an off-grid power system with a dual-bus AC/DC configuration and intermittent renewable sources to improve the reliability and efficiency of its operation. The optimal architecture of the hybrid power system is derived based on the analyzed scenarios of the system's performance over a year, given the random variability of solar radiation, wind speed, and stochastic load variability

Table 1. Calculation Results

N	N^{bat}, N^{PV}, N^W	*DL*	*Utilized capacity*	*F*(...)
1	15.621; 6.893; 3.328	0	0.2256	0
2	7.038; 27.790; 2.436	0	0.3732	0
3	9.384; 12.836; 3.171	0	0.3866	0
4	12.076; 199; 4.069	0	0.4159	0
5	12.433; 33.398; 4.241	0	0.4875	0
6	2.068; 51.802; 4.291	0	0.7508	0
7	9.220; 8.200; 4.361	0	0.5338	0
8	14.504; 55.473; 3.022	0	0.3311	0
9	6.096; 35.392; 4.867	0	0.6783	0
10	1.939; 28.149; 2.969	0	0.6308	0

in the investigated remote area.

2. This study has introduced a machine-learning algorithm designed to identify the optimal values for available wind and solar generation capacity across all scenarios. The suggested approach for generating scenarios and the algorithm for identifying optimal parameters of the hybrid system were tested in the power supply systems planned for construction in representative geographical areas in Azerbaijan.

References

[1] N. R. Rahmanov, V. G. Kurbatskiy, H. B. Guliyev, N. V. Tomin, Z. A. Mammadov, "Probabilistic assessment of power system mode with a varying degree of wind sources integration," E3S Web Conf., vol. 25, Art. no. 02003, 2017. DOI: 10.1051/e3sconf/20172502003.

[2] H. C. Chen, "Optimum capacity determination of stand-alone hybrid generation system considering cost and reliability," Applied Energy, vol. 103, pp. 155–164, 2013.

[3] S. Diaf, G. Notton, M. Belhamel, M. Haddadi, A. Louche, "Design and techno-economical optimization for hybrid PV/wind system under various meteorological conditions," Applied Energy, vol. 85, pp. 968–987, 2008.

[4] H. Yang, W. Zhou, L. Lu, Z. Fang, "Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm," Solar Energy, vol. 82, pp. 354–367, 2008.

[5] A. Khan, N. Javaid, S. Javaid, "Optimum unit sizing of stand–alone PV-WT battery hybrid system components using Jaya," in Proc. the 2018 IEEE 21st International Multitopic Conference, Karachi, Pakistan, Nov. 1–2, 2018, pp. 1–8.

[6] A. S. Al Busaidi, H. A. Kazem, H. A. Al- Bad, M. F. Khan, "A review of optimum sizing of hybrid PV–Wind renewable energy system in Oman," Renewable and Sustainable Energy Reviews, vol. 53, pp. 185–193, 2016. DOI: 10.1016/j.rser.2015.08.039.

[7] A. H. Mamaghani, S. A. A. Escandon, B. Najafi, A. Shirazi, F. Rinaldi, "Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia," Renewable Energy, vol. 97, pp. 293–305, 2016.

[8] A. Maleki, M. G. Khajeh, M. A. Rosen, "Two heuristic approaches for the optimization of grid-connected hybrid solar–hydrogen systems to supply residential thermal and electrical loads," Sustainable Cities and Society, vol. 34, pp. 278–92, 2017.

[9] A. A. Fathy, "A reliable methodology based on mine blast optimization algorithm for optimal sizing of hybrid PV–wind-FC system for remote area in Egypt," Renewable Energy, vol. 95, pp. 367–380, 2016.

[10] N. R. Rahmanov, V. G. Kurbatsky, H. B. Guliyev, N. V. Tomin, A. F. Yaqubov, "Investigation of the impact of integrating renewable sources with variable power generation, taking into account restrictions on the voltage stability limit," E3S Web Conf., vol. 461, Art. no. 01023, 2023. DOI: 10.1051/e3sconf/202346101023.

[11] P. V. Ilyushin, "Expansion of the range of permissible operating conditions for generating units of distributed generation facilities under voltage sags," Energetik, no. 11, pp. 21–27, 2018. (In Russian)

Nariman R. Rakhmanov, Dr.Eng., Professor, graduated from Azerbaijan State Oil and Chemistry Institute in 1961. N.R.Rakhmanov is an IEEE member. He is an Academician of International EcoEnergy Academy (Baku, Azerbaijan). He is currently a chief researcher at Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute. His research interests are power system operation and control, distributed systems, and alternative energy sources.

Huseyngulu B. Guliyev M.Sc., Ph.D., is a Lead Scientific Researcher, Head of Department of Power System Operating Conditions and the Problems of their Control in Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute (Baku, Azerbaijan). Currently, he is an Associate Professor of the Automation and Control Department in Azerbaijan Technical University (Baku, Azerbaijan). He has more than 200 published articles, and 3 patents. His research interests are power systems operation and control, distributed generation systems, application of artificial intelligence to power system control design, and power quality.

Ibrahimov Famil Shamil graduated from the Azerbaijan State Oil Academy, Department of Energy, majoring in Electrical Engineering and Systems in 2000. He is currently a leading engineer in the Department of Regulation and Control of Power Systems of Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute, and a post-graduate student of the Department.

Mammadov Zaur Alekper oglu graduated from the Azerbaijan Technological University in 1997, majoring in Mechanical Engineering. Currently, he is a postgraduate student at the Azerbaijan Scientific-Research and Design-Prospecting Power Engineering Institute.

Preliminary Estimates of Economic Implications of Small-Scale LNG Airship Transportation to Remote Areas

M.S. Gaivoronskaya[1,*] , V.V. Semikashev[1]

[1] Institute of Economic Forecasting, Russian Academy of Sciences, Moscow, Russia

***Abstract* — The paper is concerned with preliminary estimates regarding the impact of transporting small-scale LNG to remote locations via airship on the power output. The main production sites, assumed as sources of small-scale LNG supplies, are presented and the leading airship manufacturers in Russia are identified. The study involves estimating the cost of different options for energy supply to remote areas, including the use of petroleum products and coal. Thus, the effects for the consumer are estimated and the economic implications are assessed with a detailed description of inter-industry links. The study reveals that the manufacturing industry and the energy sector are impacted to the greatest extent. The results of the calculations are however debatable. The success of the project heavily depends on the redirection of currently used petroleum products, whose production makes a significant contribution to the economy and the budget, to other markets. On the other hand, a considerable share of the cost of petroleum products is subsidized, which in the case of switching to natural gas will free up the state's financial resources. Given the ambiguity of the conclusions for the project of small-scale LNG airship transportation to remote areas, other domains of airship use are proposed and described. These include transportation and logistics, the oil and gas sector, forestry, the electric power industry, as well as the social initiatives and housing construction. The paper concludes with future objectives in continuation of the current study.**

***Index Terms:* Cargo airships, small-scale LNG, inter-industry links, manufacturing industry, subsidies, energy sector, remote areas.**

I. Introduction

The energy supply to the northern and isolated territories of Russia is characterized by the high cost of energy resources (primarily petroleum products - diesel fuel) due to expensive transportation, as well as its complexity, duration, and unpredictability that stem from severe and changeable weather conditions. The use of hydrocarbons from the deposits situated in these territories is possible only if they are industrially developed and exploited. Even in this case, however, the cost of fuel can also be extremely high, even if the fuel is cheaper than imported energy resources.

One of the solutions to this problem is the use of cargo unmanned aerial vehicles - specifically, cargo airships – for the delivery of small-scale LNG (SSLNG), as proposed in [1].

According to estimates [1], airship transportation to northern and isolated areas will allow the delivery of SSLNG cargoes, weighing from several tons to 60 tons, in a few hours over a distance of about thousands of kilometers. These flights can be executed in 1 to 2 days, significantly reducing the current multi-week fuel delivery time. This can make fuel supplies more accessible, safer, and predictable.

SSLNG can be produced at small-scale LNG plants.

* Corresponding author.
E-mail: ms.gayvoronskaya@yandex.ru

http://dx.doi.org/10.25729/esr.2024.04.0011

Received October 1, 2024. Acc. December 24, 2024. Available online December 28, 2024.

Currently, there are about 20 such plants operating in Russia [2]. Their activities are aimed at expanding gas engine market, as well as ensuring gas supply to the population and individual facilities. In particular, they can act as a source of LNG for the proposed scheme. Provided there are available gas volumes for supply to remote areas, we can consider the following operating small-scale LNG plants: Tobolsk LNG complex (LNGC) in the Tyumen Region, Sakhalin PCC LNGC in the Sakhalin Region, Pervouralsk LNGC and Nevyansk LNGC in the Sverdlovsk Region, Gazprom Helium Service LNGC in the Amur Region and Primorsky Territory, Nizhny Bestyakh LNGC in the Republic of Sakha (Yakutia), Sibir-Energo LNGC in the Kemerovo Region, and other facilities, either under construction or newly built.

The main use of SSLNG in remote areas will be energy supply to the population, the public utilities sector, generation facilities, industrial consumers, and others.

The cost of such an energy supply option remains an open question, especially given the need to develop the production of airships, their launch, along with creation and maintenance of their fleet for these and other purposes. When addressing the energy supply problem, a significant part of the costs will be associated with airships and changes in the load of other enterprises engaged in fuel production and transportation, and the corresponding financial flows. Therefore, the economic assessment of the project for the SSLNG delivery by airship should also consider these flows and factor in possible multiplier effects, which is the focus of this paper. The estimates produced are preliminary and just enable us to understand whether it is worth further investigating this issue and refining the estimates already obtained. In addition, the experience of assessment will be useful for considering other areas of airship use.

II. Comparison of Energy Supply Options for Remote Communities

Current energy supply, along with electric and thermal energy production in remote communities, relies largely on delivered diesel fuel and coal. In 2016–2017, the cost of liquid fuel, depending on the area, ranged from 50 to 100 thousand RUB/t [3]. As a result, the electricity cost was estimated in the range of 22–68 RUB/kWh in different areas, which is 5-15 times higher than the Russian average [3]. At the same time, prices and tariffs for energy resources for the population and the public utilities sector are several times lower, that is, the cost of fuel, electricity, and heat is subsidized. The share of local budget expenditures in paying for energy supply in the areas of the Far North exceeds 30%, and in some of them, it is more than 60%, while the Russian average is about 20% [3]. In addition, a substantial portion of the Northern Delivery budget, amounting to RUB 99.7 billion in 2022 [4], is allocated to the expenses for fuel and energy resources.

The economically justified price for producing and regasifying SSLNG, not including its delivery, starts at 15 RUB/m^3. Given transportation services, the cost of gas in remote areas can reach nearly 25 RUB/m^3.

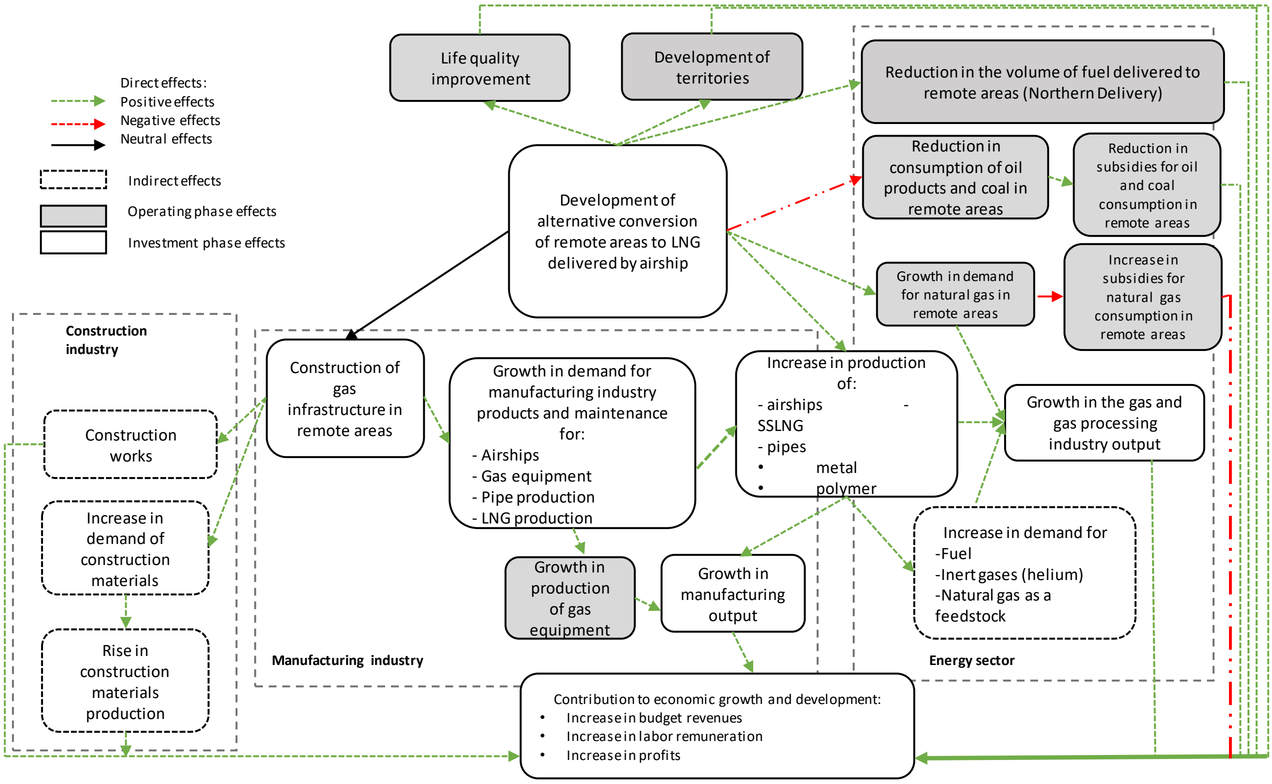
Under various conditions (the ratio between thermal and electrical energy, capacity utilization factor, regional conditions, and others), the electricity price can be about 12–20 RUB/kWh [5]. This is higher than the average Russian indicators, but lower than the current electricity cost in remote areas, i.e., this energy supply option is more economical and will require smaller subsidies. Thus, the use of LNG can lower the cost of electricity, therefore, it is important to evaluate other effects (multiplier, economic, investment, environmental, and others).

Currently, several research and production groups are involved in the development of airships in Russia:

- The company “Aerostatika” has already built several experimental airships and has eight years of experience in their operation [11].
- The Foundation for Advanced Research is developing a wind-resistant airship called "Skipper," the use of which may be relevant for the Northern Delivery [12,13].
- The company "Augur" produces the airship "Atlant,” which is considered for the coal transportation in Kuzbass [14] and
- Others.

III. Designing the Project and Assessing Its Economic Components

To assess all the economic effects of switching to LNG with its delivery by airships to remote areas with subsequent regasification and further use of natural gas by consumers, it is necessary to examine the impact of all processes arising in this regard. At the same time, it is assumed that new production facilities will make significant advancements, while existing ones will be loaded for both fuel extraction and transportation.



Source: Generated by the authors

Fig. 1. Scheme of macroeconomic effects of conversion to SSLNG delivered by airships.

Consideration is also given to manufacturing and servicing airships, as well as to establishing the infrastructure for the on-site use of SSLNG. The main changes in connection with the proposed project are shown in Fig. 1.

Let us formulate the indicators of this project for the SSLNG delivery to remote areas via airships.

1. Manufacturing airships, tank containers, and cryogenic tanks for the SSLNG transportation.

2. Converting the energy infrastructure in remote communities to gas (construction of gas infrastructure, providing buildings with gas equipment, modernization of generation facilities).

3. Organizing and maintaining SSLNG transportation by airships.

4. Increasing the production of SSLNG and helium for fueling airships for these purposes.

5. Reducing liquid fuel and coal production or redirecting them for export.

6. Minimizing transportation within the traditional scheme of fuel delivery to remote settlements.

The SSLNG transportation requires the production of not just airships but also tank containers and cryogenic tanks. This demand will enhance the production output in the manufacturing industry. To supply energy to the first 500–600 remote communities, it is proposed to produce 15 airships and about 1 600 tank containers with deliveries planned roughly every two months.

The production of helium to fuel airships will increase the demand for it, creating additional orders for the petrochemical industry. Additional helium production of approximately 0.1 million m^3 per year is expected.

The proposed option for using LNG involves the construction of gas infrastructure in remote territories. This will increase demand for distribution gas pipelines, gas distribution points, and the necessary gas pumping equipment. In addition, consumers will need new gas equipment: gas boilers, stoves, and water heaters for households and other buildings; generating equipment running on natural gas – for boiler houses and power plants. A comprehensive plan encompasses the construction of about 1.7 thousand km of gas networks and installation of 166 thousand units of gas equipment, including gas pumping systems and in-house plants. Additionally, about 0.5 thousand MW of electric power

TABLE 1. Performance of the Project for the SSLNG Delivery to Remote Areas Using Airships After Their Launch

	Quantity
1. Manufacturing industry, including construction	*for 10 years*
Production of tank containers and cryogenic tanks	1 660 pcs.
Airship production	15 pcs.
Production of pipes for local gas networks and gas equipment, including that at consumers' end	1 700 km of pipes and 166 thousand units of equipment
Modernization of generating equipment	0.5 thousand MW, 1 thousand Gcal/h
2. Energy sector, including transportation	*for 1 year*
Production, transportation, and consumption of SSLNG for remote power supply	2.5 billion m^3
Production and consumption of helium for airships	0.1 million m^3
Production, transportation, and consumption of petroleum products (diesel fuel)	-1.5 million t
Production, transportation, and consumption of coal	-0.7 million tons

Source: Authors' estimates

generation capacity and up to 1 thousand Gcal/h of thermal power generation capacity will be modernized to facilitate gas usage. All this will generate additional output in the manufacturing sector.

Conversion to gas will increase the consumption of natural gas, which will replace the currently used liquid fuel, coal, and other fuels. The annual consumption of 1.5 million tons of liquid fuel and 0.7 million tons of coal will be replaced by approximately 2.5 billion m^3 of natural gas. This will change the demand for products from the extractive industries. Thus, the main industries that will be affected by the use of SSLNG transported by airships will be the manufacturing industry and the energy sector (Table 1).

In addition, flows in the construction and transportation sectors will change. According to our estimates, however, these changes are significantly smaller than those indicated above. Moreover, neither the maintenance of new gas infrastructure, equipment, and airships, nor the maintenance of the previous energy supply system are considered in this analysis. These indicators prove comparable in size.

I. PRELIMINARY ESTIMATES OF THE PROJECT EFFECTS GIVEN INTER-INDUSTRY LINKS

The initial assessment involved calculating changes in the output for economic sectors (activities) driven by the proposed project. The calculation was conducted within the assessment of the effects over a one-year period, assuming the project operates at full capacity. To this end, flows associated with fuel supply were calculated for the conventional year 2035, and flows constituting the airship transportation system and the new LNG-based energy supply system were calculated as 1/10 of the total costs for 10 years (Table 2).

The presented calculation is preliminary and illustrative.

The total estimate of the change in output from the energy sector and the manufacturing industry during the implementation of the project aimed at switching to SSLNG delivered by airships will amount to RUB 58.76 billion per year (Table 2). That is, the costs will be reduced.

Let us consider the economic impact components.

The effect on the manufacturing industry output is positive and will amount to RUB 19.04 billion in 2035. The effect for the LNG industry will be RUB 29.90 billion. This project will also boost the output of the gas processing industry (helium production) and will enhance the airship transportation services in the transportation sector.

As a result of the proposed measures, natural gas consumption in remote areas will go up, and the consumption of petroleum products and coal, as well as the costs for their transportation and logistics, will go down.

The transition from liquid fuel and coal to natural gas will significantly reduce the output of the energy sector. On the one hand, we can expect a significant reduction in the output in the oil refining and transportation industries (particularly regarding Northern Delivery). On the other hand, a large share of current costs can be viewed as subsidies from the budget, which can be reallocated for other purposes. Consequently, the expenses for the population and the housing and utilities sector will not increase, but decrease (in some cases they may decline, while in others, they may remain at the same level).

Another important factor to consider is how many years it will take to pay for the project if the only source of funding is the reduction in subsidies. This issue will be discussed in subsequent papers.

In addition, it is worth noting that the calculations do not factor in the investment phase, which involves developing new related industries for the airship production or loading existing ones.

Calculation of multiplier effects for the project under consideration poses a separate issue, since the airship construction, alongside the SSLNG production and transportation are specialized industries, and generalized industry multipliers [6] are not suitable for their assessment. Moreover, with changes in the structure of the economy, multipliers can also change over time, which should also be considered when assessing long-term projects relying on the products of new sub-industries.

II. Other Uses of Airships

By exemplifying the use of airships for transporting SSLNG, it is shown that under certain conditions, the proposed types of transportation can be both cost-effective and highly sought for. Therefore, it is worth paying attention to other airship application areas.

Further, the ideas of A. A. Konoplyanik and V. V. Voroshilov on the use of airships are partially presented [7].

The two main valuable features of airships lie in their capacity to be transformed into a transport-and-infrastructure vehicle, which makes it possible to transport any cargo to any territory without infrastructure and associated costs, as well as their ability to transport fully-assembled equipment and various other objects, thus reducing the construction and assembly time, and enhancing quality.

The production of airships generates benefits for both producers (new industries and production are created) and consumers, that receive the service cheaper than before. This contributes to the expansion of demand for airship transportation services.

The proposed solutions have the potential to benefit several sectors, including transportation and logistics, oil and gas, forestry, electric power, as well as social and housing construction.

1. *A. Use of airships in mining*

Oil-gas and mining companies could use airships to deliver assembled equipment for geological exploration, drilling, development and maintenance of mineral deposits, and construction of oil and gas processing plants. Deliveries of already assembled equipment will save time and speed up project launches, which means greater economic efficiency. Only commissioning work will be required on site. The same principle could be used to build remote power plants (nuclear power plants, renewable energy sources, thermal power plants) – airships could be used to deliver large blocks assembled at factories to construction sites when they cannot be delivered by other means of transportation. Here, the use is similar to the solution generated by Novatek to manufacture modules for

Table 2. Estimated Output Given Inter-Industry Links for Alternative Conversion of Remote Areas to SSLNG, In 2024 Prices

	Unit of measurement	Quantity	Output, billion RUB
1. Manufacturing industry, including construction			
Production of tank containers and cryogenic tanks	pcs.	166	0.08
Airship production	pcs.	1.5	3.75
Production of pipes for local gas networks and gas equipment, including that for consumers			6.46
Maintenance of gas infrastructure and equipment			3.20
Modernization of generating equipment			2.00
Construction and installation works for SSLNG and airship infrastructure			3.55
2. Energy sector, including transportation			
SSLNG production	billion m^3	2.5	29.90
Helium production	million m^3	0.1	0.50
SSLNG transportation	billion m^3	2.5	25.00
Production of petroleum products (diesel fuel)	million t	-1.5	-89.50
Coal production	million t	-0.7	-3.70
Transportation of oil products and coal (part of the Northern Delivery)*			-30.00
Maintenance of current energy supply			-10.00
Total			-58.76

* Excluding the construction of winter roads
Source: Authors' estimates

the LNG plant in Murmansk. Instead of transporting and assembling modules on-site, they manufacture them off-site, and then deliver to the work location. According to their estimates, this provides savings in costs and time [8].

2. *B. Use of airships in the forest industry*

The use of airships in the forest industry can significantly enhance the efficiency of technological processes by enabling much of the wood pulp processing, including waste management, directly at the felling site. Thus, it is possible to achieve 100% utilization of wood pulp instead of the current 40–50%. This will allow preserving the soil cover of the forest, which is usually severely damaged by logging equipment and haulage vehicles. Technological schemes and mathematical models for the use of airships in the forest industry have already been developed, as evidenced by scientific works [9, 10].

3. *C. Use of airships in the supply sector*

Beyond their specialized application, such as transporting SSLNG, or serving individual industries, airships have potential to deliver essential life support services to remote communities. They can transport not only fuel, water, medicine, mail, and other goods, but also components of socio-cultural and housing infrastructure such as schools, kindergartens, stores, medical, and other institutions of full readiness, which, owing to their block-container design, can reduce the cost and increase the speed of construction. This option can be convenient for both temporary mobile (for example, mobile clinics) and stationary facilities.

4. *D. Specialized use of airships*

A separate strand for the advancement of unmanned cargo airships may be their specialized use, and the unmanned control function will play a key role here. Airships hold significant potential across various sectors, including the space industry, the Internet, communications and radar-location systems, agriculture, and firefighting. In the space industry, unmanned cargo airships could be used to deliver finished products, to assemble products for multiple launches (search and return of the first and second stages of rockets and descent spacecraft), rescue crew, monitor flight trajectory, establish radar systems, and others.

Many remote areas, such as the Northern Sea Route, suffer from inadequate communication infrastructure, including the Internet and radar services. Using airships could contribute to its enhancement in this region, improving emergency response times.

Moreover, airships could be instrumental in firefighting, which is currently carried out by helicopters.

Flying airships with a smaller payload (for example, 2 tons) could be used in agriculture for spraying and applying fertilizers. They can also be utilized for fishing in the northern regions and hunting game in Siberia. In the USSR, An-2 aircraft and Ka-26 helicopters were used for such purposes, but currently unmanned aerial vehicles are an alternative, but they are designed for short-term flights.

III. Conclusions

The use of cargo airships represents a promising opportunity for advancing the transportation industry. Using the example of small-scale LNG, the study has revealed the effects of replacing Northern Delivery with airship transportation of fuel to remote and inaccessible areas. Other applications of the considered aircraft are also proposed and described. To evaluate all the main effects of airship production and use in Russia, it is essential to analyze the demand for airship services across other industries, estimate the costs associated with their production and maintenance, and assess the benefits of using airships in other sectors, factoring in multiplier effects. These elements outline the focus for future research.

References

[1] V. V. Voroshilov, A. A. Konoplyanik, "From transition to gas in the Russian Trans-Urals and Arctic zone to the energy consolidation of Eurasia (part 1)," ECO, vol. 54, no. 2, pp. 236–260, 2024. (In Russian)

[2] Map of the Russian LNG industry 2023. Reference materials. [Online]. Available: http://nasslng.ru/assets/files/spravochnye-materialy-spg-karta-2023.pdf. Accessed on: Sep. 15, 2024. (In Russian)

[3] I. A. Bashmakov, M. G. Dzedzicek, "Assessment of energy supply costs in the regions of the Far North," Energosberezhenie, no. 4, pp. 40–51, 2017. (In Russian)

[4] The Northern Delivery: Life support system for the Far North areas. [Online]. Available: https://vostokgosplan.ru/wp-content/uploads/sevzavoz_digest.pdf. Accessed on: Sep. 15, 2024. (In Russian)

[5] V. V. Molodyuk, “Method for calculating tariffs for CHP plants in the regional market of electric and thermal energy provided the maximum balance profit of all market participants is achieved,” Energosovet, no. 48, pp. 29–36, 2017. (In Russian)

[6] M. Yu. Ksenofontov, A. A. Shirov, D. A. Polzikov, A. A. Yantovsky, “Estimation of multiplier effects in the Russian economy based on input-output tables,” Studies on Russian Economic Development, no. 2, pp. 3–13, 2018. (In Russian)

[7] V. V. Voroshilov, A.A. Konoplyanik, “From transition to gas in the Russian Trans-Urals and Arctic zone to the energy consolidation of Eurasia (part 2),” ECO, vol. 54, no. 3, pp. 205–233, 2024. (In Russian)

[8] A. Ivanter, “Arctic front of NovaTEK: Cold to the rescue,” Expert, no. 4, pp. 38–49, 2023. (In Russian)

[9] G. V. Bernotas, “Mathematical model of the performance of aerostatic transportation systems in the development of inaccessible forest areas,” Engineering Bulletin of the Don, no. 3, p. 154, 2015. Available: https://cyberleninka.ru/article/n/matematicheskaya-model-proizvoditelnosti-aerostaticheskih-transportnyh-sistem-pri-osvoenii-trudnodostupnyh-lesnyh-territoriy. Accessed on: Sep. 10, 2024. (In Russian)

[10] M. E. Akim, E. L. Akim, “Wood and decarbonization under sanctions,” NG-Energy, Nov. 09, 2023. [Online]. Available: https://www.ng.ru/ng_energiya/2023-09-11/13_8823_wood.html. Accessed on: Sep. 10, 2024. (In Russian)

[11] Feasibility study on new generation airships in various sectors of the Russian economy / Available: https://anav.ru/news/tpost/l4timf6la1-tehniko-ekonomicheskoe-obosnovanie-ispol

[12] https://tass.ru/ekonomika/18574551

[13] https://goarctic.ru/news/ozvucheno-nachalo-razrabotki-dirizhabley-dlya-severnogo-zavoza-no-dirizhabli-yakutii-zanimayutsya-et/

[14] https://www.kommersant.ru/doc/6787620

M.S. Gaivoronskaya, a Ph.D. in Economics, is a graduate of Moscow Institute of Physics and Technology. Currently, she is a research fellow at the Laboratory for the Energy Sector Forecasting at the Institute of Economic Forecasting of the Russian Academy of Sciences. Her research interests include energy economics, conversion to gas, and the advancement of the Russian gas industry.

V.V. Semikashev, a Ph.D. in Economics, serves as the Head of the Laboratory for the Energy Sector Forecasting at the Institute of Economic Forecasting of the Russian Academy of Sciences. His research interests include economics of the energy sector industries, forecasting the development of these industries in Russia, and energy policy.

Ranges of Cost-effectiveness of Alternative Energy Carriers for Heating Residential Buildings and Social Facilities

V.A. Stennikov[1,*], V.O. Golovshchikov[1], A.V. Penkovskii[1], and A.B. Osak[1]

[1]Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The energy system of the Irkutsk region has been characterized by excess electricity for many years, since it encompasses several large-scale hydropower and co-generation power plants, and a developed electrical network operating at various voltage levels. In the last three years, the southern part of the region has faced a shortage of electrical power, which has received significant attention and become the subject of discussion and control by federal and regional authorities. The study shows that the shortage of electrical power in the region stems not only from cryptocurrency mining but also from the rapid surge in individual housing construction with electric heating systems. This construction was not coordinated with plans for the development of electrical networks. This paper explores a potential solution to reduce the shortage of electric power by promoting the adoption of natural gas in new individual houses at average Russian prices.**

***Index Terms* — Energy system, shortage of electrical power, crypto mining, electric heating, natural gas.**

* Corresponding author.
E-mail: sva@isem.irk.ru

http://dx.doi.org/10.25729/esr.2024.04.0012

Received September 24, 2024. Acc. December 5, 2024. Available online December 28, 2024.

I. INTRODUCTION

In the last three years, the southeastern part of the Siberian Federal District (SFD), and primarily the southern part of the Irkutsk region, has experienced a shortage of electrical power driven by an increased demand for electricity. This came as a surprise to everyone, because the power grid of the region had always had excess electric power. It includes one and a half dozen large power plants (hydropower and cogeneration power plants) with a well-developed electrical grid infrastructure, including power transmission lines and substations of various voltage classes (from 0.4 to 500 kV). The presence of such a developed infrastructure until now has made it possible to fully provide electricity to consumers in the region, and transmit the excess part of it to neighboring regions: the Republic of Buryatia and the Krasnoyarsk Territory. When considering the problem of shortage, it is necessary to keep in mind, first of all, the shortage of power, since there is currently no shortage of electricity (as an integrated index) in the Irkutsk region. The country has consistently faced a temporary and localized shortage of electrical power, resulting from inaccurate consumption forecasts, inadequate development of electrical networks, and failure to implement plans for the construction of energy facilities. The most important factor, however, which has been characteristic of decision-making in the last 30 years, is the lack of a systems approach when analyzing the current situation and generating solutions for the development of the electric power industry. In particular, the studies previously conducted by the Melentiev Energy Systems Institute of the Siberian Branch of the Russian Academy of Sciences (ESI SB RAS), which involved a systems analysis of internal and external challenges, revealed negative trends in the emergence of a shortage of electrical power. However, no one paid enough attention to this. The current power shortages occur primarily during the autumn and winter months, when demand for electricity is at its peak. They are localized in areas with developed economies and social infrastructure, which are the primary consumers of electricity.

The escalating severity of the power shortage issue required its consideration not only at the regional level, but also at the level of the Siberian Federal District and the Federation [1]. To this end, meetings, conferences, round tables, and other events of various levels involving participants of diverse backgrounds and expertise are periodically held to address electrical power shortages in the Irkutsk region and the potential risk of facing them in other regions of the southeastern part of the Siberian Federal District.

II. Reasons for the Growth of Electric Power Shortage in the South of Eastern Siberia and the Siberian Federal District

The severity of the electrical power shortage problem in the region under consideration is partly confirmed by the Development Scheme and Program (DSP) materials, which are formulated by the System Operator of the Unified Energy System (SO UES) of the Russian Federation. According to the data of DSP extended for the period of 2024–2029, the power shortage is expected in 2028 (1 100 MW) and 2029 (1 225 MW) (equal to the capacity of two Irkutsk hydropower plants) with its further growth in subsequent years. According to the forecasts of SO UES of the Russian Federation, by 2030, the maximum consumption of overall power in the Irkutsk region may reach 13 GW (13 000 MW), which is almost equal to the installed capacity of all power plants in the Irkutsk region. The peak power consumption in the Irkutsk region power system, 10 168 MW, was recorded on December 13, 2023. The analysis reveals that the main reasons for the increase in power consumption in the Irkutsk region are: 1) the unforeseeable rise in power demand driven by cryptocurrency mining; 2) an escalated power consumption from the population, including electric heating and household electricity use. A significant rise in power consumption for mining is due to low electricity rates (prices) in the Irkutsk region compared to the average values for Russia, while the growing consumption from population is due to the lack of alternatives, in particular gas supply. At the same time, mining is conventionally divided into “white” mining, where mining farms are registered as legal entities, and “gray” mining, which is carried out at the household level by both legal entities and individuals. In the case of “gray” mining, electricity is paid for at the same rates as the population. According to the Regional Dispatch Office of the Irkutsk region (part of the SO UES of the Russian Federation), the total consumption of electrical power in 2023 by “white and gray” mining was about 800 MW. It is worth noting that periods of cold weather in the region also contributed to the increased peak electricity consumption by the population, especially due to electric heating.

The critical situation unfolding in the south of the Irkutsk region necessitates its careful analysis and the development of specific proposals to minimize the power shortage. The implications of these proposals should be the construction of new generating sources, the development of electrical networks, and the adoption of organizational and legislative measures, considering the DSP developed by SO UES of the Russian Federation [2, 3].

Detailed analysis of cryptocurrency mining and its impact on the electrical power shortage problem in the Irkutsk region and other regions of the Russian Federation, primarily in the south of Eastern Siberia, requires separate consideration. However, it should be emphasized that the distribution of cryptocurrency mining is increasing in the Russian Federation, despite the cost of electricity to power mining equipment. For example, the power consumed by mining in the Krasnoyarsk Territory exceeded the power consumed by mining in the Irkutsk region. The release of a federal law regulating cryptocurrency mining in the Russian Federation at the beginning of August 2024 brings hope of alleviating the problem of power shortages, since it prohibits this type of activity in regions with a shortage of electrical power [4].

Before the advent of mass mining in the Irkutsk region, the primary factor driving the surge in electricity consumption in the south of the region was the rapid growth in the demand for power from individual households (for electric heating and domestic needs) and the social infrastructure. The reasons for this were the desire to improve comfortable living conditions, the active process of relocation to individual houses built in suburban areas, affordable rates for the population of the Irkutsk region, and the absence of gas infrastructure in the area. As a result, a significant overload occurred in the electrical distribution networks, especially those operating at 35 kV and below. The increased load led to emergency situations and a widespread inability to meet the demand of many hundreds of consumer applications for technological connection to networks within a reasonable timeframe. To date there have been over seven thousand applications that have been refused.

The Socio-Economic Development Strategy (SEDS) of the Irkutsk region until 2036, which was approved at the beginning of 2022, predicts a demand for electrical power in the amount of 29 MW. The document also outlines the plans for the construction of 1.3 million m^2 of individual housing. However, by the beginning of 2023, the number of concluded contracts for technological connection had exceeded 10 thousand, resulting in an increase in power of about 155 MW. In that situation, many substations were unprepared for such a rise in loads, which led to their overload significantly exceeding the standard values for these substations (there are about 50 such substations in the southern part of the Irkutsk region).

The power shortage and the necessity to develop measures to reduce it in individual housing construction (IHC) were assessed by ESI SB RAS upon the instructions from the Administration of the Irkutsk region. The institute examined the necessary power consumption levels for various types of individual houses (for example, with an area of 100 m^2) in the Irkutsk region. The analysis was carried out for the three most common options of structures: wooden beams, brickwork, and aerated concrete. Each option was considered with and without additional thermal insulation in accordance with the approved regulatory framework for design and construction in the Russian Federation, taking into account the climatic conditions of the Irkutsk region. Calculations and analysis of their results show that the electrical power required for the considered house options is about 25–30 kW (including household power consumption). If we assume that 25 thousand houses in the Irkutsk region (approximate estimate for city suburbs and partly for rural settlements) have individual electricity supply, then about 700 MW of power (the power of the Irkutsk hydropower plant) will be required. If at least half of the houses do not have high-quality thermal insulation (which is actually observed) or they are panel-built, the required power will increase by 40%. The problem of electrical power shortage is likely to worsen, since, with the emerging trends in the credit policy of the Russian Federation, individual housing construction is becoming virtually the only opportunity for the population to acquire homes. With the new standards of mass individual housing construction, it is necessary to strive to increase energy efficiency of housing, since energy-saving measures will reduce the electricity consumption by 200−250 MW.

Electric heating is a specific feature not only of the Irkutsk region. For example, electric heating will be feasible in the cities in Russia such as Krasnoyarsk, Ulan-Ude, and others. In this context, it is interesting to note that the Republic of Belarus planned to predominantly develop electric heating, with the exception of territories with district heating and central gas supply, as stated in Resolution of the Council of Ministers of the Republic of Belarus No. 899 of November 28, 2017.

As noted above, the most effective way to reduce (or even completely eliminate for a certain period of time) the shortage of electrical power, without harming the interests of consumers, is the modernization and development of generating sources and electrical networks. However, the modernization and construction of new electric power facilities are a lengthy and highly costly process. Moreover, it must begin with the energy systems themselves. It is unlikely that calls to save electricity in all areas of activity in the Russian Federation will help. Increasing electricity rates for the population, especially to tackle the issue of the so-called “cross-subsidization” (which seems far-fetched), is unacceptable, as it can lead to adverse social consequences.

III. Analysis of the Cost-Effectiveness of Alternative Energy Carriers for Heating Residential Buildings and Social Facilities

The level of gas infrastructure development in many regions of the Russian Federation, with the exception of Eastern Siberia and partly the Far East, reaches 90%. This enables a widespread utilization of gas as the primary energy source for heating and household needs, resulting in a significant reduction in electricity consumption. The Krasnoyarsk Territory, the Republic of Khakassia, the Republic of Tyva, the Republic of Buryatia, the Trans-Baikal Territory, and especially the Irkutsk region, which hold vast reserves of natural gas, lack proper gas infrastructure. For example, the level of gas infrastructure development in the Irkutsk region is no more than 1.1–1.2% [5]. The expansion of gas infrastructure in the region could significantly reduce the shortage of electrical power in its southern part. Unfortunately, the timing of gas infrastructure development in the Irkutsk region is unknown due to the uncertain period for the construction of the Power of Siberia 2 gas pipeline. The Government of the Irkutsk region instructed the ESI SB RAS to assess the cost-effectiveness of various energy resources (energy carriers) for heating individual houses and social facilities. The aim is to evaluate the competitiveness of alternative options, with the view to reducing electric heating and, thus addressing the power shortage in the southern part of the Irkutsk region. The energy resources chosen for the analysis were electric heating, firewood, pellets, liquefied petroleum gas (LPG), and liquefied natural gas (LNG). All calculations were carried out for two price brackets for each resource (approximate estimates as of the beginning of 2024). Based on these calculations, the cost-effectiveness ranges were determined for alternative energy carriers through their intercomparison, aiming to identify a fuel type that is most beneficial to consumers. Integrated indices were calculated for the materials used for the enclosing structures of an individual residential building. These materials were wooden beams, bricks, and aerated concrete. Calculations were carried out for two values of the electricity cost in the Irkutsk region (since July 01, 2024): RUB 1/kWh (rate for the rural population) and RUB 1.58/kWh (rate for the population categories other than rural). The calculations show that the most expensive energy supply option for an individual residential building is heating with wood at a price range of RUB 4 000/m^3 (RUB 8 000/t) to RUB 5 000/m^3 (RUB 10 000/t), and the cheapest one is heating with coal, with a price range of RUB 3 000/t to RUB 5 000/t. The cheap coal in the Irkutsk region is a factor hindering the development of gas infrastructure in the region. According to the Ministry of Energy of the Russian Federation and JSC Gazprom, any option of gas infrastructure development in the Irkutsk region will be cost-ineffective compared to a coal-based scenario. However, there is a certain understanding that the federal "clean air" program cannot be implemented in the Irkutsk region without gas infrastructure development. The use of pellets is inferior in economic efficiency to the use of electricity and coal, but more profitable than the use of LNG and LPG. A comparison of the electricity and LNG options for the population shows that equal economic efficiency of LNG at price brackets of RUB 12 728 /m^3 and RUB 14 098/m^3 will only be possible if the cost of electricity in the Irkutsk region rises to RUB 2.82/kWh and RUB 3.09/kWh, respectively.

Estimations were also made to compare the costs of electric heating and piped gas heating for the consumers of the category "population", provided the gas infrastructure appears in the Irkutsk region (for example, the construction of the Power of Siberia 2 gas pipeline). According to the Ministry of Housing Policy and Energy of the Irkutsk region and the Tariff Service of the Irkutsk region, electricity consumed for electric heating needs in the Irkutsk region amounted to 3.43 billion kWh in 2023. Annual costs (payments by the population) at a rate of RUB 1.42/ kWh (at the beginning of 2024) amounted to RUB 4.87 billion. The equivalent consumption of piped gas for heating will be 365.5 million m^3 annually. Annual expenses of the population at an average cost of gas in the Russian Federation of RUB 7.4/ m^3 and provided that the entire gas distribution infrastructure is established in the Irkutsk region, would amount to RUB 2.71 billion annually. Consequently, financial losses (the so-called "lost profit") for the population would amount to RUB 2.16 billion annually. With the electricity rate in the Irkutsk region equal to the Russian average at the level of RUB 4/kWh, the "lost profit" would increase more than five times and could amount to more than RUB 11 billion annually. The above calculations indicate that the use of piped gas for heating in individual homes can significantly reduce the heating cost for the population and decrease the reliance on electricity for electric heating, which in turn will help reduce the shortage of electrical power.

IV. Conclusion

1. The calculations have revealed that for any option of energy supply to an individual residential building, heating with wood is the most expensive option, while heating with coal is the cheapest one. The use of coal as an option appears unpromising due to environmental problems and its significant consumption stemming from a lower calorific value of coal compared to natural gas.

2. The use of piped gas from the main gas pipeline and LNG (the situation with which is very uncertain) can only

be economically feasible if the average price for piped gas in Russia is RUB 7.4/m^3 and an electricity rate is RUB 0.78/kWh. In this case, the gas infrastructure development will alleviate the electricity shortage issues by reducing the volume of electric heating. With the current electricity rate of RUB 1.42/kWh, the "lost profit" (financial loss) in the case of electric heating will amount to more than RUB 2 billion annually. The use of gas for heating significantly reduces the shortage of electrical power and improves the environmental situation, although CO_2 emissions remain.

3. The implementation of all options of fuel types in question depends on their price and calorific value, which can vary within wide limits, including those for liquefied petroleum gas (LPG). The use of LNG and LPG can become economically profitable with a significant increase in electricity rates. Preliminary estimations, including calculations of "lost profit" (financial loss) for the population, allow authorities to make informed decisions about the energy supply to the affected areas, particularly with regard to piped gas under the conditions of uncertainty.

4. The use of electricity for heating purposes (plus consumption by household appliances) is an effective option for supplying energy to individual households at current prices for energy resources in the Irkutsk region, especially considering environmental requirements.

5. Clarification and detailing of the research data are included in the Energy Strategy of the Irkutsk Region (until 2036 and beyond until 2050), currently being developed by the ESI SB RAS.

Acknowledgment

The work was carried out within the framework of the project under State Assignments No. FWEU-2021-0001 and No. FWEU-2021-0002 of the Program of Fundamental Research of the Russian Federation for 2021–2025.

References

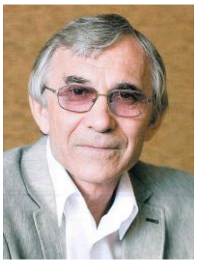
[1] "Putin instructed to take measures to prevent a shortage of electricity in the southeast of Siberia," Tass.ru, May 10, 2023. [Online]. Available: https://tass.ru/ekonomika/17715835. Accessed on: Jun. 05, 2024. (In Russian).

[2] V. A. Stennikov, V. O. Golovshchikov, "Energy industry of the Irkutsk region: trends, challenges, and threats in the current context," Energy Policy, no. 12(178), pp. 56–71, 2022. DOI: 10.46920/2409-5516.2022_12178.56. (In Russian).

[3] V. A. Stennikov, V. O. Golovshchikov, O. B. Osak, "Problems and prospects for the development of electric power industry in the eastern regions of Russia," Energy Policy, no. 6(184), pp. 20–37, 2023. (In Russian).

[4] Federal Law of the Russian Federation (2024, Aug. 08). No. 221-FZ, On Amendments to Certain Legislative Acts of the Russian Federation. [Online]. Available: www.consultant.ru/document/cons_doc_LAW_482417. Accessed on: Aug. 05, 2024. (In Russian).

[5] V. A. Stennikov, V. O. Golovshchikov, "Challenges and prospects for development of gas industry in the Siberian federal district," Energy Policy, no. 12(191), pp. 24–37, 2023. DOI: 10.46920/2409-5516_2023_12191_24. (In Russian).



V.A. Stennikov, D.Eng., an Academician of the Russian Academy of Sciences, Professor, is the Director of the Melentiev Energy Systems Institute (ESI SB RAS). His research interests include systems research in the energy sector, theory of hydraulic circuits, mathematical modeling, optimization methods, heat supply systems, district heating systems, cogeneration, reliability, energy efficiency, energy saving, and intelligent energy systems. V. Stennikov has authored and co-authored over 500 scientific publications.

V.O. Golovshchikov, Ph.D., serves as the Chief specialist of ESI SB RAS, specializing in electric power systems. His research interests include the operation and expansion of electric power systems, particularly in competitive market environments. V.O. Golovshchikov has authored and co-authored over 50 scientific papers, 3 monographs, and 2 USSR copyright certificates for the invention of methods and devices for controlling facilities within electrical power systems.

A. V. Penkovskii, Ph.D., serves as a Senior Researcher in the Subdepartment of Heat Supply Systems at ESI SB RAS, Irkutsk, Russia. He received the Ph.D. degree in engineering from ESI SB RAS in 2017. His research interests include energy systems, district heating systems, mathematical modeling, energy markets, optimization methods, energy efficiency, the prosumer concept, and game theory. A. Penkovskii has authored and co-authored over 140 scientific publications.

A. B. Osak serves as the Head of the Electric Power Sector at ESI SB RAS. His research interests include optimization of operation and expansion of electric power systems, electric power shortfalls and methods to overcome them. A. Osak has authored and co-authored over 20 scientific papers, 3 monographs, 4 patents for inventions, and 3 certificates of registration of computer programs.

Field Studies of Technologies for Reducing Frost Heaving of Line Supports in the Conditions of the Republic of Sakha (Yakutia)

K.N. Bolshev[1,3,*], V. M. Efimov[2], V.M. Belyakov[3], A.S. Unzhakov[4]

[1] V.P. Larionov Institute of the Physical-Technical Problems of the North of the Siberian Branch of the RAS, Yakutsk, Russia
[2] Yakutsk Design Research Institute of Construction, Yakutsk, Russia
[3] Ural Plant of Polymer Technologies "Mayak", Chelyabinsk, Russia
[4] PJSC "Yakutskenergo", Yakutsk, Russia

***Abstract* – Frost heaving of power transmission line supports in regions with permafrost soils directly affects the reliability and uninterruptible operation of power supply systems. The article provides information on the work on field studies of the effectiveness of using anti-heaving coatings and shells "Reline" in application to wooden and concrete foundations of overhead power transmission line supports to reduce the tangential forces of frost heaving of soils in the climatic and geocryological conditions of the Republic of Sakha (Yakutia). During the work, a test site was set up on a heaving site in the city of Yakutsk, 12 cycles of monitoring the altitude position of the support foundations and the temperature regime of the soil were carried out. The obtained results demonstrate the efficiency of using the tested coatings in the conditions of the Republic of Sakha (Yakutia).**

The work was carried out by Yakutsk Design Research Institute of Construction and Ural Plant of Polymer Technologies "Mayak" by order of PJSC "Yakutskenergo".

[*] Corresponding author.
E-mail: k.bolshev@mail.ru

http://dx.doi.org/10.25729/esr.2024.04.0013

Received October 18, 2024. Acc. November 18, 2024. Available online December 28, 2024.

***Index Terms* – Overhead conductors, permafrost, line supports, frost heaving, anti-heaving coatings.**

I. Introduction

Operation of overhead conductors in the complex geocryological conditions of the Republic of Sakha (Yakutia) is associated with a number of features and problems, one of which is frost heaving of supports. Frost heaving is caused by freezing and expansion of moisture in a closed volume of soil pores during periods of negative air temperatures. In addition to the expansion of water during freezing, liquid water is drawn to the freezing front, due to which the degree of vertical displacement of the soil can be significantly greater than the volumetric expansion of the freezing water [1–3]. The occurrence of incoming frost heaving creates strong stresses (tangential and normal) aimed at pushing the supports out of the soil volume Studies show that the intensity of heaving is influenced by many factors, the main ones being the heaving of the soil [4–6], its humidity [7, 8], salinity and content of organic components [9, 10], as well as the freezing rate [6, 11, 12]. The latter factor is especially characteristic of the extreme climatic conditions of the Republic of Sakha (Yakutia), as a result of which frost heaving processes occur faster and more intensively.

For low-load structures, which line supports are, the heaving forces, exceeding the load on the support, change its design position in environment, creating a risk of collapse. The change in the position of the support has both a cyclical nature, with a rise in the cold season and a lowering in the warm season, and a progressive nature, when the height of the support extrusion increases every

Fig. 1. PSPP "Reline" anti-heaving polymer coating for piles.

year.

In regions with permafrost soils, deformations of transmission line supports due to frost heaving are widespread, which leads to an emergency situation. Heaving deformations of pile foundations are observed both on thawed and permafrost soils, including low-temperature soils (below –2C°) [13, 14]. This is confirmed by the results of inspections of overhead power line supports in Yakutsk, showing that one of the main causes of deformations is strong and excessive heaving of the soils of the active layer. At the same time, the average heaving rate of untreated support foundations (footings) in heaving soils is 10 cm/year. The critical heaving value is 50 cm, i.e. the service life of support adjuncts in heaving areas does not exceed 5 years on average. After which either the support collapses and subsequent emergency restoration work occurs, or it is routinely dismantled and a new one is installed. Both the first and second developments entail interruptions in supply and power outages for the duration of the emergency response or scheduled maintenance on the lines.

Thus, solving the frost heaving problem will not only significantly increase the service life of the foundations of the transmission line supports, directly reducing the costs associated with emergency recovery and repair work, but also reduce the number of interruptions in supply and undersupply of electricity, increasing the overall reliability of power supply systems. This is especially relevant for the conditions of the Far North, where uninterrupted power supplies are very important for life support systems.

Methods for reducing frost heaving forces or anti-heaving measures are divided into three types [15]:

- meliorative, which reduce soil moisture content or prevent its water saturation;
- chemical, examples of which may be soil hydrophobization with binders, lowering the freezing temperature of pore moisture with salt solutions or introducing polymer additives into the soil that compensate

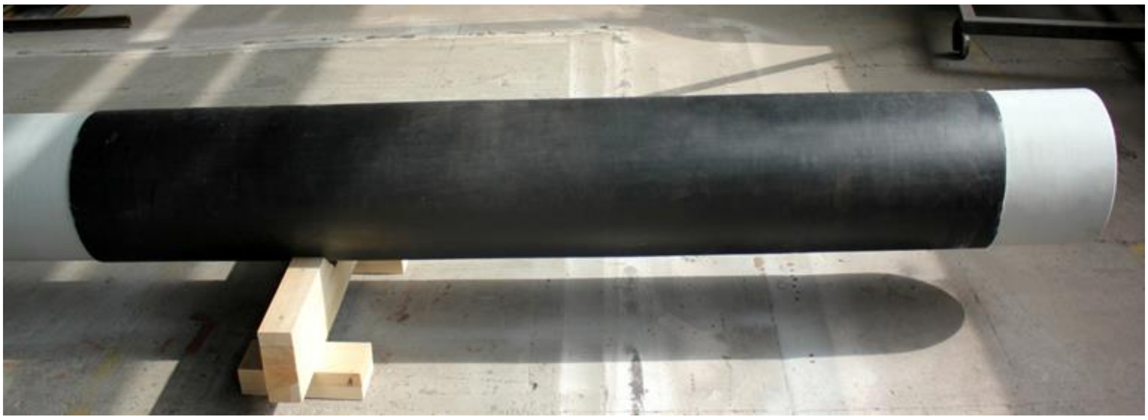


Fig. 2. OSPT "Reline" anti-heaving heat-shrinkable shell for piles.

for soil heaving when moisture freezes;

- construction and structural, which consist of increasing the depth of the foundation, adapting the above-ground parts of the structure to heaving deformations and reducing the forces and deformations of heaving.

The last group includes methods for reducing tangential heaving forces by creating a sliding surface on the underground part of the supports.

One of these technologies is the “Reline” polymer coatings and shells developed and produced by Ural Plant of Polymer Technologies “Mayak”.

The PSPP “Reline” anti-heaving polymer coating for piles (Fig. 1) is a protective layer made of modified polymer epoxy material, which after application and hardening creates a durable coating resistant to various impacts.

The OSPT “Reline” anti-heaving heat-shrinkable shell for piles (Fig. 2) is a two-layer sleeve consisting of a heat- and light-stabilized, cross-linked and longitudinally oriented polyolefin composition and an adhesive sublayer based on modified hot-melt adhesive compositions.

II. Methodology

The field studies were conducted in order to determine the efficiency of using “Reline” coatings and shells for wooden and concrete foundations of line supports in reducing the tangential forces of frost heaving of soils in the climatic and geocryological conditions of the Republic of Sakha (Yakutia). To conduct the studies, a test site was equipped in an area with heaving soils in the city of Yakutsk.

The methodology and testing were carried out in three stages:

1. Preparatory stage, including:
   - conducting engineering and geological surveys at the site of field tests to determine its geological and geocryological conditions;

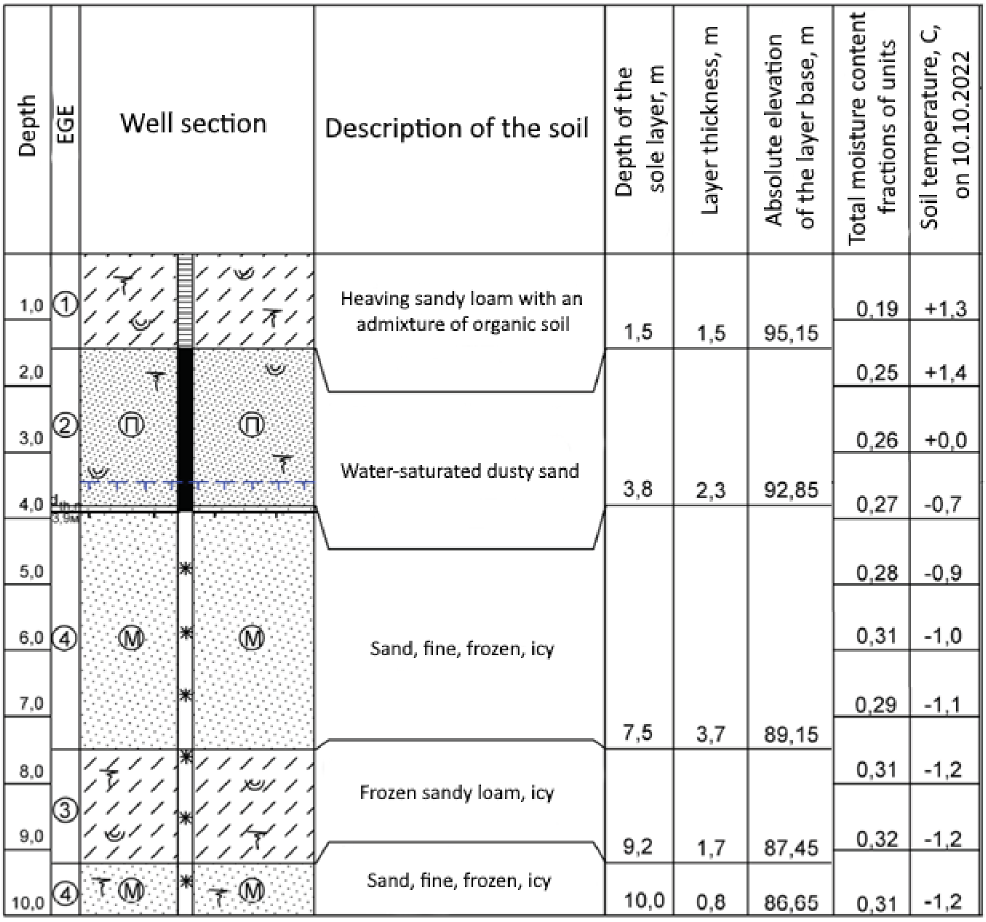


Fig. 3. Engineering and geological section of the field test site.

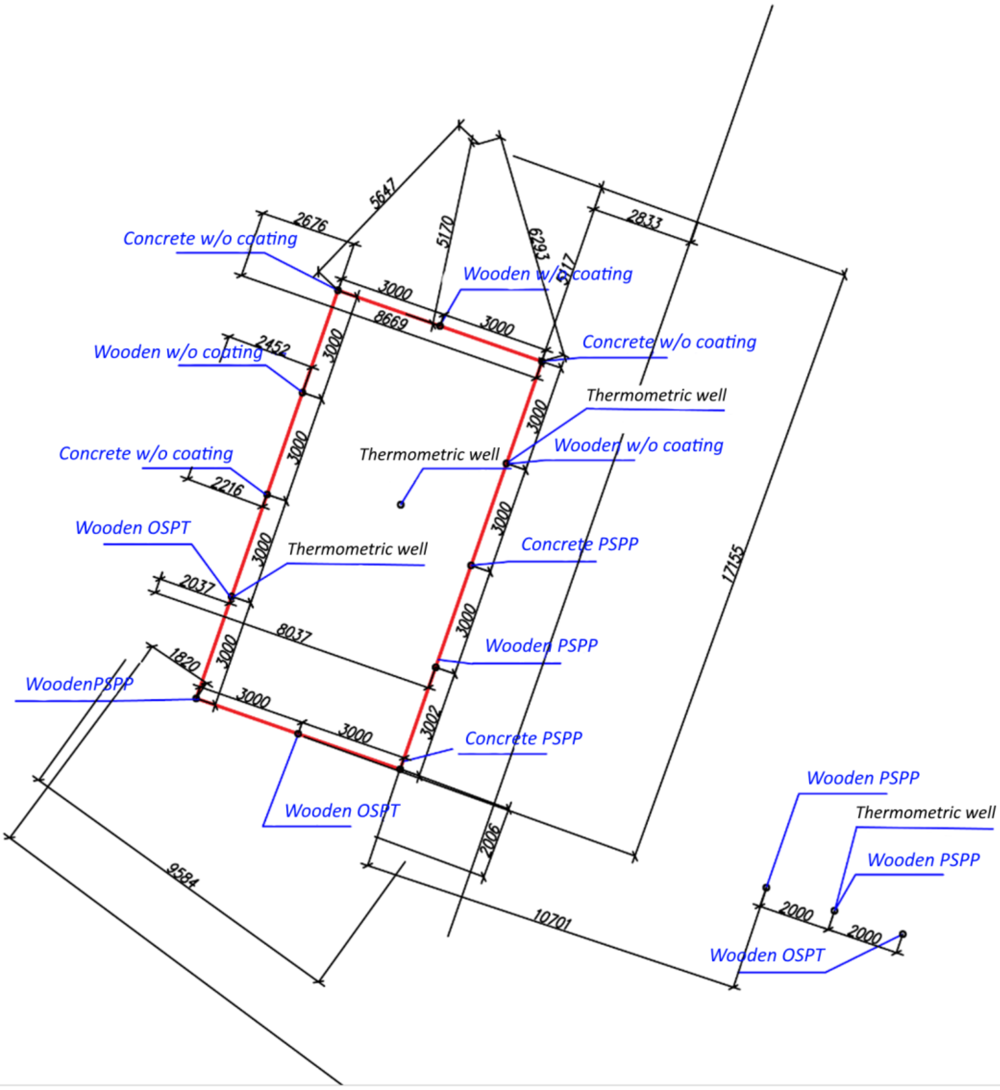


Fig. 4. Layout of the samples of line supports foundations (footings) at the site of field tests.

- selection and description of the test foundations of supports (footings) with options for the design of anti-heaving coatings;
- normative calculations of footings for bearing capacity and resistance to tangential forces of frost heaving in specific engineering and geocryological conditions;
- determination of the test load on the foundations;
- test site equipment sequence;
- requirements and conditions for conducting tests;
- program of visual and instrumental monitoring.

2. Stage of visual and instrumental monitoring, including:

- visual survey;
- instrumental determination of vertical displacements;
- soil temperature measurements in thermometric wells.

3. Final stage, including:

- processing, analysis and presentation of test results;
- preparation of a scientific and technical report (upon completion of the experimental part).

Figure 3 shows the results of engineering and geological surveys, showing that the geological section of the site is represented by four engineering and geological elements: highly heaving sandy loam with an admixture of organic matter, silty water-saturated sand, saline icy sandy loam

Fig. 5. The way of fastening the ballast to transfer the test load to the footings.

with an admixture of organic matter and fine, icy sand.

Based on the experience of use in the Republic of Sakha (Yakutia), 2 types of foundations (footings) for line supports were selected as test foundations (footings):

- PT-60 reinforced concrete footing according to series 3.407-57/87;

- wooden footing made of larch according to GOST 9463-2016 [16].

For each footing type, tests are carried out for samples without a special anti-heaving coating and samples with an applied OSPT anti-heaving coating (wooden footing) and PSPP (reinforced concrete and wooden footing) of the Reline series. According to the design documentation for the construction of various line supports, the typical depth of immersion of the footing into the ground is 4.0 m.

Thus, the following types of footings for transmission line supports were installed:

- PT-60 reinforced concrete footing without anti-heaving coating – 3 pcs.;

- PT-60 reinforced concrete footing with the “Reline” PSPP coating – 3 pcs.;

- wooden footing made of larch without anti-heaving coating – 3 pcs.;

- wooden footing made of larch with the “Reline” OSPT coating – 3 pcs.;

- wooden footing made of larch with the “Reline” PSPP

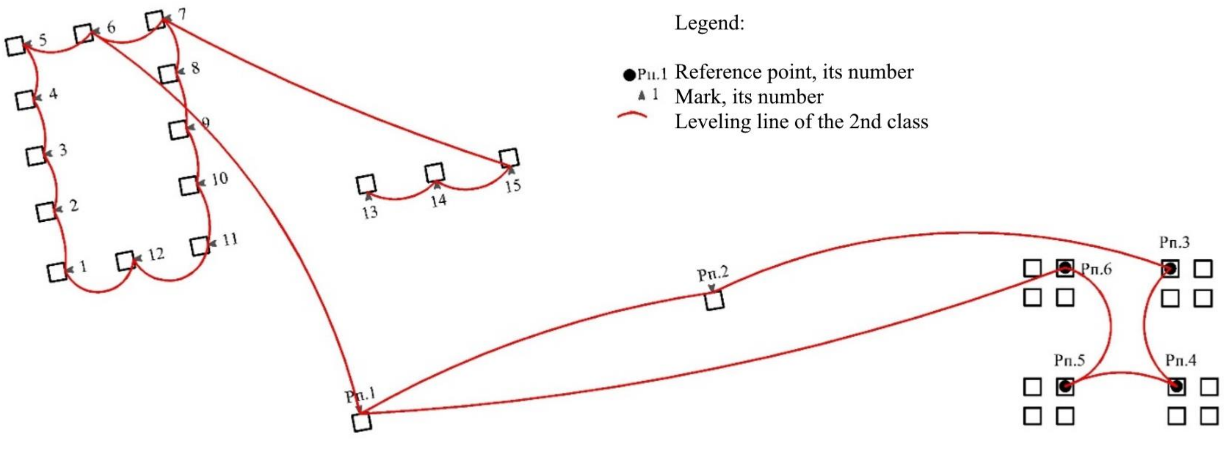


Fig. 6. The layout of reference points and deformation marks.

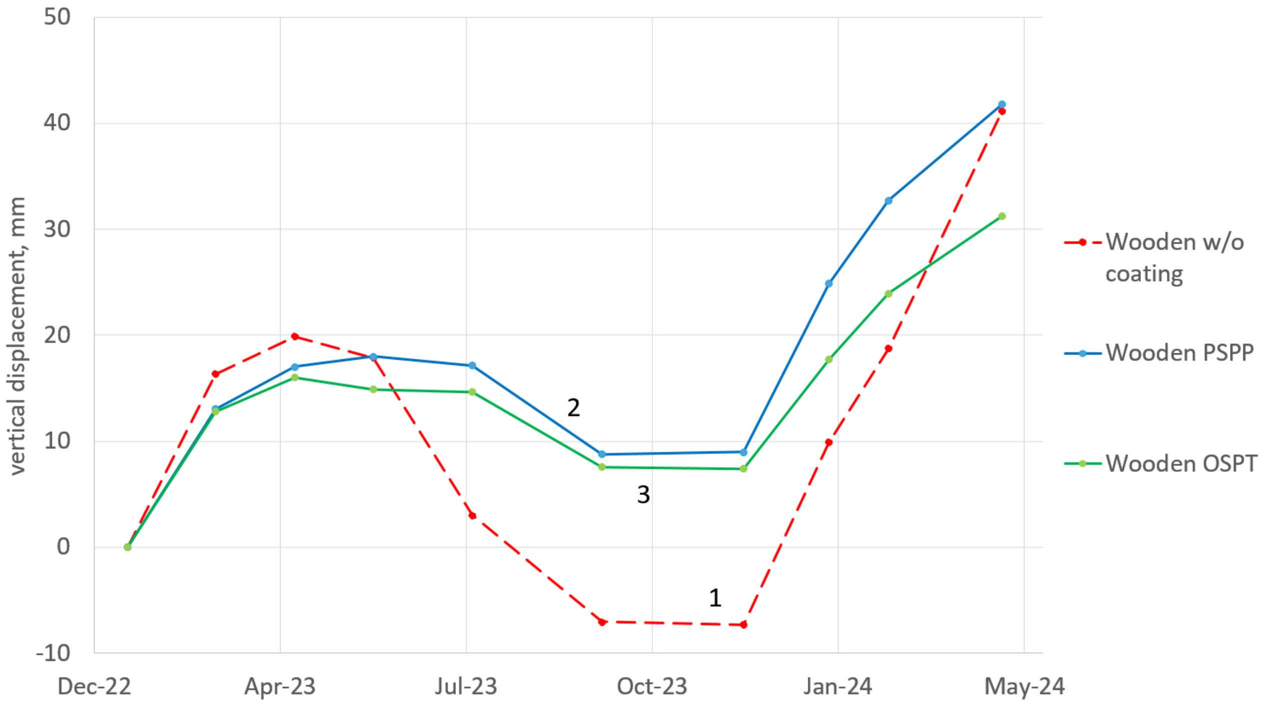


Fig. 7. Averaged data on vertical displacements of larch footings.

coating – 3 pcs.;

The layout of the samples of line supports foundations (footings) at the site of the field tests is shown in Fig. 4. Four thermometric pipes were also installed to monitor the temperature at the depth of the footings:

According to standards, the weight of the tested line supports with associated elements is:

- for a support on a reinforced concrete footing – 0.454 tons;

- for a support on a wooden footing – 0.375 t.

The footings were loaded with corresponding test load using concrete ballasts, the method of fastening the ballast is shown in Fig. 5.

During the preparatory work, PSPP coatings were applied to the tested footings and OSPT “Reline” shells were installed. Anti-heaving coatings were applied taking into account the estimated depth of seasonal freezing of 3.9 m.

The vertical displacements of the footings were determined using the geometric leveling method of class II in accordance with GOST 24846-2019 [17]. The layout of reference points and deformation marks is shown in Fig. 6.

The soil temperature was measured using a multi-zone digital temperature sensor (MDTS) in accordance with GOST 25358-2020 [18].

III. Results

In total, 11 cycles of monitoring vertical displacements of the footings and 7 cycles of soil temperature measurements were performed during the field tests from December 2022 to April 2024.

The effectiveness of anti-heaving coatings was assessed based on a comparative assessment of the vertical displacements of attachments with anti-heaving coatings and without coatings.

The comparison of vertical displacements was taken based on the average values for each of the installed groups of the footings - the second cycle (January 12, 2023), performed after the installation of test loading ballasts and stabilization of the vertical position of the attachments, was taken as the zero reading of vertical displacements.

Figure 7 shows the average values of vertical displacements for larch footings. Line 1(a dotted line), corresponds to the average displacement of footings without an anti-heaving coating. Line 2 corresponds to the average displacement of footings with the PSPP anti-

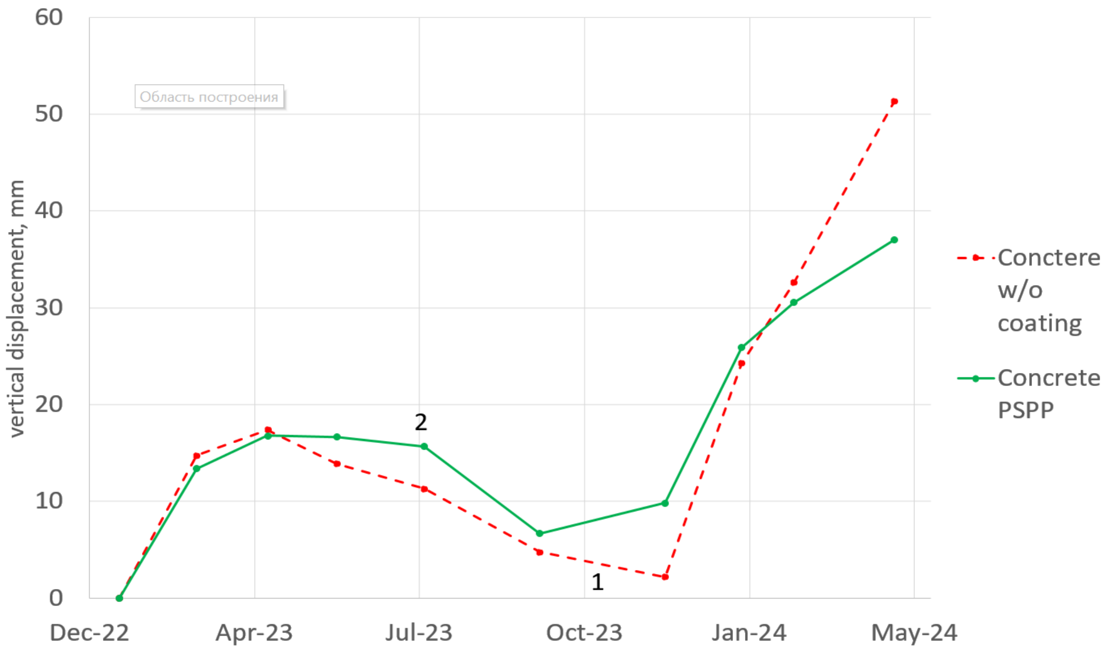


Fig. 8. Averaged data on vertical displacements of concrete footings.

heaving coating, line 3 – the average displacement of footings with the OSPT shell.

Figure 8 shows the average values of vertical displacements for concrete footings. Line 1 (a dotted line), corresponds to the average displacement of footings without an anti-heaving coating. Line 2 corresponds to the average displacement of footings with the PSPP anti-heaving coating.

The effectiveness of anti-heaving coatings was assessed as a percentage for two heaving periods:

- from January 12, 2023 to April 12, 2023, from the moment of stabilization of the vertical position to the peak value of the footing displacement;

- from September 24, 2023 to April 26, 2024, from the beginning of the cold season to the peak values of heaving, based on the data obtained in 2023.

The analysis of the research data is given in Table 1. Since the first heaving period from the moment of site arrangement in January 2023 was only 90 days, the second period, the duration of which is 215 days, provides more complete data.

IV. Conclusions

The obtained results show that in the soil conditions of the test site, the surface heaving soil layer of which consists of sandy loam with an admixture of organic matter with a

Table 1. Comparison of Vertical Displacements for Two Heaving Periods

Footing type	January 2023 – April 2023		September 2023 – April 2024	
	Vertical displacement, mm	Reduction of heaving effect, %	Vertical displacement, mm	Reduction of heaving effect, %
Wooden w/o coating	19.88		48.18	
Wooden PSPP	17.03	14.4	33.07	31.4
Wooden OSPT	16.00	19.6	23.70	50.8
Concrete w/o coating	17.41		46.59	
Concrete PSPP	16.77	3.6	30.39	34.8

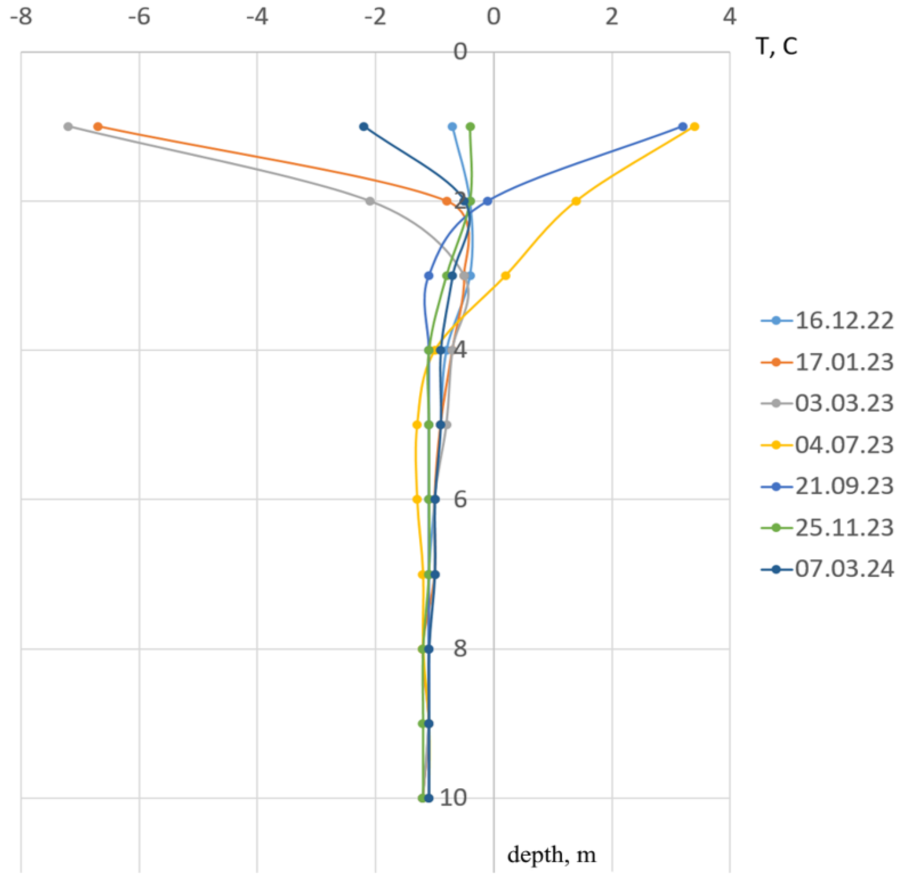


Fig. 9. Results of measurements in a thermometric well in the center of the test site.

total moisture content of 19% to a depth of 1.5 m, and silty sand with a total moisture content of 25–27% to a depth of 4 m, the PSPP coating on average reduces the frost heaving of larch and concrete footings of line supports by 31.4–34.8%, and the OSPT coating reduces the frost heaving of larch footings of line supports by 50.8% during the heaving period from September to April.

Thus, it can be concluded that the results obtained during the field studies allow us to positively assess the effectiveness and confirm the prospects for using the "Reline" PSPP and OSPT anti-heaving coatings in the cryolithozone of Yakutia.

References

[1] S. Taber, "Frost Heaving," Journal of Geology, vol. 37, no. 5, pp. 428–461, 1929.

[2] S. Taber, "The mechanics of frost heaving," Journal of Geology, vol. 38, no. 4, pp. 303–317, 1930.

[3] S. S. L. Peppin, R. W. Style, "The Physics of Frost Heave and Ice-Lens Growth," Vadose Zone Journal, vol. 12, no. 1, pp. 1–12, 2013. DOI: 10.2136/vzj2012.0049.

[4] State Standard 25100-2020. Soils. Classification. Moscow, Russia: Standartinform Publ., 2020, 37 p. (In Russian)

[5] B. I. Dalmatov, The impact of frost heaving of soils on the foundations of buildings. Leningrad, USSR: Gosstroyisdat, 1957, 60 p. (In Russian)

[6] A. V. Boyarintsev, A. Y. Shorina, E. S. Rodionova, V. A. Matyushina, "Experimental Determination of Frost Heaving Speed for Various Types of Soils According to the Degree of Heaving," in Proceedings of ARCTD 2021. Lecture Notes in Civil Engineering, vol. 206, E. Rybnov, A. Nikolaev, O. Skotarenko, Eds. Springer, Cham, 2023. DOI: 10.1007/978-3-030-99626-0_22.

[7] Zh. Dong, Li. Xu, Sh. Ruslan, A. Ermolina, "Experimental study on the influence of initial water saturation on segregation frost heaving behavior in silty clay columns," in Proc. 6th International Symposium on Civil Engineering of Soil Structures in Transport in Cold Regions (TRANSOILCOLD 2023), Moscow, Russia, Oct. 2–5, 2023. Moscow, Russia: Publishing and Trading Corporation "Dashkov i K," 2023, p. 54.

[8] N. A. Citovich, Foundations and bases on frozen soils. Moscow, USSR: USSR Academy of sciences, 1958, 168 p. (In Russian)

[9] L. Wang, "Experimental Study on Frost Heave Characteristics of Silty Clay Beneath Operating Stations in Twin Tunnel Freezing," in Advanced Construction Technology and Research of Deep-Sea Tunnels. Lecture Notes in Civil Engineering, vol. 490. G. Mei, Z. Xu, F. Zhang, Eds. Springer, Singapore, 2024, pp. 245–256. DOI: 10.1007/978-981-97-2417-8_22.

[10] R. Bai, Y. Lai, W. Pei, M. Zhang, "Study on salt-frost heave characteristics, improvement effect, and curing mechanism of loess-like sulphate soil," Cold Regions Science and Technology, vol. 224, 103525, 2022. DOI: 10.1016/j.coldregions.2022.103525.

[11] N. A. Puzakov, Water-thermal regime of the roadbed. Moscow, USSR: Avtotransisdat, 1960, 166 p. (In Russian)

[12] L. T. Roman, Mechanics of frozen soils. Moscow, Russia: MAIK Nauka/Interperiodika, 2002, 426 p. (In Russian)

[13] A. L. Lyazgin, et al., "Leveling of pile foundations of transmission line supports by the method of controlling the temperature regime of the foundation soils," Soil Mechanics and Foundation Engineering, no. 1, pp. 20–23, 2004. (In Russian)

[14] A. L. Lyazgin, et al., "Experience in preventing frost heaving of pile foundations of transmission line supports in northern conditions," Electric stations, no. 4, pp. 49–51, 2004. (In Russian)

[15] E. D. Filatova, D. G. Zolotozubov, "Analysis of modern methods of protection against frost heaving of soil," Modern technologies in construction. Theory and practice, vol. 1, pp. 96–103, 2023. (In Russian)

[16] State Standard 9463-2016. Round timber of coniferous species. Technical conditions. Moscow, Russia: Standartinform Publ., 2016, 6 p. (In Russian)

[17] State Standard 24846-2012. Soils. Methods for measuring deformations and foundations of buildings and structures. Moscow, Russia: Standartinform Publ., 2014, 16 p. (In Russian)

[18] State Standard 25358-2020. Soils. Field temperature determination methods. Moscow, Russia: Standartinform Publ., 2021, 11 p. (In Russian)

Konstantin N. Bolshev. Candidate of technical sciences, senior researcher of the V.P. Larionov Institute of the Physical-Technical Problems of the North of the Siberian Branch of the RAS, deputy director of the Yakutsk Design Research Institute of Construction, Russia, Republic of Sakha (Yakutia), Yakutsk. Research interests: heat and mass transfer, heat engineering, thermal power engineering.

Vasiliy M. Efimov. CEO of the Yakutsk Design Research Institute of Construction, Russia, Republic of Sakha (Yakutia), Yakutsk. Research interests: geotechnical monitoring, construction in permafrost conditions, pipeline transport.

Andrey S. Unzhakov. Chief specialist of the Innovation and Development Department of the PJSC "Yakutskenergo", Russia, Republic of Sakha (Yakutia), Yakutsk. Research interests: electric power transportation and production, power engineering.

Vladimir M. Belyakov. Technical director of the Ural Plant of Polymer Technologies "Mayak", Russia, Chelyabinsk,
Research interests: protective coatings, polymer technologies.

Priorities for the Energy Sector of Buryatia in Long-Term Socio-Economic Development Plans

Z.B.-D. Dondokov[1,*]

[1] Institute of Mongolian Studies, Buddhology and Tibetology of Siberian Branch of the Russian Academy of Sciences, Ulan-Ude, Russia

***Abstract* — This study examines the stages of the energy sector development in the Republic of Buryatia alongside the relevant strategic planning documents. The conclusion is made about the decisive role of the energy sector in the long-term development plans of the Republic. The main challenges facing the energy sector in the Republic of Buryatia are identified, highlighting the importance of completing the construction of the Ulan-Ude combined heat and power plant -2 as a solution.**

***Index Terms* — Hydrogen infrastructure projects, hydrogen technologies, Baikal region.**

I. Introduction

Energy sector is the most important branch of the economy, determining the prospects for the development of the entire economic complex of the country and its regions. Since the launch of the state plan for the development of the electric power industry (GOELRO), the significance of the energy sector in long-term planning has become increasingly undeniable [1, 2]. Strategic planning of energy development at the federal and regional levels, along with the planning at the level of energy companies, serves as an essential tool for determining the prospects of the sector [3].

The creation of long-term energy development plans as an integral part of strategic planning documents is crucial for the subjects of the Russian Federation that are economically underdeveloped. These areas often rely heavily on federal financial support, lack local resources for energy advancement, and do not have significant energy companies based within the region. One of these regions is the Republic of Buryatia.

* Corresponding author.
E-mail: dzorikto@mail.ru

http://dx.doi.org/10.25729/esr.2024.04.0014

Received November 29, 2024. Acc. November 29, 2024. Available online December 28, 2024.

II. Literature Review

The fundamental document of strategic energy development planning in Russia is the Energy Strategy of the Russian Federation until 2035 (hereinafter referred to as the Energy Strategy). This document outlines the long-term goals, priorities, and pathways for the sector development [4].

The scientists from leading specialized scientific institutes and universities analyze the development scenarios, identifying priorities and outlining key directions for the energy sector development in Russia, particularly regions of Siberia and the Far East, including the Republic of Buryatia [5–10]. The challenges and prospects for the energy development in the Republic of Buryatia were explored by G.O. Borisov and other employees of the Department of Regional Economic Research of the Buryat Scientific Center, Siberian Branch of the Russian Academy of Sciences in the 2010s [11–13].

At the same time, recent years have seen significant transformations in the strategic planning framework for energy development, including the adoption of the Energy Strategy, initiation of federal projects, and formulation of long-term plans for the comprehensive socio-economic development of cities in the Far East. There is a growing interest in the previously suspended major investment projects in the Republic of Buryatia. These factors underscore the significance of investigating the future prospects of the Republic's energy sector.

III. Methodology

The methodological framework of the study is strategic planning, considered in two aspects: sectoral (energy) and territorial (Republic of Buryatia). The information support relies on the data contained in the sectoral strategic planning documents of the Russian Federation. These documents encompass the Energy Strategy, the schemes and programs for the development of electric power systems of Russia (SPD EPS of Russia), as well as the strategic planning documents formulated at the level of the constituent entities of the Russian Federation, such as Strategies for the socio-economic development of the Republic of Buryatia, implementation action plans, and the state programs of the Republic.

This paper highlights the main stages of the energy sector development in the Republic of Buryatia:

- The early stage of the energy sector of the Republic (1923–1933);

- The establishment of the energy sector of Buryatia (1934–1963);

- The integrated development of the energy sector of the Buryat ASSR (1964–1991);

- The transformation of the energy system of the Republic of Buryatia (1992–2016);

- The evolution of the energy sector of Buryatia in the new paradigm of the Republic's development (since 2017).

The main avenues for the sector’s development in the long-term plans for the socio-economic development of Buryatia over the last three periods are analyzed.

This work is a continuation of a series of studies aimed at substantiating prospective pathways for the development of the energy sector in the Republic of Buryatia and analyzing its interaction with the energy systems of neighboring regions of Russia and Mongolia. It was conducted by the Department of Regional Economic Investigations of Buryatia Scientific Center of SB RAS within the framework of a state assignment, in response to official requests from the Federation Council of the Federal Assembly of the Russian Federation, and with the support of several grants from the Russian Foundation for Basic Research.

IV. Results and Discussion

By the time the Buryat-Mongolian ASSR was formed in 1923, there had been virtually no industry in the Republic. The Republic's energy sector was in its infancy during the first 10 years. Electricity production, which amounted to 0.3 million kWh in the first year of Buryat-Mongolia's existence, increased only slightly [14].

The second stage of the energy sector development began in 1934 with the construction of the first major energy facility (Ulan-Ude combined heat and power plant-1) and the launch of a turbogenerator with a capacity of 12 thousand kW. The electricity generated met the needs of the largest enterprises in Buryatia, including the Ulan-Ude locomotive plant, a meat processing facility, a flour mill, and a glass factory [15].

In the following 30 years, the Timlyui combined heat and power plant was the only significant energy generation facility constructed and commissioned in Buryatia. This was largely due to the relatively low rates of growth in industrial production, which is the main sector of the national economy that determines the demand for electricity. Thus, over 25 years, starting in 1940, the growth rates of gross industrial output in the Buryat ASSR were almost 1.5 times lower than in the RSFSR and 2 times lower than in the East Siberian Economic Region, including the Irkutsk Region and Krasnoyarsk Territory, where the construction of major industrial facilities began in the post-war years (Table 1).

A new stage in the development of the energy sector in Buryatia began in the mid-1960s with the commissioning of the largest 100 MW turbogenerator in Transbaikalia at the Ulan-Ude cogeneration heat and power plant (CHPP)-1 and the start of construction of the Gusinoozerskaya State

Table 1. Growth Rates of Industrial Production in the RSFSR and Its Individual Regions [16, 17]

Administrative-territorial entities	Growth rates of gross industrial output for 1940–1965, %	Growth rates of overall industrial output for 1965–1975, %
Russian Soviet Federative Socialist Republic (RSFSR)	715	211
East Siberian Economic Region	947	239
Buryat Autonomous Soviet Socialist Republic (ASSR)	498	241
Chita Region	312	202

District Power Plant (SDPP).

An indicator of the importance of an industry in a planned economy was the inclusion of construction projects of specialized facilities in the "Main Directions for the Development of the National Economy." In the Buryat ASSR, the first such facilities were energy enterprises. In accordance with the documents adopted at the XXV–XXVII Congresses of the Communist Party of the USSR, the list of the most significant construction projects in the USSR included projects for the construction of the Gusinoozerskaya State District Power Plant and the Tugnuisky coal mine, along with the commissioning of capacities at the Ulan-Ude CHPP-2 [18–20].

With the collapse of the planned economy in the early 1990s, the unified electric power system of Buryatia was liquidated. The restructuring of the energy sector led to the emergence of various owners within generation: Gusinoozerskaya SDPP became the property of Wholesale Generating Company No. 3, Territorial Generating Company No. 14 acquired ownership of Ulan-Ude CHPP-1 and CHPP-2, Selenginskaya CHPP became the property of OJSC Selenginsk Pulp and Cardboard Mill, and the grid assets went to the branch of Interregional Distribution Grid Company of Siberia, i.e., Buryatenergo.

The general decline in industrial production in Buryatia resulted in the suspension and freezing of major investment projects in the energy sector, including the completion of the construction of Ulan-Ude CHPP-2 and the construction of the Mokskaya hydropower plant with the Ivanovo hydropower plant serving peak loads.

At the same time, the government of the Republic of Buryatia took various actions to stimulate the development of the region's economy, including repeated appeals to the leadership of the Russian Federation. In 1996, the Federal Program for the Socio-economic Development of the Republic of Buryatia until 2005 was adopted with the subprogram "Energy Sector" being its integral part [21]. It provided for the implementation of several large investment projects in the energy sector, including the reconstruction of Ulan-Ude CHPP-1, the construction of the 1st stage of Ulan-Ude CHPP-2, and the construction of the 2nd stage of Gusinoozerskaya State District Power Plant (SDPP). In addition, non-conventional energy was recognized as a separate strand of the subprogram. The list of investment projects included micro hydropower plants on small rivers in the Bauntovsky, Okinsky, and Kurumkansky districts of Buryatia. It is important to note that all of the specified investment projects were never implemented. The main reason for this was the lack of financial resources for the Federal Program, which led to its cancellation in 2002 [22].

Another attempt to revive investment projects in the energy sector was made in 2007, when the government of the Republic of Buryatia approved a long-term strategy for the development of the region, which included the construction of the Mokskaya hydropower plant, the construction of the 7th power unit at the Gusinoozerskaya State District Power Plant, and the installation of two 220 MW power units at the Ulan-Ude CHPP-2. In the context of the global financial crisis of 2008–2009, which also affected Russia, investors chose to curtail the planned projects [23]. The Russian Government returned to these projects in 2016, including them in the "Scheme of territorial planning of the Russian Federation in the field of energy" [24]. Until recently, however, there have been practically no real progress on them. As a result, the general state of the industry worsened.

V. Energy Development Challenges in Buryatia and Possibilities for Coping with Them

Currently, the energy sector of the Republic of Buryatia is in a pre-crisis state. One of the main problems facing the industry is the alarming state of energy security [25].

Firstly, the share of the largest generating source, Gusinoozerskaya State District Power Plant, is too high in the energy sector of Buryatia. As a result, emergency situations periodically occur in the Republic. For example, an accident in June 2022 de-energized almost all of Buryatia. It should be noted that Ulan-Ude is the only city in Siberia and the Far East that is not balanced in terms of electricity consumption. With a consumption capacity of 450 MW, generation is 148 MW. In the context of growing demand for electric and thermal energy, the energy security issue is becoming increasingly acute. Secondly, the depreciation of the main production assets in the energy sector of the Republic is extremely high. In 2022, it amounted to 50.6%, despite the reconstruction of power unit No. 4 of the Gusinoozerskaya SDPP and the replacement of turbogenerator No. 7, which was disabled due to a fire at Ulan-Ude CHPP-1.

Another challenge facing the energy sector of Buryatia is its low efficiency, due to the insignificant share of cogeneration. The Ulan-Ude CHPP-2 construction has not been completed and the plant is operating as a peak boiler.

The thermal capacity is 380 Gcal/hour. According to the original project, however, the electric capacity of the 1st stage of construction was 360 MW and the thermal capacity – 930.2 Gcal/hour. The full designed electric capacity was 720 MW and 1 840 Gcal /hour. In the coming years, a significant increase in electricity consumption is expected in the Republic (see Table 2). In this regard, the energy capacity shortage is becoming a more acute issue.

In recent years, the Republic has made significant strides in the development of solar energy. In 2017, the Bichurskaya solar power plant (SPP) with a capacity of 10 MW was built. In 2019, SPPs were commissioned in the Khorinsky, Kyakhtinsky, Tarbagataisky, and Kabansky districts with a capacity of 15 MW each. Solar power plants, while beneficial, cannot fully meet the growing electricity demand of the Republic. Thus, the need to establish new generation sources in Buryatia persists.

The urgency of addressing air pollution in the city of Ulan-Ude is difficult to overstate. The main polluter is the private sector, which numbers 67 274 households using coal and firewood as fuel. It is worth noting that Ulan-Ude is included in the federal project “Clean Air.”

Given the uncertain prospects for gas infrastructure expansion in Buryatia, one of the pathways to address this issue is to transition private households to electric heating. At the same time, the city's power supply network is currently facing significant challenges, including:

• severely depreciated fixed assets, such as equipment, building structures, and others;

• outdated and technically obsolete equipment;

• chaotically built distribution networks in the area of private residential development;

• overburdened power supply centers.

Under these circumstances, it is essential to undertake reconstruction, major repairs, or new construction of power grid facilities in the city. For these purposes, the Government of the Republic of Buryatia adopted a regional program for the modernization of the power grid, which involves reconstruction and construction of power grids in suburban areas of Ulan-Ude, and provides subsidies to residents for the costs associated with connecting their homes to the grid as they transition to electric heating [27].

The key strategy for addressing the challenges in Buryatia’s energy sector is the completion of the Ulan-Ude CHPP-2 construction project [28]. Following a long and intricate discussion that harmonized the interests of the project stakeholders, the Government of the Russian Federation decided to include the design and survey work, the development of documentation, and construction of the second stage of the Ulan-Ude CHPP-2 with a steam boiler with a capacity of 360 Gcal/h in the “Long-Term Plan for the Comprehensive Socio-economic Development of the Ulan-Ude Urban Agglomeration until 2030,” which was adopted in July 2023 [29]. In early 2024, the Ulan-Ude CHPP-2 reconstruction project won a competition held by the Russian Ministry of Energy. A 65 MW power unit will be installed at the plant, which will improve the reliability of the city's energy supply.

VI. Conclusion

The conducted study allowed us to draw the following conclusions:

1. Strategic planning of energy development plays a crucial role in shaping the future of the entire economic landscape of the country and its individual regions.

2. Analysis of the primary trajectories of energy development in the long-term socio-economic development plans of Buryatia revealed the features of the pivotal stages of the energy sector evolution: energy as a driver of economic growth in the Republic during the 1970s and 1980s; the transformation of the regional energy system marked by a production decline and a halt in investment projects (1992–2016); a new paradigm for the Republic's energy sector (since 2017).

3. The main challenges facing the energy sector of the Republic of Buryatia are described. These are the

Table 2. Projected Electricity Consumption in the Energy System of the Republic of Buryatia [26].

Indicator	2024	2025	2026	2027	2028	2029
Electric energy consumption, million kWh	6 859	7 383	8 415	9 473	9 699	9 745
Absolute increase in electric energy consumption, million kWh	476	524	1 032	1 058	226	46
Annual growth rate, %	7.46	7.64	13.98	12.57	2.39	0.47

precarious energy security state; the low efficiency stemming from an insignificant share of cogeneration; a critical shortage of energy capacities; and the deteriorating condition of the power grid in the city of Ulan-Ude.

4. The identified pathway to address Buryatia's energy challenges is to finalize the construction of the Ulan-Ude CHPP-2 project.

Acknowledgment

The study was carried out within the framework of the State Assignment of the Institute of Mongolian Studies, Buddhology and Tibetology of Siberian Branch of the Russian Academy of Sciences No. 121030500092-7.

References

[1] E. P. Volkov, "GOELRO plan and the development of modern electric power industry in Russia," Proceedings of the Russian Academy of Sciences. Power Engineering, no. 6, pp. 7–16, 2020. (In Russian)

[2] A. A. Makarov, T. A. Mitrova, "Centenary of the GOELRO plan: opportunities and problems of a planned economy," Thermal Power Engineering, no. 11, pp. 5–16, 2020. (In Russian)

[3] N. I. Voropai, A. M. Kler, Yu. D. Kononov, B. G. Saneev, S. M. Senderov, V. A. Stennikov, "Methodological foundations of strategic planning of energy development," Energy Policy, no. 3, pp.35–44, 2018. (In Russian)

[4] Order of the Government of the Russian Federation (2020, Jun. 09). No. 1523-r, On the Energy Strategy of the Russian Federation until 2035. [Online]. Available: https://www.garant.ru/products/ipo/prime/doc/74148810/. (In Russian)

[5] I. Y. Ivanova, A. V. Lagerev, K. S. Smirnov, V. N. Khanaeva, B. Sodov, G. O. Borisov, "Development of electric power industry," in Fuel and energy complex of the Baikal region: Current state, development prospects, B. G. Saneev, Ed. Novosibirsk, Russia: Academic Publishing House "Geo," 2015, pp. 102–114. (In Russian)

[6] Regional Development Strategy: Republic of Buryatia – 2015, A.G. Granberg, P.A. Minakir, L.V. Potapov, Eds. Moscow, Russia: Economika, 2005, pp. 313–400.

[7] N. I. Suslov, V. F. Buzulutskov, "Application of the information-software-modeling complex OMMM-TEK for scenario analysis of the energy development in regions: Methodological aspects," Region: Economics and Sociology. no. 3(95), pp. 215–237, 2017. (In Russian)

[8] O. V. Demina, "Prospects for the energy sector development in the Far East in the context of energy transition," Regionalistics, vol. 9, no. 1, pp. 20–33, 2022. (In Russian)

[9] A. P. Dzyuba, I. A. Solovieva, "Prospects for Managing Energy Demand in Russian Regions," Regional Economy, vol. 17, no. 2, pp. 502–519, 2021. (In Russian)

[10] L. D. Gitelman, V. V. Dobrodey, M. V. Kozhevnikov, "Instruments for sustainable development of regional energy," Economy of Regions, vol. 16, no.4, pp. 1208–1223, 2020. (In Russian)

[11] G. O. Borisov, "Current energy challenges in scientific works of the Department of regional economic research of the Buryat Scientific Center of the Siberian Branch of the Russian Academy of Sciences," Bulletin of the Buryat Scientific Center of the Siberian Branch of the Russian Academy of Sciences, no. 2(30), pp. 116–122, 2018. (In Russian)

[12] G. O. Borisov, D. Z. Ubonova, "Strategic directions for the development of electric power industry in the Republic of Buryatia," Bulletin of the East Siberian State University of Technology and Management, no. 1(58), pp. 54–60, 2016. (In Russian)

[13] Z. B.-D. Dondokov, G. O. Borisov, "Economic development of the BAM zone: problems and prospects for the integrated development of the north of the Baikal region," Regional Economics: Theory and Practice, no. 48, pp. 15–25, 2015. (In Russian)

[14] B. A. Tsybenov, "Formation of the Economy of the Buryat-Mongolian ASSR in the Pre-War Period," in Analysis and Modeling of the Socio-Ecological-Economic Development of the Republic of Buryatia, Collected Monographs [Electronic Edition], A. O. Baranov, Z. B.-D. Dondokov, Eds. Ulan-Ude, Russia: Publishing House of the BSC SB RAS, 2022, pp. 7–20. [Online]. Available: http://publisher.bscnet.ru/wp-content/uploads/2023/02/%D0%BC%D0%BE%D0%BD%D0%BE%D0%B3%D1%80_%D0%94%D0%BE%D0%BD%D0%B4%D0%BE%D0%BA%D0%BE%D0%B2_-1.pdf

[15] D. D. Dorzhiev, "Results of socialist construction of the Buryat-Mongolian ASSR and prospects for its economic and cultural development in the second five-year plan," in Problems of the Buryat-Mongolian ASSR: Proceedings of the 1st Conference on the study of the productive forces of the Buryat-Mongolian ASSR. Moscow, Leningrad, Russia: Publishing house of the USSR Academy of Sciences, 1935, vol. 1, pp. 9–25. (In Russian)

[16] National economy of the RSFSR in 1965. Statistical yearbook. Moscow, Russia: Statistics, 1966, pp. 48–49. (In Russian)

[17] National economy of the RSFSR in 1975. Statistical yearbook. Moscow, Russia: Statistics, 1976, pp. 47–48. (In Russian)

[18] Main directions for advancing the national economy. The 25th Congress of the CPSU (February 24 – March 5, 1976): Verbatim report, vol. 2. Moscow, Russia: Politizdat, 1976, 295 p. [Online]. Available: https://djvu.online/file/AYUWlbEVfAQQx. (In Russian)

[19] The main directions for economic and social development of the USSR for 1981–1985 and until 1990. Moscow, Russia: Politizdat, 1981, 58 p. [Online]. Available: https://docs.historyrussia.org/ru/nodes/354109-osnovnye-napravleniya-ekonomicheskogo-i-sotsialnogo-razvitiya-sssr-na-1981-locale-nil-1985-gody-i-na-period-do-1990-goda-utverzhdeny-2-marta-1981-g#mode/inspect/page/58/zoom/4. (In Russian)

[20] The 27th Congress of the Communist Party of the Soviet Union, February 25 – March 6, 1986. Verbatim report. [In 3 volumes], vol. 2. Moscow, Russia: Politizdat, 1986, 277 p. [Online]. Available: http://www.uaio.ru/5/85/xxviit2.htm. (In Russian)

[21] Decree of the Government of the Russian Federation (1996, Apr. 15). No. 442, On the Federal Program for the Socio-Economic Development of the Republic of Buryatia. [Online]. Available: https://docs.cntd.ru/document/9033344. (In Russian)

[22] Decree of the Government of the Russian Federation (2002, Aug. 24). No. 630, On the amendment, suspension of effect and recognition as invalid of certain acts of the Government of the Russian Federation in connection with the Federal Law "On the Federal Budget for 2002." [Online]. Available: https://docs.cntd.ru/document/901825695?marker=7DK0K8. (In Russian)

[23] Decree of the Government of the Republic of Buryatia (2007, Dec. 15). No 410, On the Strategy for the Socio-Economic Development of the Republic of Buryatia until 2025. [Online]. Available: https://docs.cntd.ru/document/446260821. (In Russian)

[24] Order of the Government of the Russian Federation (2016, Aug. 1). No 1634-r, On the territorial planning scheme of the Russian Federation in the field of energy. [Online]. Available: https://www.garant.ru/products/ipo/prime/doc/71361324/. (In Russian)

[25] G. O. Borisov, "Problems and prospects of energy development in Buryatia," ECO, no. 10, pp. 49–64, 2018. (In Russian)

[26] Supporting documents. Scheme and program for the development of electric power systems of Russia for 2024–2029. Energy system of the Republic of Buryatia. [Online]. Available: https://www.so-ups.ru/fileadmin/files/company/future_plan/public_discussion/2024/final/45_Respublika_Burjatija.pdf. (In Russian)

[27] Order of the Government of the Republic of Buryatia (2024, Feb. 20). No 123-r, On approval of the Regional Program of the Republic of Buryatia "Modernization of the electric grid in order to create conditions for the transfer of private households from coal (wood) heating to electric" (Action Plan). [Online]. Available: https://base.garant.ru/408587803/. (In Russian)

[28] G. O. Borisov, R. A. Zdarov, "On the efficiency of constructing CHPP-2 in Ulan-Ude," Bulletin of the Buryat State University. Economics and Management, no. 4, pp. 11–21, 2019. (In Russian)

[29] Order of the Government of the Russian Federation (2023, Jul. 31). No 2058-r, On approval of long-term plans for the integrated socio-economic development of the Yuzhno-Sakhalinsk, Ulan-Ude urban agglomerations and urban districts "City of Severobaikalsk," "City of Chita," "City of Tynda" until 2030. [Online]. Available: https://www.garant.ru/products/ipo/prime/doc/407361697/. (In Russian)

Zorigto Bato-Dugarovich Dondokov, Dr.Sc. in Economics and Professor, earned the Ph.D. degree in Economics from the Plekhanov Moscow Institute of the National Economy in 1989, and the Dr.Sc. degree in 2000 from Irkutsk State University of Economics. Currently serving as the Chief Researcher at the Institute of Mongolian Studies, Buddhology and Tibetology, he is project coordinator of the Department of Regional Economic Research. His research interests include intersectoral analysis, regional economy, modeling of socio-economic processes, strategic planning and the proejction of regional development.

A Simulation Model for Compiling Projected Regional Energy Balances

R.I. Muzychuk[1], A.D. Sokolov[1,*]

[1] Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The great uncertainty in the values of technical and economic indicators of energy sector development hinders the compilation of projected (calculated) regional energy balances. To address this issue, we propose using the indicator-based analysis aided by simulations to develop projected regional energy balances. This study contributes a simulation model for compiling projected balances, which is meant to facilitate projections of energy sectors of the regions of Russia. The model determines the necessary volumes of extraction, production, and imports of energy resources to ensure that the projected levels of consumption and exports of energy resources outside the region are maintained. The presented model was used to construct indicative fuel and energy balances of the Asian regions of Russia for 2050.**

***Index Terms* — Energy sector, energy balance, Asian regions of Russia, indicator-based analysis, simulation model, projection.**

I. Introduction

The Order of the Ministry of Energy of the Russian Federation No. 1169 dated October 29, 2023 [1] obliges the executive branch agencies of subjects of the Russian Federation and local municipal authorities to prepare projected energy balances every five years. The balances are made up of interrelated indicators that reconcile in quantitative terms the supplies of fuel and energy resources (FER) and their consumption within the area of a subject of the Russian Federation, or a municipality. They establish the distribution of FER among different supply systems (electricity, heating, fuel), as well as among individual FER consumers and their groups, and determine the efficiency of their use.

Due to the high degree of inherent uncertainty of projections of the development of the energy sector in a region, the compilation of projected balances becomes an extremely arduous task [2, 3]. We propose to solve it with the aid of the indicator-based analysis that sets the value of key projected parameters (indicators) that need to be achieved to meet the region's needs for fuel and energy resources and to ensure the required exports.

II. Simulation Model of the Projected Energy Balance

In order to construct the energy balance of a region, one needs to make a scenario-based projection of key technical and economic indicators, structural changes, as well as imports and exports of energy resources. Based on the above data, the demand for fuel and energy resources (FER) is calculated for each of the considered scenarios and the volumes of extraction and production of energy resources required to meet this demand are determined.

We propose using a simulation model to implement the indicator-based approach to projecting the energy balance of a region. The simulation model solves consecutively the expressions (1)–(21).

The construction of regional indicator-based energy balances relies on projected balances of final consumption of fuel and energy as input data:

$$\sum_{i=1}^{I} B_i^{fc} + W^{fc} + Q^{fc} = B^{fc}, \tag{1}$$

* Corresponding author.
E-mail: sokolov@isem.irk.ru

http://dx.doi.org/10.25729/esr.2024.04.0015

Received November 29, 2024. Acc. November 29, 2024. Available online December 28, 2024.

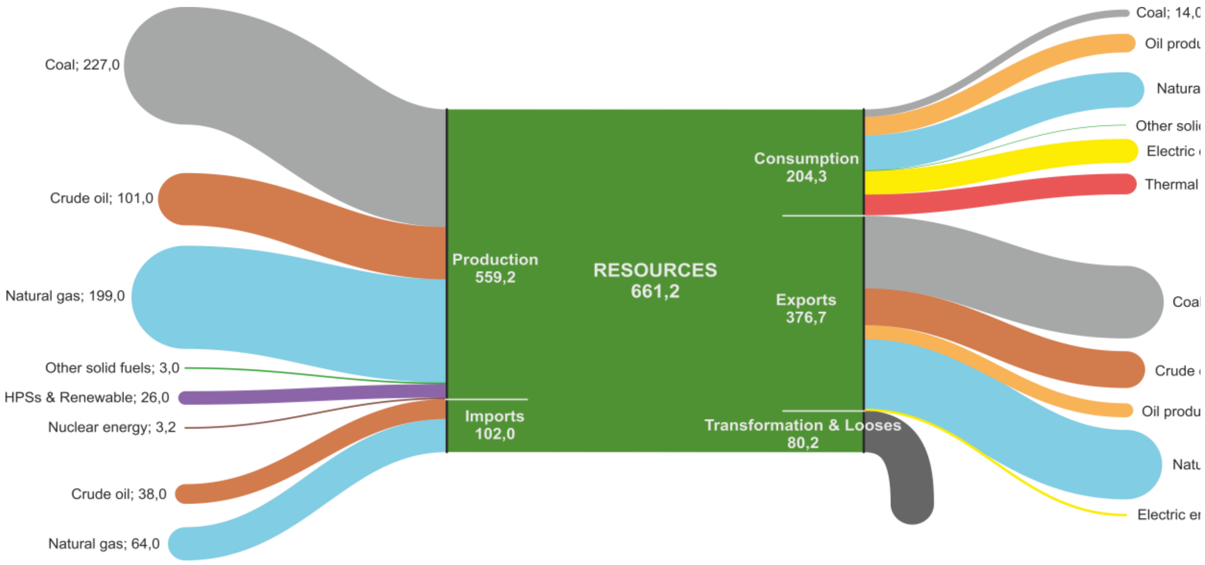


Fig. 1. Fuel and energy flows diagram for Asian regions of Russia for 2050, million t.c.e.

where B_i^{fc} is the final consumption of the *i*-th type of fuel (coal, gas, oil, etc.);

W^{fc} is the final consumption of electricity;

Q^{fc} is the final consumption of heat.

The first step in building the energy balance is to determine the required volumes of electricity and heat production. These volumes can be calculated based on the following relations:

$$W = W^{fc} + W^{aux} + W^{nl} + W^{exp} - W^{imp} + W^{EB}, \tag{2}$$

$$Q = Q^{fc} + Q^{aux} + Q^{nl}, \tag{3}$$

where W and Q are the required volumes of electricity and heat production, respectively;

W^{aux} and Q^{aux} are auxiliary consumption of electricity and heat by their producers (power plants and boiler plants);

W^{nl} and Q^{nl} are losses in electric and heat networks;

W^{imp} are electricity imports from outside the region;

W^{exp} are electricity exports from the region;

W^{EB} is electricity consumption at electric boiler plants.

Auxiliary consumption and network losses are determined by predicting or specifying the percentages (standardized values) of losses. Auxiliary consumption of electricity and heat as well as losses are calculated according to the next expressions:

$$W^{aux} = n^{aux} W, \tag{4}$$

$$W^{nl} = n^{nl}\left(W - W^{aux}\right), \tag{5}$$

$$Q^{aux} = m^{aux} Q, \tag{6}$$

$$Q^{nl} = m^{nl}\left(Q - Q^{aux}\right) \tag{7}$$

where n^{aux} is the percentage of auxiliary electricity consumption;

n^{nl} is percentage of electricity losses in networks;

m^{aux} is percentage of auxiliary heat consumption;

m^{nl} is percentage of heat losses in distribution networks.

The volumes of electric (W) and thermal (Q) energy production are determined from the given relations (2)–(7).

Electric and thermal energy production at power plants and boiler plants of various types is calculated using the balance relations:

$$W = W^{TPP} + W^{HPP} + W^{NPP} + W^{ncRES}, \tag{8}$$

$$Q = Q^{TPP} + Q^{boil} + Q^{EB} + Q^{NPP} + Q^{HRP}, \tag{9}$$

where W^{TPP}, W^{HPP}, W^{NPP}, W^{ncRES} are electricity production at TPPs, HPPs, NPPs, and non-conventional renewables, respectively; Q^{TPP}, Q^{boil}, Q^{EB}, Q^{NPP}, Q^{HRP} are heat production at TPPs, boiler plants, NPPs, electric boilers, and heat recovery plants, respectively.

All the above values are specified in calculations, except for electricity production at TPPs and heat production at TPPs and boiler plants.

Heat production at TPPs (Q^{TPP}) and boiler plants (Q^{boil}) is determined by specifying their percentage in heat production:

$$Q^{TPP} = p^{TPP}\left(Q - Q^{EB} - Q^{NPP} - Q^{HRP}\right), \tag{10}$$

$$Q^{boil} = p^{boil}\left(Q - Q^{Eb} - Q^{NPP} - Q^{HRP}\right), \qquad (11)$$

$$p^{TPP} + p^{boil} = 1, \qquad (12)$$

where p^{TPP}, p^{boil} are percentages of heat production at TPPs and boiler plants.

Having determined the volumes of electricity and heat production at TPPs and boiler plants, we calculate the demand for fuel required for electricity and heat production. To that end, we use metrics such as the projected fuel consumption rate for heat production at boiler plants (b^{boil}) and the efficiency of power plants (η^{TPP}):

$$B^{TPP} = \frac{W^{TPP} + Q^{TPP}}{\eta^{TPP}}, \qquad (13)$$

$$B^{boil} = Q^{boil} b^{boil}. \qquad (14)$$

To determine the demand for specific types of fuel i at TPPs and boiler plants, we specify the mix of fuel consumption (τ_i^{TPP} and τ_i^{boil}):

$$\sum_{i=1}^{I} \tau_i^{TPP} = 1, \qquad (15)$$

$$\sum_{i=1}^{I} \tau_i^{boil} = 1. \qquad (16)$$

Therefore, the demand for a particular fuel type i is determined as follows:

$$B_i^{TPP} = \tau_i^{TPP} B^{TPP},\ i = 1, \ldots, I, \qquad (17)$$

$$Q_i^{boil} = \tau_i^{boil} Q^{boil},\ i = 1, \ldots, I. \qquad (18)$$

By specifying fuel imports (B_i^{imp}) and exports (B_i^{exp}), it is possible to determine the required fuel production (extraction) (B_i^{prod}):

$$B_i^{prod} = B_i^{fc} + B_i^{boil} + B_i^{TPP} + B_i^{exp} - B_i^{imp},\ i = 1, \ldots, I. \qquad (19)$$

If the production and imports of energy resources in the region are specified, possible exports are determined as follows:

$$B_i^{exp} = B_i^{prod} - B_i^{fc} - B_i^{boil} - B_i^{TPP} + B_i^{imp}, \qquad (20)$$

or, in the case of specified production and exports, we find the required imports using the expression:

$$B_i^{imp} = B_i^{fc} + B_i^{boil} + B_i^{TPP} + B_i^{exp} - B_i^{prod}. \qquad (21)$$

The compiled regional energy balance enables us to determine the volumes of extraction and production of energy resources and makeup of production and consumption of energy resources for the considered time horizon with respect to the specified indicator-based parameters of the region's energy sector development.

III. Implementation of the Simulation Model

Using the described model, a projected fuel and energy balance for 2050 was compiled for the Asian regions of Russia, including the territories of the Siberian and Far Eastern Federal Districts.

The following indicators were set as the main ones:

TABLE 1. Projected Fuel and Energy Balance for Asian Regions of Russia for 2050, Million t.c.e.

Indicators	Coal	Crude oil	Oil products	Natural gas	Other solid fuels	Hydro energy and NRES*	Nuclear energy	Electric energy	Thermal energy	Total
Production of fuel and energy resources	**227**	**101**	**-**	**199**	**3**	**26**	**3.2**	**-**	**-**	**559**
Imports	-	38	-	64	-	-	-	-	-	102
Exports	-140	-71	-27	-134	-	-	-	-4.7	-	-377
Primary energy consumption	**87**	**68**	**-27**	**129**	**3**	**26**	**3.2**	**-4.7**	**-**	**285**
Hydropower plants and NRES, nuclear power plants	-	-	-	-	-	-26	-1.9	28	-	-
Thermal power plants	-32	-	-0.8	-46	-1	-	-	29	23	-28
Boiler houses	-6	-0.2	-0.6	-12	-1.6	-	-	-	19	-1.4
Electric boiler houses and heat recovery units	-	-	-	-	-	-	-1.3	-0.8	3.6	1.5
Coal processing	-35	-	-	-	-	-	-	-	-	-35
Oil refining	-	-65	64	-	-	-	-	-	-	-1.0
Auxiliaries	-	-	-	-	-	-	-	-2.3	-2.1	-4.4
Transmission losses	-	-3	-	-4	-	-	-	-3.3	-3.1	-13
Final consumption of fuel and energy resources	14	-	35.9	68	0.4	-	-	46	40	204

* NRES – non-conventional renewable energy sources

• Final consumption of fuel and energy resources;

• Percentage of thermal and electrical energy losses in networks;

• Auxiliary consumption for the thermal and electric energy production;

• Specific fuel consumption for the thermal energy production at boiler houses;

• Efficiency of thermal power plants;

• Projected volumes of thermal energy production;

• Volumes of FER imports and exports;

• Structure of thermal energy production;

• Structure of fuel consumption at boiler houses and power plants;

For these indicator values, the required volumes of extraction/production of fuel and energy resources were established and a fuel and energy balance was projected for the Asian regions of Russia (Table 1).

In order to gain a deeper comprehension and visual representation of the energy balance table, we use Sankey diagrams. These diagrams show how resources are obtained from the production and import of FER and how they are distributed for final consumption, export, and losses. This is illustrated in Fig. 1, which represents the data from Table 1 as the fuel and energy flows for Asian regions of Russia in 2050, in million tons of coal equivalent.

IV. Conclusion

This approach is universally applicable and can be recommended for enhancing the methodology used to compile regional fuel and energy balances, especially in the face of high uncertainty regarding initial data to be projected.

Acknowledgment

The research was conducted as part of the State Assignment Project (no. FWEU-2021-0004) under the Fundamental Research Program of the Russian Federation for 2021–2030, utilizing the resources of the High-Temperature Circuit Shared Research Facility (Ministry of Science and Higher Education of the Russian Federation, project no. 13.CKP.21.0038).

References

[1] Order of the Ministry of Energy of the Russian Federation. No. 1169, “On Approval of the Procedure for the Compilation of Energy Balances of Subjects of the Russian Federation and Municipal Entities.” (In Russian)

[2] Decision of the State Duma Energy Committee (2024, Jan. 17). No. 3.25-5/97, On approval of the recommendations of the parliamentary hearings of the State Duma Energy Committee on “Construction of energy balances of Russia and its regions: problems and solutions.” (In Russian)

[3] N. M. Storonsky, I. V. Tverskoy, V. N. Tolmachev, R. R. Sibgatullin, “The gaping unknowns. How to reconcile the projected energy balance?” Neftegazovaya Vertikal', no. 9, pp. 14–21, 2022. (In Russian)

Roman I. Muzychuk graduated from Irkutsk State University in 2005. Currently, he is a researcher at the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia. His research interests include the energy sector, energy balances, and energy efficiency.

Alexander D. Sokolov graduated from Krasnoyarsk Polytechnic Institute in 1974. He received the D.Sc. in Engineering in 2006. Currently, he is a senior researcher at the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia. His research interests include the energy sector, energy balances, and energy efficiency

Energy industry of the Republic of Sakha (Yakutia): Development Opportunities, Environmental Aspect

N.V. Pavlov[1,*], A.D. Sokolov[2]

[1] Larionov Institute of the Physical-Technical Problems of the North of Siberian Branch of Russian Academy of Sciences, Yakutsk, Russia
[2] Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract*— This study reveals the significant difference between the fuel and energy sector in the North of Russia and that in other regions of the country, driven by severe climatic conditions, the remoteness of communities, and intricate transportation networks. These factors constrain prospects for the development of the region and the advancement of its energy systems specifically. To ensure reliable and uninterrupted energy supply, it is essential to carefully consider all energy development factors. It is crucial to take into account the central role of energy in the socio-economic development of the region, as well as the need to reduce environmental impact and ensure the safety of energy infrastructure. According to the Federal Law "On Strategic Planning," the strategic directions for energy development in the northern and Arctic regions should be continually updated. To accomplish these objectives, the theory and methods of the systems approach in energy development studies are applied. Concurrently, it is essential to use tools that ensure the completeness and integrity of the information base for effective strategic planning.**

* Corresponding author.
E-mail: sokolov@isem.irk.ru

http://dx.doi.org/10.25729/esr.2024.04.0016

Received December 20, 2024. Acc. December 20, 2024. Available online December 28, 2024.

***Index Terms*— northern region, energy sector, energy supply, distributed generation, environmental impact.**

I. Introduction

The Republic of Sakha (Yakutia) is a region of Russia whose energy potential significantly exceeds both its current and future needs. It has the capacity to substantially influence the fuel and energy balance of the Far East, Eastern Siberia, and the entire country. Developing a prospective fuel and energy balance for the regional energy industry requires the use of a systems approach. This approach involves analyzing the situation and justifying appropriate actions.

Within this approach, the object under consideration is a set of enterprises and companies that together constitute the fuel and energy sector as an integrated entity. Their operations are interconnected, as they are linked by the production and consumption of energy resources. At the same time, this set is open to interaction with other regional and interregional economic and energy structures [1].

The energy sector of the Republic of Sakha (Yakutia) is a well-developed system encompassing all the key components of the fuel and energy complex, with the exception of nuclear energy. It includes the coal, oil, and gas industries; electricity and heat supply, as well as networks that supply energy resources to consumers. The energy sector plays a pivotal role in the Republic's economy, determining its state and future prospects. It contributes up to 38% of tax revenues to the republican budget and fully meets the region's needs for coal, natural gas, electricity, and thermal energy.

The contribution of the energy industry to the Republic's tax revenue increased from 17% in 2007 to 38% in 2020. Notably, the oil and gas sector, with its well-developed pipeline infrastructure, experienced significant growth.

The energy industry and fuel and energy supply systems in the North, as subjects of study, differ considerably from similar systems in other Russia's populated regions. A specific methodology is required for projecting energy needs and justifying energy policy in the North to:

- Ensure reliable and uninterrupted energy and fuel supply to consumers;
- Maintain the leading role of energy in regional development;
- Provide fuel and energy supplies to areas with resource shortages and for export;
- Redirect the development of the energy industry to meet the needs of the population and the social sphere, ensuring the survival and improved living standards of people;
- Reduce the impact of the energy industry on the environment and human health, while adhering to stricter environmental regulations and safety standards for energy facilities.

The development of an innovative strategy for the energy industry must consider several factors that hinder socio-economic development in many Northern regions. These are an underdeveloped natural resource base, inadequate transport infrastructure, high energy and transport tariffs, a reliance on federal budget support, and limited domestic investment resources due to specific regional features. Each of these factors is characterized by inefficiency and requires extensive large-scale research for effective resolution [2].

Harsh climatic conditions, the remoteness of communities, and intricate transportation networks limit the development of the region and its energy supply systems. To effectively organize the operation of the energy system under such conditions, a well-thought-out energy development strategy is essential. The use of standard schemes and programs may be ineffective due to the unique climatic and geographic features of the region.

Let us now consider in more detail the various aspects involved in devising a strategy for energy development in the northern region. Based on many years of research, a logical framework for the formulation and implementation of regional energy policy has been established. It encompasses an analysis of specific trends in energy development in northern regions, given their natural, climatic, and socio-economic characteristics; offers a rationale for various possible scenarios for their socio-economic development, and delivers a mechanism for implementing the energy strategy that creates the necessary conditions for such development [3].

Many areas in the Republic of Sakha (Yakutia), particularly the northern ones, are not connected to the unified energy system. In these areas, electricity is supplied by autonomous power plants. Severe climatic conditions lead to quick wear and tear of equipment, resulting in increased maintenance and repair costs. Heat supply to the residential and industrial consumers in the region is also a critical socio-economic task. However, the heat supply facilities scattered over a large territory pose significant challenges for ensuring a reliable and high-quality thermal energy supply.

II. Stages Of Energy Development in the Republic of Sakha (Yakutia)

In 2020, the first stage of implementing the Energy Strategy of the Republic of Sakha (Yakutia) until 2030 was completed. Its main goal is to identify feasible and economically achievable conditions for the extraction (production) of energy resources, to enhance the existing energy industry, and foster the development of innovative fuel and energy solutions. This is essential to ensure the continued dynamic development of the Republic and improve the quality of life for its citizens [4].

During the review period, large trunk "ESPO-1" oil pipeline and the "Power of Siberia" gas pipeline were commissioned as part of the energy system of the Republic of Sakha (Yakutia). Impressive 110–220 kV power grid facilities were commissioned in the electric power industry. A new gas turbine power plant was built in the Central energy area, and all previously isolated load areas were connected to the Interconnected Power System of the East (IPS East) and the non-price zone of the Wholesale Electricity Market, along with several other advancements [5–9].

The stage from 2035 to 2050 is anticipated to be a period of the innovative energy development in Russia, marked by the transition to new technological capabilities for the efficient use of traditional energy resources and new energy sources, alongside the emergence of the active consumer [10].

Thus, the potential for the sustainable advancement of the Republic's energy industry can be achieved through:

1. The modernization and the implementation of innovative technologies that facilitate the more efficient use of natural resources. Current energy trends – especially the advancement of energy technologies – contribute to a more integrated technological connection across all phases: conversion, generation, transportation, and storage of energy. For example, implementing integrated heating and cooling systems at thermal power plants with gas turbine units, including district cooling supply for consumers through absorption chillers that use exhaust gas heat to generate cooling energy, can significantly enhance the efficiency of combined energy production in summer [11].

2. The integration of energy-efficient technologies in construction and public services, which will lead to reduced energy consumption. The use of advanced thermal insulation materials, automatic lighting and heating control systems, and other innovations will lower heat and electricity losses, thereby reducing the need to generate additional energy. Moreover, energy-efficient buildings and structures improve quality of life and decrease utility costs.

3. The widespread adoption of renewable energy sources for isolated and hard-to-reach consumers, which can significantly decrease reliance on expensive diesel fuel and cut the carbon footprint [12, 13].

An example is the potential for broader use of hydropower in the future. The Department of Energy Problems at the Larionov Institute of Physical and Technical Problems of the North, Siberian Branch of the Russian Academy of Sciences, has assessed the hydropower resources in Yakutia. After years of intensive research, an extensive body of knowledge has been gathered regarding the water energy resources of small rivers in the Arctic zone of the Republic of Sakha (Yakutia). This comprehensive and meticulous work, which involved the analysis and processing of large amounts of cartographic material, alongside years of field expeditions, was conducted for the basins of the Anabar, Olenek, Yana, Indigirka, and Kolyma rivers.

4. The sustainable development and minimization of environmental impact, which must be a priority, given the region's environmental characteristics. The specific features of local ecosystems must also be taken into account when developing state programs and investment projects for new energy generation solutions. Furthermore, constant environmental monitoring and assessments are necessary to minimize environmental damage. Research on optimizing the interaction between coal mining hubs in South Yakutia and the natural environment reveals critical areas for further investigation. This includes examining resource and natural-geographical conditions such as cryogenic and other hazardous natural processes. Additionally, it is essential to assess the potential for absorption and dispersion of pollutants in emissions and effluents, all while considering region's specific natural and economic conditions [14–16].

5. An integrated systems approach, which is essential to ensure the safe and reliable operation of complex technical and human-machine systems in industrial enterprises across the Republic of Sakha (Yakutia), particularly under the extreme climatic conditions of the North and the Arctic. The use of materials specifically designed for the climatic conditions of the Arctic and Central Yakutia will reduce failures and accidents [17].

The implementation of these pathways will not only reduce the negative environmental impact but also enhance the efficiency of energy resources.

III. Conclusion

The analysis of the current energy industry of the Republic of Sakha (Yakutia) revealed several categories of factors, which are essential for effective energy development planning. These factors include socio-economic, natural and climatic, industrial, energy-related, and environmental. It is important to recognize that these factors are interrelated and should be considered when building future development scenarios.

The accelerated advancement of the Arctic region necessitates the state support for the "Materials and Technologies for the Russian North and Arctic" program to be formulated as part of the Strategy for Scientific and Technological Development of the Russian Federation.

In accordance with the Federal Law "On Strategic Planning," the strategic areas for energy development in the northern and Arctic regions must be continually revised and updated. The theoretical foundation for accomplishing the tasks relies on the theory and methods of systems studies of energy development. It is imperative that the tools employed in this context ensure a comprehensive and cohesive information base required for effective strategic planning.

At present, a vital and urgent priority for the long-term development of our country and its northern and Arctic regions is the formulation of a scientifically informed strategy for the long-term advancement of the fuel and energy sector of the country and its northern and Arctic territories, especially in the context of the ongoing energy transition.

Acknowledgment

The work was carried out within the framework of the:
- State Assignment Project No. FWRS-2024-0031 of the fundamental research program of the Russian Federation for 2021-2030.
- State Assignment Project (no. FWEU-2021-0004) of the Basic Research Program of the Russian Federation for 2021–2030 and benefited from the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

References

[1] L. A. Melentiev, Systems research in energy. Moscow, USSR: Nauka, 1983. 455 p. (In Russian)

[2] N. A. Petrov, “Scientific and methodological foundations and practice of forming strategies for the development of energy in the regions of the North (using Yakutia as an example),” Abstract of a dissertation for the degree of Doctor of Technical Sciences, Irkutsk, Russia, 1996. 63 p. (In Russian).

[3] N. Petrov, N. Petrova, “On the experience in development of regional energy policy and strategy,” E3S Web of Conferences, vol. 77, Art. no. 03008, 2019. DOI: 10.1051/e3sconf/20197703008.

[4] Energy strategy of the Republic of Sakha (Yakutia) to 2030, G. F. Alekseev et al, Eds. Yakutsk, Irkutsk, Russia: Yakutia Media Group, etc., 2010, 328 p. (In Russian)

[5] N. A. Petrov, S. V. Podkovalnikov, I. V. Ryabykh, N. V. Pavlov, V. E. Zakharov, “The integration of isolated power systems of Yakutia’s central and western parts into the unified power system of Russia: prerequisites, stages, effects,” Electric Power. Transmission and Distribution, no. 5, pp. 28–35, 2021. (In Russian)

[6] N. Pavlov, N. Petrov, “Coal industry of the Republic of Sakha (Yakutia): tools and forecast,” E3S Web of Conferences, vol. 77, Art. no. 03002, 2019. DOI: 10.1051/e3sconf/20197703002.

[7] A. N. Kuzmin, E. Yu. Mikheeva, N. V. Pavlov, Prospects for the development of small-scale district heating in the Republic of Sakha (Yakutia). Novosibirsk, Russia: Publishing house SB RAS, 101 p. (In Russian)

[8] V. Zakharov, D. Prokhorov, N. Pavlov, “Russian arctic region energy balance (Republic of Sakha (Yakutia)),” E3S Web of Conferences, vol. 114, Art. no. 02005, 2019. DOI: 10.1051/e3sconf/201911402005.

[9] N. V. Pavlov, V. V. Lepov, V. E. Zakharov, D. V. Prokhorov, “On Development Prospects of the Energy Industry in the Russian Far North,” Energy Systems Research, vol. 6, no. 1, pp. 55–61, 2023. DOI: 10.25729/esr.2023.01.0008.

[10] B. G. Saneev, “Regional priorities of the eastern energy strategy of Russia: the past, the present, and an outlook for the future,” Energy Systems Research, vol. 6, no 1 (21), pp. 5–10, 2023. DOI: 10.25729/esr.2023.01.0001.

[11] S. Vasilev, N. Pavlov, A. Ivanova, A. Starostina, “Assessment of system effects in the operation of an integrated heating and cooling systems in North,” E3S Web Conference, vol. 470, Art. no. 01034, 2023. DOI: 10.1051/e3sconf/202347001034.

[12] N. V. Pavlov, V. E. Zakharov, D. V. Prokhorov, A. E. Ivanova, T. N. Petrova, S. S. Vasiliev, I. Y. Ivanova, E. P. Maysyuk, “Assessment of environmental safety and energy security for the development options of heat supply to a settlement in the Arctic,” Arctic: Ecology and Economy, vol. 13, no. 3, pp. 417–427, 2023. DOI: 10.25283/2223-4594-2023-3-417-427. (In Russian)

[13] I. Yu. Ivanova, D. D. Nogovitsyn, T. F. Tuguzova, Z. M. Sheina, L. P. Sergeeva, “An analysis of solar power plants operation in the off-grid area of the Republic of Sakha (Yakutia),” in International Scientific Journal Life and Ecology, no. 10–12 (258–260), pp. 12–22, 2018. DOI: 10.15518/isjaee.2018.10-12.012-022. (In Russian)

[14] N. Pavlov, D. Pinigin, “Features of development and technogenic impact of the Elga coal complex on the natural environment,” in Energy of Russia in the 21st century. Innovative development and management, Irkutsk, Russia, Sep. 3–5, 2015, p. 511–515. (In Russian)

[15] D. D. Nogovitsyn, D. D. Pinigin, Z. M. Sheina, L. P. Sergeeva, “The impact of coal deposits in South Yakutia on the environment,” Life Safety, no. 8(260), pp. 30–33, 2022. (In Russian)

[16] D. Nogovitsyn, D. Pinigin, N. Nikolaeva, Z. Sheina, L. Sergeeva, “Assessment of landscapes transformed during the development of the Verkhne-Taluminskoye field using remote methods,” E3s Web of Conferences, vol. 470, Art. no. 01035, 2023. DOI: 10.1051/e3sconf/202347001035.

[17] V. V. Lepov, N. A. Petrov, N. V. Pavlov, “System analysis of the modern materials and technologies in power engineering and industry for the Russian North and Arctic,” AIP Conference Proceedings, vol. 2552, no. 1, Art. no. 080026, 2023. DOI: 10.1063/5.0112831.

Nikita V. Pavlov serves as the Head of the Energy Problems Department at the Larionov Institute of the Physical-Technical Problems of the North, SB RAS, Yakutsk. His research interests include methodological approaches, model systems, software tools, and databases for investigating, forecasting, and selecting optimal pathways for energy development in the North region. He has authored over 85 publications, including chapters and sections in four monographs.

Alexander D. Sokolov graduated from Krasnoyarsk Polytechnic Institute in 1974 and received the D.Sc. degree in Engineering in 2006. He is a senior researcher at the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia. His research interests include fuel and energy sector, fuel-energy balances, energy efficiency.

The Impact of Sizing and Packaging of the Dzhebariki-Khaya Coal on Carbon Emissions Embodied in Final Demand

V.E. Zakharov[1]

[1] Larionov Institute of the Physical-Technical Problems of the North of Siberian Branch of Russian Academy of Sciences, Yakutsk, Russia

***Abstract*— The paper provides a quantitative assessment of carbon dioxide emissions from coal-fired boiler plants serving large areas of the Northeast of Russia. The assessment is exemplified by a case study of boiler plants fired by the coal sourced from the Dzhebariki-Khaya deposit. The calculations were made under the assumption that all the carbon contained in the delivered coal, including its loss in transit, through spillage and dust, and during combustion, is eventually converted into carbon dioxide through various oxidation processes. The method of calculation relies on a model of the change in the net calorific value of coal during long-term bulk storage in open stockyards and takes into account coal losses that occur throughout a complex supply chain. Two cases are analyzed: (1) the current conditions and (2) with the adoption of coal sizing and big bag packaging. The carbon dioxide emissions produced by the boiler plants running on the Dzhebariki-Khaya coal currently total about 670 thousand tons per heating season. However, coal sizing and bagging can reduce coal deliveries and, consequently, CO_2 emissions by 21%.**

***Index Terms*— Russia, carbon footprint, district heat, coal sizing, coal bagging, transportation.**

* Corresponding author.
E-mail: vasss@mail.ru

http://dx.doi.org/10.25729/esr.2024.04.0017

Received December 20, 2024. Acc. December 20, 2024. Available online December 28, 2024.

I. Introduction

In 2021, the Russian Federation adopted the Strategy for socio-economic development with low greenhouse gas emissions to 2050. Among the basic approaches to reducing greenhouse gas emissions, it specifies “realizing the full potential of cutting greenhouse gas emissions contributed by coal-fired power generation.” Although the task of improving the efficiency of power generation has essentially remained unchanged, this introduces an additional criterion for comparing alternative options for the development of the industry. Previous studies [1–4] indicated the possibilities of improving the efficiency of coal-fired boiler plants in the Republic of Sakha (Yakutia), relying on investigation of coal supply chain and changes in coal quality during its transportation and storage. The main conclusion from those studies is the necessity to supply boiler plants with sized coal and to deliver and store it in a packaged form.

Most researchers suggest reducing greenhouse gas emissions from coal-fired power generation by introducing renewable energy sources or switching to natural gas. In the case of northeastern Russia, however, such an approach is currently feasible only near deepwater ports with LNG shipping infrastructure or in a narrow strip of the coastal area where there is some wind potential. In the distributed power sector, photovoltaic inverters can effectively replace 10–15% of the annual output of diesel power plants. In general, the battle to reduce carbon dioxide emissions from small consumers spread over a large area comes down to curtailing the overall consumption of

Fig. 1. The geography of the use of the Dzhebariki-Khaya coal and routes of its delivery by water.

conventional fuels. Other solutions, such as CO_2 capture and disposal for small consumers, are still far from being economically viable.

In the heating sector, the potential for efficiency improvements is huge and covers many areas: from primary fuel extraction and treatment technologies to heat use conditions [5]. Study [6] provides quantitative assessment of carbon dioxide and methane "non-emissions" after the implementation of energy efficiency measures at some boiler plants in the Republic of Sakha. Paper [7] compares district heating and an individual heating system in terms of CO_2 emissions. Emissions from transportation can start to affect the carbon footprint when long distances and complex haul routes are involved [8].

II. Background Information

Coal accounts for 50% of the energy balance of the Arctic zone of Sakha and 70% of energy demand for heating [9]. Such a balance was formed due to the relatively low cost of coal and a number of other factors, such as: 1) the need to operate a large fleet of oil storage facilities for liquid hydrocarbons, 2) a limited number of oil tankers capable of navigating the waters of small rivers, especially low tonnage vessels, etc. Although these issues have been addressed, coal is still expected to retain its dominant role in Yakutia's heating sector for a long time to come.

Despite a long history of coal use, it is a rather complex fuel in terms of its structure. Almost every deposit produces coal of different specifications that depend on metamorphism, oxidation, chemical composition, etc. In 2010–2011, we attempted to study the changes in ash and moisture content of Dzhebariki-Khaya coal, which is widely used in the heating sector of the Republic. On the basis of experimental data, we proposed a model of change in the net calorific value of Dzhebariki-Khaya coal as a function of the duration of storage. Model calculations showed that packaging coal in soft containers (big-bags) is a feasible option. Coal bagging also facilitates accurate coal measurements, significantly reduces oxidation rate, and nearly eliminates spontaneous combustion of coal. Bagged coal also has such advantages as quick suppression

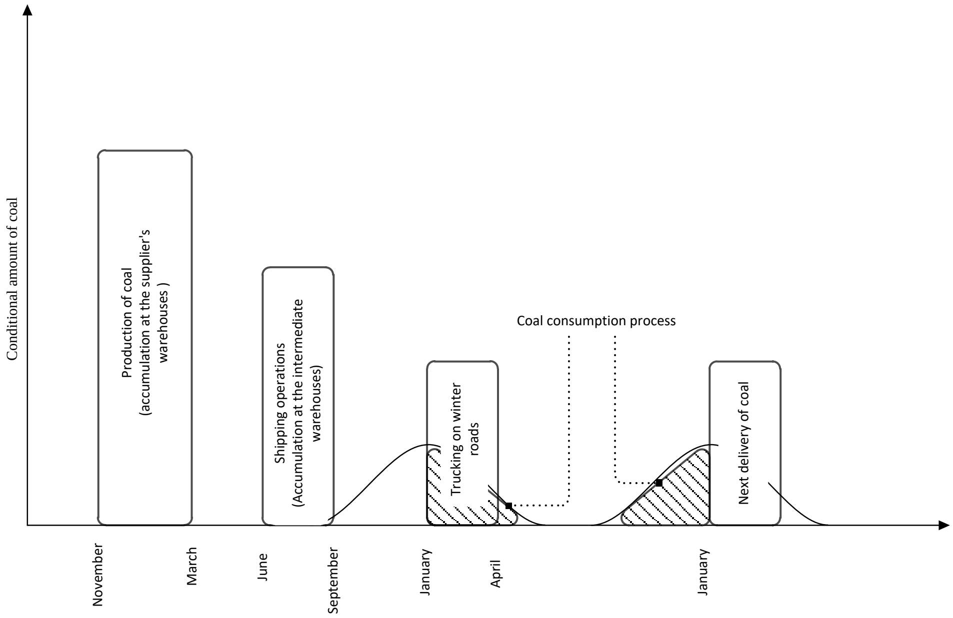


Fig.2. A representative coal delivery schedule in the Republic of Sakha (Yakutia)

of self-heating spots, no coal losses when building up pile beds in stockyards, significant reduction in requirements for coal storage areas, etc. Thus, coal bagging is a way to save coal as it significantly decreases coal loss in transit and besides makes coal theft more difficult.

The low efficiency of boiler plants results, among other things, from the use of run-of-mine (ROM) coal containing a large number of fines, and it is difficult to automate the combustion of ROM coal [4, 10, 11].

Thus, the reduction of carbon dioxide emissions in district heating of the Republic depends on the efficiency of fuel use, especially that of coal. The most effective measures to that end are coal sizing and bagging. This paper assesses the effect of such measures on the reduction of CO_2 emissions for the area supplied with the coal from the Dzhebariki-Khaya deposit.

The Dzhebariki-Khaya deposit is located in the middle course of the Aldan River. Figure 1 shows the municipal districts and local areas that consume the coal of the deposit. The main transport corridors are the navigable sections of the Aldan, Amga, Lena, Vilyui, and Yana rivers, along with an extensive network of winter roads. Year-round roads are used to serve only part of the consumers in the Amga, Tomponsky, and Oymyakonsky districts. Consumers in the Verkhoyansk district have the most involved haul route [1, 2]: it normally takes up to 2.5 years from production to consumption of coal there (Fig. 2) and in the case of using reserve stockpiles, this period can extend to 3.5 years. To put things into perspective, the typical timeframe for other consumers is 1.5–2 years.

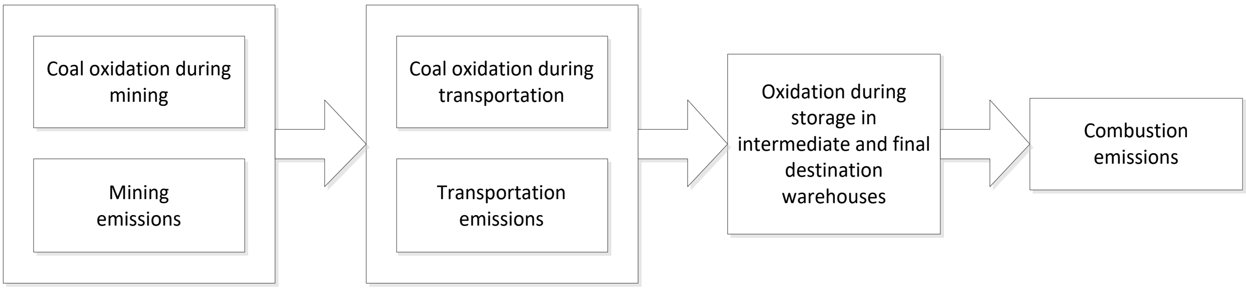
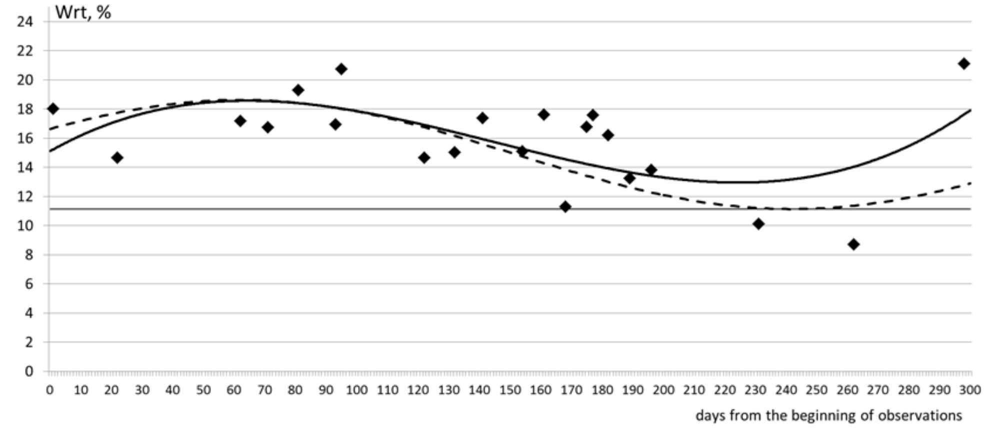
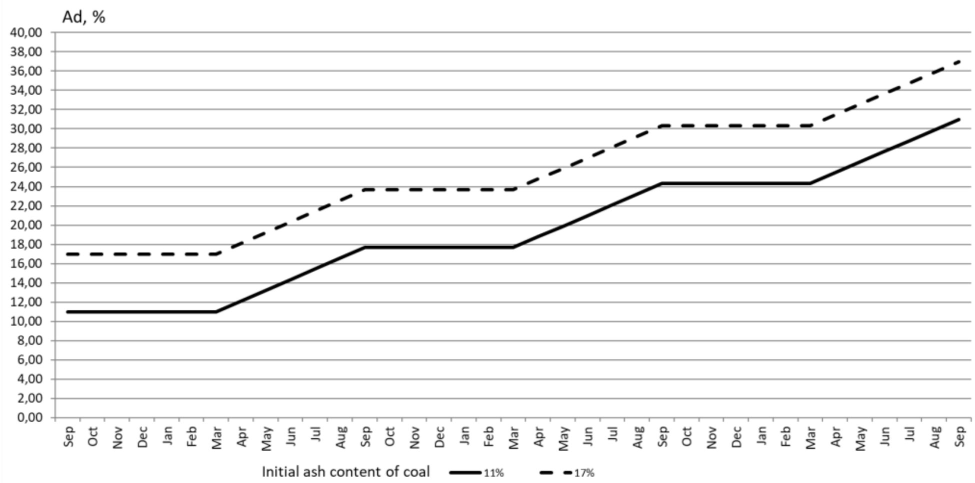


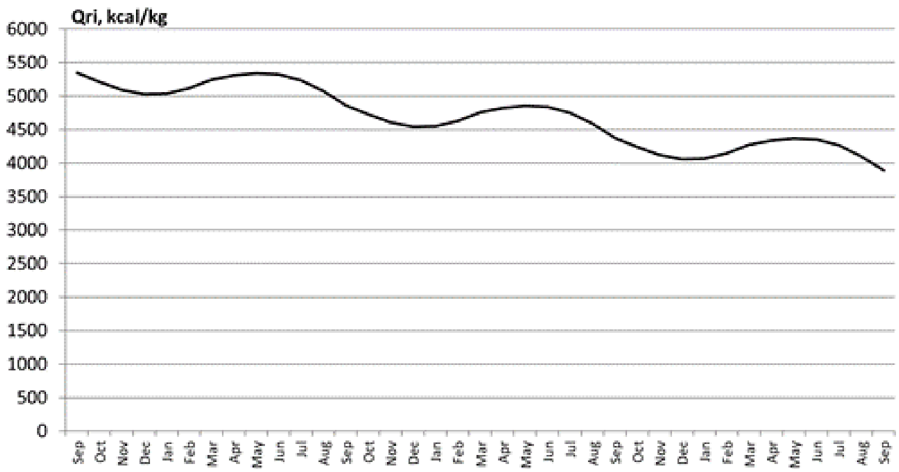
Fig.3. Key stages of carbon dioxide emissions throughout the process chain of coal use in heating systems.



(*a*)



(*b*)



(*c*)

Fig.4. (a) The pattern of moisture change, (b) the pattern of ash content change, and (c) the pattern of net calorific value change for ROM coal of the Dzhebariki-Khaya deposit during outdoor storage.

TABLE 1. Coal Losses During Transportation

Stage	Normal loss %
Transportation of coal from mining sites to truck loading points	0.15
Transportation by river and sea	1.5
Transportation by road:	
up to 100 km	1
up to 350 km	1.5
up to 750 km	1.8
Ship-to-ship transshipment	0.8
Transshipment	1
Unloading and transshipment in stockyards	0.5
Storage for over 6 months	1
Transportation from stockyards to boiler plants	0.2

Similar supply schedules are common for the majority of coal consumers in the Northeast of Russia.

III. MODELS

Emissions of greenhouse gases, including carbon dioxide, are generated throughout the entire coal supply chain: beginning with coal extraction and culminating in its combustion (Fig. 3). Low-temperature oxidation takes place during the storage and delivery phases. Coal transportation also leads to indirect emissions from the combustion engines of river and sea vessels, crane ships, motor vehicles, and tractors. In the case of coal deliveries to the northern regions of the Republic of Sakha (Yakutia), this is more pronounced due to the intricate and long haul route and the reliance on shallow river routes.

Long-term storage of coal in numerous open stockyards, as well as continuous transportation by river and road, significantly accelerate its oxidation process. Storing coal outdoors alters its humidity. Humidity is at its highest in winter when coal is consumed. These factors reduce the heat of combustion of coal and lead to its overconsumption. Study [8] proposes a model of the decline in the net calorific value of ROM coal as a function of the storage duration. This model is based on the data of periodic testing of Dzhebariki-Khaya coal for the consumer in the Ust-Yansky district (Fig. 4). The model

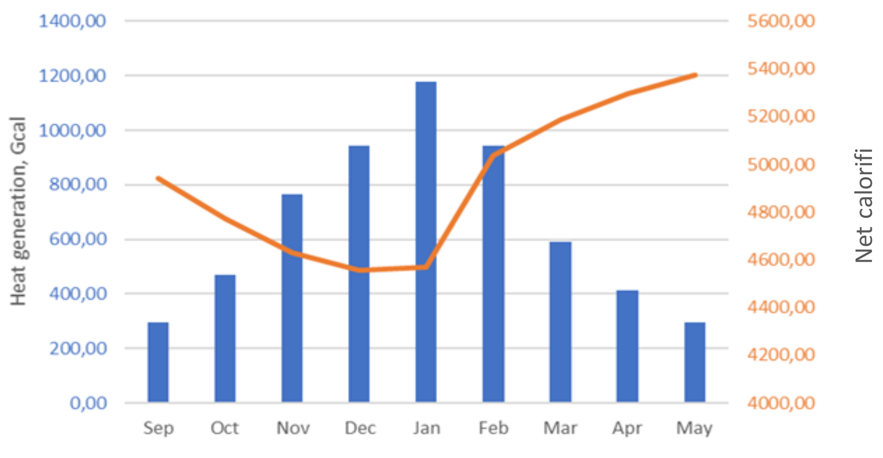


Fig.5.Correlation between the amount of coal consumed and the net calorific value during the heating season (the case of the boiler plant in Amga).

TABLE 2. Results of the Assessment of CO_2 Emission Reduction Due to Coal Sizing and Bagging at the Dzhebariki-Khaya Deposit.

	Boiler consumption, thous. tons	Loss in transit, thous. tons	Coal demand, thous. tons	Same, in %	CO_2 emissions, thous. tons	Same, in %
Current state	331.7	20.6	352.3	100.0	669.7	100.0
Coal bagging + installation of Class 1 boilers	246.7	0.0	246.7	70.0	525.4	78.4

assumes a sinusoidal seasonal moisture fluctuation and a piecewise linear pattern of changes in ash content of the coal during bulk storage in an open stockyard.

Numerous handling operations in intermediate stockyards and rehandling, which involves various means of transportation, result in major coal losses through spillage and dust during bulk transportation. Accurately assessing such losses experimentally is extremely challenging, as there are multiple influencing factors that are not tractable. Expected loss of coal during transit is determined by standardized values outlined in [13]. Table 1 shows normal loss percentages for coal at each stage of transportation, derived from these established standards.

IV. METHOD FOR ESTIMATING CO_2 EMISSIONS

We assume that all the carbon contained in coal delivered for heating, including loss in transit, through spillage and dust, and during combustion, is finally converted into carbon dioxide through various oxidation processes. Thus, carbon dioxide emissions E_{CO_2} are estimated from the total coal demand according to the procedure detailed in [10]:

$$E_{CO_2} = FC \cdot EF_{CO_2} \cdot OF_{CO_2} \,, \qquad (1)$$

where $EF_{CO_2} = 2.76$ t CO_2/tce is the coefficient of carbon dioxide emissions during combustion for the coal produced in Sakha;

$OF_{CO_2} = 1$ is the coal oxidation factor;

FC is total mass of coal.

The total mass of coal, given loss in transit, is calculated as per the following equation:

$$FC = t\sum_n k_n \cdot \sum_i \frac{1000 Q_{in}}{q_i \eta_n} \,, \qquad (2)$$

where t is the coal equivalent (tce) conversion factor;

k_n is the transportation loss coefficient for the boiler plant n;

Q_{in} is the heat output by boiler plant n in month i of the heating season, Gcal;

q_i is the average net calorific value of coal under the operating conditions assumed for month i of the heating season (calculated by the model given in [12]), kcal/kg;

η_n is the efficiency of boiler plant n.

V. RESULTS

The calculations were based on the data from the proprietary database of 169 boiler plants in the Republic of Sakha (Yakutia) that run on the coal from the Dzhebariki-Khaya deposit, as of the end of 2021. The demand for coal was calculated for the current combustion efficiency and existing supply chain. The obtained results were compared with the calculations made for the case of sized coal, the coal combustion efficiency compliant with Class 1 as per [15] (gross efficiency of 82%), and coal shipment in special closed soft containers that prevent losses and deterioration of coal quality. Depending on the location of the boiler plant, parameters of the haul route and the delivery time were input into the calculation model to determine the heat of coal combustion at the time of consumption and the coal loss in transit. For example, Fig. 5 shows the correlation between coal consumption and net calorific value during the heating season at the boiler plant in the village of Amga. Table 2 summarizes the final results of the assessment of the reduction in carbon dioxide emissions achieved through the implementation of coal sizing and bagging at the Dzhebariki-Khaya coal deposit.

VI. CONCLUSION

Quantitative assessment of greenhouse gas emissions is becoming a mandatory parameter for strategic planning of energy sector development, regardless of the scale of production. The key strategy for reducing emissions in the northern areas of Russia lies in enhancing the efficiency of hydrocarbon use throughout the entire supply chain, from extraction to end use.

The introduction of coal sizing and bagging in soft containers at the Dzhebariki-Khaya deposit can lower CO_2 emissions from the municipal sector by 21.6%.

Energy conservation efforts, both by consumers and within the district heating sector, can significantly reduce demand for coal and decrease CO_2 emissions.

This study has not considered carbon dioxide emissions produced by the machinery needed for coal mining and transportation. Therefore, the next stage of the research project will focus on developing a model to quantify carbon dioxide emissions associated with this machinery.

Preliminary estimates indicate that the municipal energy sector of the Republic of Sakha (Yakutia) can achieve a twofold reduction in CO_2 emissions by fully leveraging all available strategies to enhance the efficiency of fuel and energy supply.

Acknowledgment

The research was supported by the basic research program of the Siberian Branch of the Russian Academy of Sciences, as part of the project FWRS-2024-0031 “Comprehensive studies of the priorities of energy sector development in the Republic of Sakha (Yakutia) considering the environmental impacts and the development of approaches and methods for improving energy efficiency and reliability of local power systems of remote and isolated communities of the North and the Arctic.”

References

[1] V. E. Zakharov, D. V. Prokhorov, V. L. Gavrilov, “Loss of energy value of raw coal in transit to Arctic consumers of the Republic of Sakha (Yakutia),” Power Engineering: research, equipment, technology, no. 5–6, pp. 13–22, 2013. (In Russian)

[2] V. E. Zakharov, “Features of the transport system of the Republic of Sakha (Yakutia) and the substantiation of the need for searching of ways to increase the reliability of coal supply,” E3S Web of Conferences, vol. 77, Art. no. 04001, 2019. DOI: 10.1051/e3sconf/20197704001.

[3] V. E. Zakharov, “Improved metering of stored coal supplied to remote consumers,” in Proc. the Eurasian symposium on the issues of reliability of materials and machines in cold climate regions (EURASTRENCOLD-2018), Yakutsk, Russia, Sep. 3–5, 2018, vol. 2, pp. 260–269. (In Russian)

[4] A. E. Ivanova, V. E. Zakharov, T. N. Petrova, “The current state, problems and perspective of development on the North region’s Housing and Utilities: After the example of the Republic of Sakha (Yakutia),” in International Multi-Conference on Industrial Engineering and Modern Technologies, FarEastCon 2020, Vladivostok, Russia, Oct. 06–09, 2020, pp. 1–4. DOI: 10.1109/FarEastCon50210.2020.9271489.

[5] I. V. Petrov, “Economic valuation of energy efficiency of coal power technologies,” Mining Informational and Analytical Bulletin (scientific and technical journal), no. 1, pp. 180–189, 2014. (In Russian)

[6] T. N. Gavril’yeva, A. V. Nogovitsyn, “Impact of energy and resource conservation programs on carbon emission dynamics in the Republic of Sakha (Yakutia),” The Arctic. The XXI century. Natural Sciences, no. 1(4), pp. 29–42, 2016. (In Russian)

[7] E. G. Gasho, A. I. Kiseleva, A. M. Fokina, “Carbon footprint of heating systems in relation to the type of a heat source,” Energy Systems, no. 1, pp. 55–60, 2022. DOI: 10.34031/es.2022.2.007. (In Russian)

[8] R. W. Howarth, “The greenhouse gas footprint of liquefied natural gas (LNG) exported from the United States,” Energy Sci & Eng., vol. 12, no. 11, pp. 4843–4859, 2024. DOI: 10.1002/ese3.1934.

[9] A. E. Ivanova, V. E. Zakharov, T. N. Petrova, “The Issue of Electricity Subsidizing in the Arctic zone of Sakha Republic (Yakutia),” in International Multi-Conference on Industrial Engineering and Modern Technologies, FarEastCon 2019, Vladivostok, Russia, Oct. 01–04, 2019, pp. 1–4. DOI: 10.1109/FarEastCon.2019.8934234.

[10] V. E. Zakharov, D. V. Prokhorov, N. V. Pavlov, “Russian Arctic region balance (Republic of Sakha (Yakutia)),” E3S Web of Conferences, vol. 114, Art. no. 02005, 2019. DOI: 10.1051/e3sconf/201911402005.

[11] V. E. Zakharov, A. E. Ivanova, T. N. Petrova, “Energy of the Arctic zone of the Republic of Sakha (Yakutia): current state and development prospects,” Economics of Russian East, no. 1, pp. 81–86, 2019. (In Russian)

[12] V. E. Zakharov, A. N. Kozlov, I. G. Donskoy, “Modeling the change in the heat of combustion of coal during its transit to the regions of the Far North: a case study of the Republic of Sakha (Yakutia),” Izvestiya RAN. Energetika, no. 6, pp. 132–141, 2018. DOI: 10.31857/S000233100003526-2. (In Russian)

[13] Resolution of the Government of the Republic of Sakha (Yakutia) (2005, Jul. 14). No. 433, On approval of fuel and energy resource consumption rates for heat generation by heating and industrial boiler plants of the Republic of Sakha (Yakutia). (In Russian)

[14] Order of the Ministry of Natural Resources of Russia (2022, May 27). No. 371, On approval of methods for quantitative assessment of greenhouse gas emissions and greenhouse gas absorption. (In Russian)

[15] State Standard (GOST) 30735-2001 “Hot water heating boilers with heat output up to 4.0 MW.” (In Russian)

Vasily E. Zakharov is a Research Fellow in the Department of General Energy Problems at the Larionov Institute of Physical and Technical Problems of the North, Siberian Branch of the Russian Academy of Sciences. His research interests include regional energy security, enhancement of the efficiency of fuel and energy supply to consumers in the Arctic region.