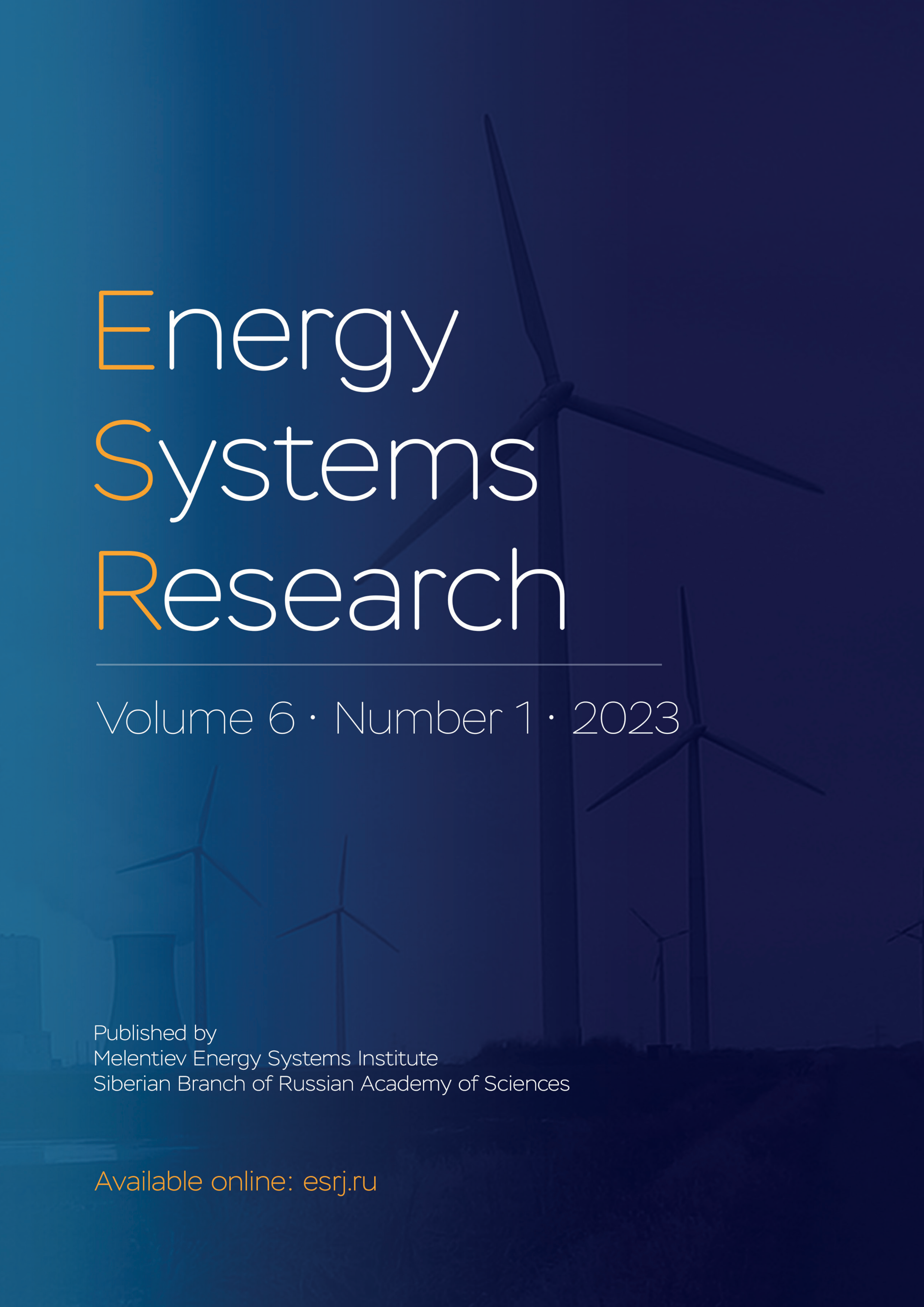

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Energy Systems Research is an international peer-reviewed journal addressing all the aspects of energy systems, including their sustainable development and effective use, smart and reliable operation, control and management, integration and interaction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

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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.

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Contacts

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

Contents

Regional Priorities of the Eastern Energy Strategy of Russia: the Past, the Present, and an Outlook for the Future

B.G. Saneev[1,*]

[1] Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The study elucidates key defining features of Russia's economic development in the new economic context that made it necessary to reconsider energy policy priorities. We present the initial conditions, targets, and strategic directions for development of the energy sector in the eastern regions of the country. The study highlights priority areas of energy cooperation in technological innovations between Russia and countries of Northeast Asia and lists prerequisites and initiatives needed for their successful implementation.**

***Index Terms*: Eastern Siberia, Russian Far East, Northeast Asian countries, eastern energy policy, energy sector, energy cooperation, international cooperation in technological innovations.**

I. Introduction

The unique features of Russia's economic development under the changed economic conditions have necessitated a reconsideration of the priorities of its economic and energy policy that had been adopted earlier.

Russia's national interests require intensifying its mutually beneficial energy cooperation with China, Japan, South Korea, and other countries of East and Northeast Asia [1, 2]. This priority direction of the country's energy sector development is referred to as «The Eastern Vector of Russia's Energy Policy» in official documents [3, 4], the essence of which, in conceptual terms, can be summarized as follows:

- creation of new energy hubs in the East of the country will help increase the energy security of Russia, restore and strengthen broken fuel and energy links between regions, solve a number of important problems on federal and regional levels;
- creation of mature energy infrastructure in the East of Russia and in Northeast Asia in the form of cross-border gas and oil pipelines and power transmission lines will reduce energy costs, increase the reliability of energy and fuel supplies to consumers in different countries, and be instrumental in addressing environmental issues.

Russia's eastern energy policy, being a part of its economic policy, is not an end in itself but a tool for facing many fundamentally important challenges at the federal, cross-regional, and regional levels.

II. Methodology

The basis for the development of a regional energy strategy can be a system of interconnected models, allowing for the development of energy programs of individual regions. The Melentiev Energy Systems Institute (ESI SB RAS) has developed appropriate methods and approaches to set up such a system of models [5, 6]. The Energy Systems Institute as part of its activities on the justification of the Energy Strategy of Russia-2030 and at the request of the regional authorities completed a large series of studies on the justification of long-term directions of development of the energy sector of the country and its eastern regions and several federal subjects of the Russian Federation situated within their borders [14–19].

As part of the overall research scheme (see Fig. 1) we have developed methods, models, software and information support for a comprehensive study of the problems of development and implementation of energy policy of Russia.

The basic methods and models (systems of models) of this general scheme include:

- models or studying external energy markets, i.e., the energy markets of the Northeast Asian countries;
- methods and a model for studying and making projections of the country's energy sector;
- methods and models for studying regional energy sectors and systems.

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

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III. Key Issues in the Development of a Regional Energy Policy

To develop an energy strategy, it is necessary to consider and address properly a number of important objectives: social, economic, political, geopolitical as well those related energy.

Social objectives are about improving the comfort, style, and quality of life of the population of Russia's eastern regions Economic objectives are related to improving operating efficiency and competitiveness of the economic system of the East of Russia, increasing the level of resource availability of the country and accessibility of the interior of the country, expanding active economic space of Russia, creating preconditions for attracting foreign capital and advanced technologies. Political objectives are related to the consolidation and integration of the federal subjects of the Russian Federation, strengthening the unity of the country's economic and energy space. Geopolitical objectives are aimed at strengthening Russia's position in the world economic system and in the community of Central and Northeast Asian states.

Addressing energy-related issues enables improving energy security performance of the country and its regions and ensuring greater adaptability and reliability of energy and fuel supply to consumers. Improvement of the territorial and production structure of the country's energy sector and especially its eastern regions, as well as the establishment of transport and energy infrastructure in eastern Russia (systems of oil and gas pipelines, power transmission lines enables creating a unified transport and energy space in Russia.

The eastern regions of the country – Eastern Siberia and the Russian Far East – with their powerful economic and energy potential are an outpost in the realization of Russia's national interests in this strategically important region of the world.

At present, Russia has completed a complex and laborious stage of work on forming a large number of policy documents, determining the strategic development of the economy and energy in the East of the country to 2030, taking into account energy cooperation between Russia and the countries of Northeast Asia: «The Energy Strategy of Russia to 2030» [4], the Eastern Gas Program – «The program of creating in Eastern Siberia and the Far East of a unified system of gas production and transport as well as gas supply considering possible gas exports to the markets of China and other countries of Asia-Pacific Region» [8], «Strategy of socio-economic development of the Russian Far East and Baikal area to 2025» [9], «Strategy of socio-economic development of Siberia to 2020» [10], etc.

The strategy for the long-term development of the energy sector of Eastern Siberia and the Russian Far East assumed a number of initial conditions and targets, the key among which are the following two.

1. In the next 15–20 years Russia will not be able to face head-on the challenge of making a foray into the

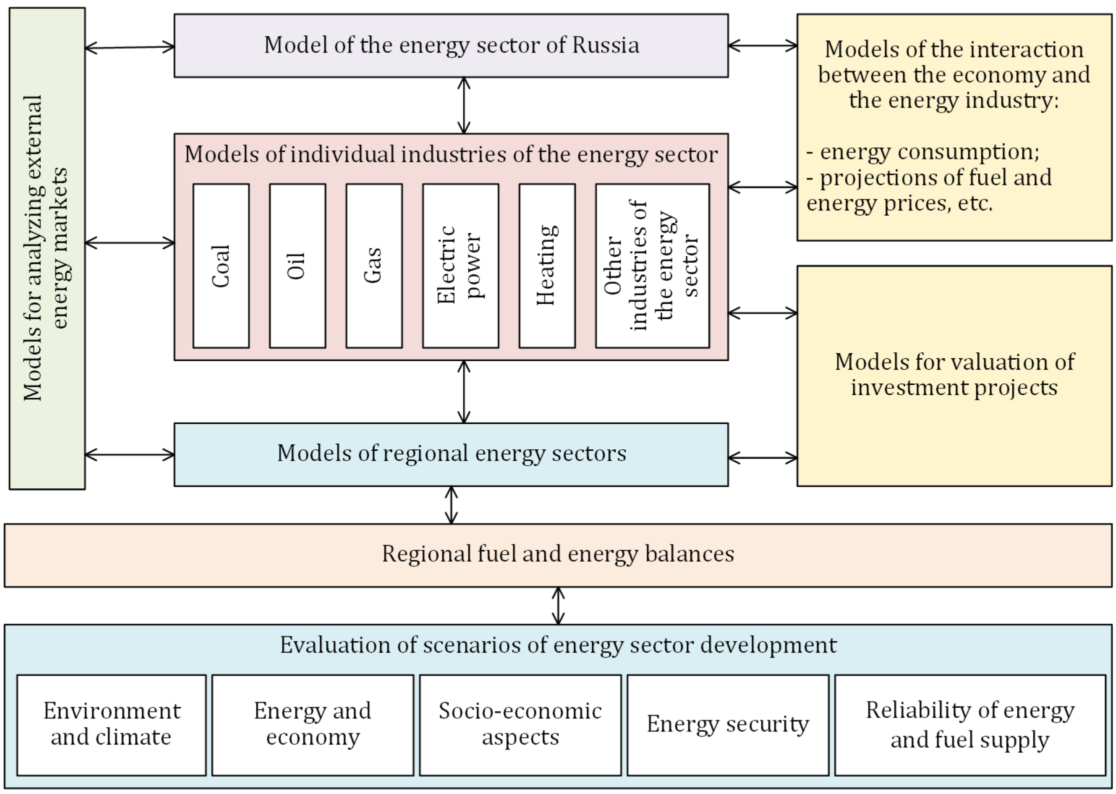

Fig. 1. The general scheme of hierarchical modeling of research on the development of the energy sector of the country and its regions.

undeveloped areas of Eastern Siberia and the Russian Far East. Therefore, the key is to preserve and strengthen the basis for future development.

This can be achieved by implementing the so-called strategic scenario of economic development of these regions. The strategic scenario of economic development of the eastern regions assumes that the economy of Russia and the eastern regions in qualitative and quantitative terms should approach the current average European level. At the same time, the economic growth rates in the regions under consideration should be above the Russian average. It is also envisaged to increase the share of these regions in the total population of the country.

2. Development of the energy industry in Eastern Siberia and the Russian Far East within the time frame under consideration will be focused not only on meeting its own demand for energy carriers but also on ensuring exports of Russian fuel and energy resources to energy markets of Northeast Asian countries.

Our analysis of the energy markets in China, South Korea, Japan, and other countries of Northeast and East Asia indicates that these countries have a niche for Russian energy resources, and Russia is ready to supply these countries with the following quantities of fuel and energy resources on mutually acceptable terms [4, 7, 11]: oil – from 69 mln tons in 2016 to 75–80 mln tons in 2030; natural gas – from 15 bln m^3 in 2016 to 50–60 bln m^3; coal – from 70 mln tons in 2016 to 75–85 mln tons; electric power – from 3.6 bln kWh in 2016 to 45–50 bln kWh.

In the context of new global and regional challenges, it is fundamentally important for Russia to pursue an active policy on technological innovations in its cooperation with the Northeast Asian countries in addition to trade in energy resources.

IV. Priority Areas of Energy Cooperation in Technological Innovations Between Russia and the Northeast Asian Countries

Russia's participation in the creation and joint management of *new oil and gas-chemical clusters* requires consideration of the following factors.

1. Currently, in Russia at all levels we are clearly aware of the need to supply international markets not only with mineral resources but also with its elaborately processed products with high added value. To this end, it is proposed to increase the production of petroleum products in the eastern regions of Russia, to create new industries for them to specialize in: oil-, gas-chemical industries, the demand for the products of which in Russia, globally, and in Northeast Asia is large enough. In the future, Russia could become the largest net exporter of polymer products in the region.

2. It is known that the oil and gas fields of the Siberian platform are unique for their helium and ethane content. For example, natural gas from Siberian platform fields contains 0.3–0.5% helium and 4.6–7.2% ethane. Helium reserves (categories C1+C2) of the Siberian platform are estimated at 8.5 bln m^3, or approximately 30% of the world's reserves. In the long term, Russia could become the largest exporter of helium.

The Ministry of Energy of Russia worked out the Plan of oil- and gas-chemical development in Russia to 2030, which was approved by the government commission on the energy sector on December 28, 2011, and its elaboration (Stage II) [12] was approved by Order No. 79 of the Ministry of Energy of Russia of March 01, 2012. The Plan provides for the creation of six new oil- and gas-chemical clusters in Russia by 2030:

- Northwestern;
- Caspian;
- Volga;
- West Siberian;
- East Siberian;
- Far Eastern.

Russia is interested in fruitful cooperation with foreign companies to form new oil and gas chemical clusters in the East of the country and to have joint sales of produced polymer products in Russian and foreign markets.

Russia's participation in the formation of cross-border power interconnections in Northeast Asia involves cross-border integration and cooperation in the area of electric power and is one of the components of Russia's Eastern Energy Strategy. This cooperation presupposes the development of cross-border electric power connections of eastern regions of Russia with «neighboring» countries: Mongolia, China, Japan, North and South Korea. What it involves is the possible parallel operation of the power systems of Eastern Russia (Eastern Siberia and the Russian Far East), Mongolia, the People's Republic of China, North and South Korea, and Japan. The area covered by such a cross-border power super-interconnection could include various types of power plants (thermal, hydro, nuclear, wind, etc.) with a total installed capacity of more than 500 million kW.

Eastern Siberia and the Russian Far East have built a major power base for the country: over 20% of the capacity of all Russian power plants is installed in these regions. The electric power export potential of the eastern regions that can be quickly deployed, according to various estimates, is 10–15 million kW, including 6–7 million kW in Eastern Siberia and 4–8 million kW in the Russian Far East.

Our calculations are supportive of the claim that reconstruction of existing power plants, completion of construction projects of power plants that are currently in progress, and commissioning of new power plants scheduled for construction in the near future in Eastern Siberia alone will allow for a large surplus of electricity (according to various estimates, from 30 to 40 billion kWh). This amount of electricity can be delivered via high-voltage power transmission lines both to the southeast (Mongolia, China) and to the Russian Far East. The construction of a high-voltage power transmission line between Eastern Siberia and the Russian Far East will enable the IPSs (integrated power systems) of Siberia and the Russian Far East to operate in parallel, which will improve the reliability of power supply to consumers in these regions and create the necessary preconditions for the formation of the Eastern Wing of the global electric power system [13, 14].

At present Russian companies are investigating the possibility of joint construction in Russia, in cooperation with foreign companies, of export-oriented power plants and high-voltage power lines for large-scale electricity exports (in the amount of 60–70 billion kWh) from the eastern regions of Russia to the People's Republic of China, 20–25 billion kWh to the Republic of Korea, and 25–30 billion kWh to Japan. Russia and China can actively and fruitfully cooperate with Mongolia to form the cross-border Russia-Mongolia-China electric power system [15].

Russian electric utilities along with research and design institutes are actively involved in developing the concept of forming the Asian Super Grid [16].

Russia can actively and effectively cooperate with Mongolia in forming the Gobitec and using the potential of solar and wind power to create the Asian Super Grid.

Cooperation on innovative technologies in the coal sector is related to joint projects on integrated and involved processing of lignites and the creation of a new industry for the differentiation of the East of Russia in the form of coal-chemical production clusters.

The reserves of lignites in Eastern Siberia and the Russian Far East amount to more than 85 billion tons [17]. The largest lignite deposits include:

- deposits of the Kansk-Achinsk Basin in the Krasnoyarsk territory;
- Svobodninskoye and Sergeevskoye deposits in the Amur region;
- Kangalasskoye deposit in the Republic of Sakha (Yakutia);
- Ushumskoye deposit in the Jewish autonomous region;
- Mukhinskoye deposit in the Khabarovsk territory;
- Solntsevskoye deposit in the Sakhalin region.

Given the relatively low costs of coal production, it makes sense to organize joint ventures with foreign companies for comprehensive advanced processing of lignited on the basis of these deposits.

Products of advanced processing of coal (primarily motor fuel) can be supplied to Russian and foreign consumers.

Cooperation in securing *a reliable energy supply to isolated and remote consumers* in Russia's eastern regions through the construction of facilities that use renewable energy sources is also a promising area to be addressed by the regional energy policy. The draft of the Energy Strategy of Russia-2035 [18] provided during this period for a large-scale adoption of renewables (RES): it predicted an increase in the penetration of RES into total electricity generation from the current 0.2% to 3% in 2035. This is especially important for the economy of the eastern regions.

The use of renewable energy sources (mini-HPPs, geothermal power plants, solar and wind power plants) is a strategic priority for the development of the energy sector in the northern and remote communities of the East of Russia.

Total RES capacity additions in the areas of decentralized and unstable power supply in the eastern regions of the Russian Federation to 2035 are estimated at 600–870 MW under the baseline and moderately optimistic scenarios, respectively [19]. The largest share of the capacity of renewable energy sources commissioned in Eastern Siberia is accounted for by solar power plants (287–318 MW). In the regions of the Russian Far East, wind farms (84–155 MW) account for the great bulk in the mix of capacity additions. The total installed capacity of RES in the eastern regions by 2035 will increase 5.5–7.5 times and will reach 727–1,000 MW, of which 335–385 MW is solar power plants, and 100–210 MW is wind farms.

The most promising for the development of wind power in the East of Russia are the Kamchatka territory, Kuril Islands of the Sakhalin region, Arctic coast of the Krasnoyarsk territory and the Republic of Sakha (Yakutia), the eastern part of the Magadan region, Khabarovsk and Primorsky territories, and the north-east of the Chukotka autonomous district.

Priority areas for the development of solar power are the republics of Buryatia, Tyva, Khakassia, Sakha (Yakutia), Transbaikal territory, southern areas of Irkutsk and Amur regions.

We can expect fruitful cooperation with foreign companies in the construction of renewable energy sources and the creation of joint ventures in Russia's eastern regions.

Examples of such cooperation are joint projects with the Japanese companies Komichaltes Inc. and MITSUI & CO., LTD. for the construction of wind farms in the urban locality of Ust-Kamchatsk, Kamchatka territory, and the urban locality of Tiksi, Republic of Sakha (Yakutia).

V. Conclusion

Key takeaways from the research conducted to identify the regional priorities of Russia's Eastern energy strategy, both at present and in the future, are as follows:

1. The implementation of Russia's Eastern Energy Strategy is a very complex issue. Its complexity is due to its comprehensive nature as well as that it is implemented on a vast territory and involves a large number of Russian and foreign participants. Furthermore, program activities (especially cross-border fuel and energy projects) are very capital-intensive, and their implementation presupposes close international energy cooperation of countries at the federal (state), regional, and cross-regional levels.

2. The time is ripe to develop a strategy (roadmap) for energy cooperation between Russia and the countries

of Northeast Asia. Such a strategy, being backed by solid research data, should make clear what are the sequence of development of fuel and energy resources, the sequence and timing of their supply to their own consumers, the volume of exports/imports. It should also assess the socio-economic and other consequences of specific cross-border projects not only for individual companies but also for regions and the country as a whole.

3. To promote mutually beneficial forms of energy cooperation between Russia and the NEA countries, at the very least the following five conditions are to be met:

1) There must be a political will and a seriousness of intention on the part of the participants to implement a specific energy project that is mutually beneficial to each of the countries involved.

2) The economic and energy policies of central and regional authorities and businesses of the countries must be aligned during the formation of international projects in the field of energy.

3) A comprehensive, systematic assessment of the consequences (effects) for countries, regions, and energy companies resulting from the implementation of large international energy projects (especially so under great uncertainty of future development, economic risks, and global challenges) have to be carried out.

4) Mutually acceptable mechanisms for implementing international energy projects (organizational, economic, legal, and other mechanisms) have to be developed.

5) Projects that are international in their nature should be developed and implemented by an international team (at all stages: from the feasibility study and design work to their practical implementation).

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Boris G. Saneev, Prof. Dr. of Sciences in Engineering, Research Leader in Complex Energy Problems and Regional Energy Policy, Head of Department of Complex and Regional Problems in Energy at the Melentiev Energy Systems Institute SB RAS, Irkutsk, e-mail: saneev@isem.irk.ru

Change in the Architecture of Energy Markets in North-East Asia

S.P. Popov*, D.V. Maksakova, O.A. Baldynov

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The paper aims to identify promising areas of energy cooperation between Russia and the countries of East Asia. A review of the main groups of factors (technological and techno-economic, energy security, geopolitical, and economic), which influence the change in the existing architecture of energy markets, is made. Assumptions are made about the directions for the development of the transport and institutional infrastructure for energy export from Russia. The findings indicate the need for accelerated development of hydrogen technologies and emphasize the importance of energy cooperation institutions. The paper proposes creating a new regional market, i.e., the market for green certificates for hydrogen.**

***Index Terms*: North-East Asia, regional energy markets, energy infrastructure, energy policy, international energy cooperation, hydrogen technology.**

I. Introduction

At the beginning of the 21st century, “The world is on the verge of global changes in energy,” as the title of the paper by A.M. Mastepanov emphasizes [1]. The external conditions for these changes are created by close interrelation and interweaving of the circumstances such as the limited and depleted hydrocarbon resources most accessible technically and economically; the high rates of scientific and technological progress, and the commercialization of renewable energy technologies; the growing human welfare and the increasing political significance of social and environmental factors; as well as a deep systemic crisis of the globalization process.

The totality of these circumstances regarding the object at issue, i.e., energy markets in the region of North-East Asia (NEA), indicates a rapid increase in the influence of the geopolitical factor on these markets. It clearly manifested itself in February 2022, after the start of a special military operation by Russia against the Nazification and militarization of Ukraine.

This event became a catalyst for the creation of new coalitions to build a multipolar world, the process that had already started by that moment. The political engagement of such an “ideal” political occasion is seen in the official statements made by the leaders of the “Western” institutes for economic and energy cooperation. F. Birol, director of the IEA OECD, pointed out in the preface to the forecast for the world energy development until 2050: “When people misleadingly blame climate and clean energy for today’s [energy] crisis, what they are doing – whether they mean to or not – is shifting attention away from the real cause: Russia’s invasion of Ukraine” [2]. Confirmation of the seriousness and long-term intentions of the coalition of “Western” countries (including such organizations as the G-7, AUKUS, etc.) in relation to Russia can be found in an analytical article on the new mechanism for regulating oil markets, prepared by T.A. Mitrova, Research Fellow at Columbia University’s Center for Global Energy Policy. A document published in mid-December 2022 by the Carnegie Endowment states that “… in a decade, Russia’s status as an energy superpower, which it claimed, will be a thing of the past” [3].

On the other hand, it must be underscored that the depletion of non-renewable energy resources (NRER – coal, hydrocarbon raw materials, uranium), the extraction of which is economically justified, is objective and inevitable. Thus, the energy transition (Energy transition is a long-term change in the energy consumption structure affected by resource, techno-economic, environmental, and geopolitical factors) process is currently beginning to take on the features of a struggle for appropriation of part of the natural resource rent of NRER between Russia and non-“Western” countries exporting hydrocarbon raw materials, and some energy importing countries.

Next, we will consider the main factors influencing the transformation of the architecture of energy markets in the NEA region.

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

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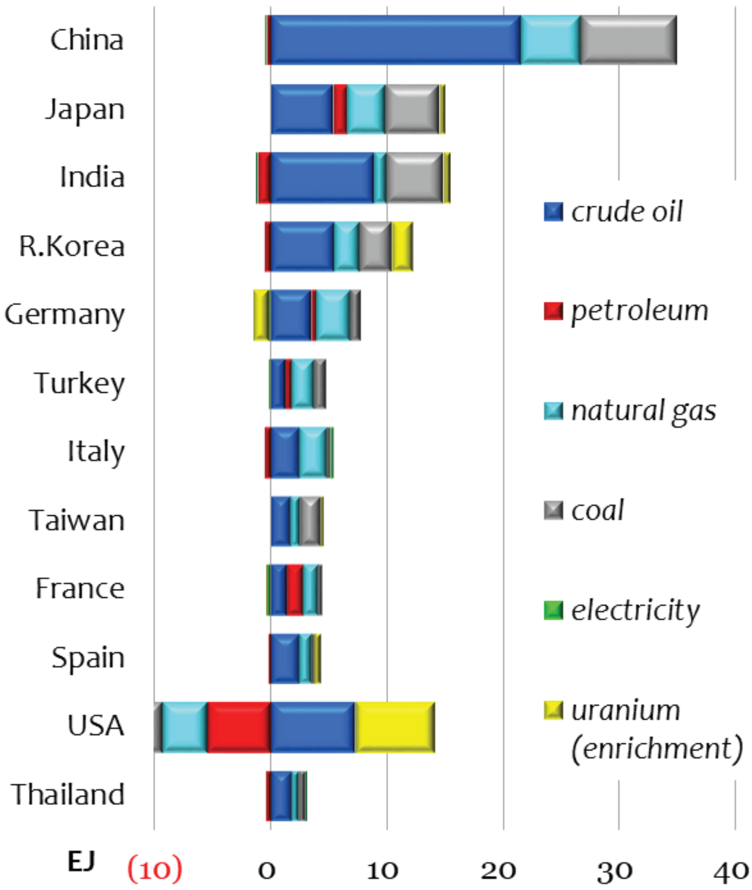

Fig. 1. Top net energy importers in 2021 (EJ).

II. Factors of Changing the Architecture of Energy Markets

The last decade was characterized by the growing role of the geopolitical factor in the development of energy infrastructure and the formation of a situation in the energy market. European market saw energy consumption stagnation accompanied by the statements about the need to diversify supplies and cut down the dependence on Russian imports, later supplemented by binding targets to reduce greenhouse gas emissions by eliminating the use of fossil fuels. At the same time, the high rates of economic growth and the increase in the well-being of the population in some of Asian countries, and in particular in East Asia, contributed to the growth in demand for energy carriers, primarily for oil and natural gas. On the supply side, the shale revolution in the United States allowed this country, after 50 years, to enter the global hydrocarbon market, which significantly diminished the possibilities of the regulatory mechanism within the OPEC.

Analyzing the current state of the world energy markets, we will take as an initial premise the statement that "any geopolitical changes are based mainly on the parameters of the capital redistribution, namely, competition for resources and access to them, for commodity flows, for redistribution of existing markets and capture of new ones, increase in the profits, for a wider area of application of their currency, etc." [4]. Without pretending to comprehensively consider the impact of the "energy transition" on the world trade in energy resources, we will focus on the groups of factors, which determine the changes in the architecture of the energy markets in the countries of East Asia (EA). These are technological and techno-economic factors, energy security, struggle of industrial and financial capital for world markets for energy carriers and energy technologies, and geopolitics.

Technological and techno-economic factors of the global energy transformation

The growth in the cost of conventional energy resources (another name for NRER) and their limitations at the end of the second decade of the 20th century led the world to adopt a new energy development paradigm based on the concept of "energy transition." It is based on the rejection of the use of fuel energy resources (coal and hydrocarbons), and the transition to "carbon-free" energy. In the strict sense of this term, "carbon-free" energy refers to renewable energy sources (RES) only, including hydropower and biomass, but excludes nuclear energy. However, recently, there has been more support to the view that nuclear energy should also be classified as "carbon-free" or "green" energy (with the criterion of environmental efficiency identified as the criterion of CO_2 emissions).

The rapid (by historical standards) depletion of economically viable NRER reserves (not resources!) had become one of the main factors in the growth of the political narrative for globalization and the adoption of sustainable development goals by the UN before signing the 2015 Paris Agreement on “combating climate change.”

The requirements for the enhancement of the energy efficiency stem from the increasing cost of energy carriers and reflect the finiteness of the NRER. For a long time after the first world oil crisis in 1973, Japan acted as an example of the development and implementation of a national energy saving strategy. Such a policy, in the context of the rapidly developing economy of the country, was used both as a mechanism to reduce the need for energy imports and as a driving force for the growth of exports of energy-efficient goods and technologies.

The commercialization of wind and solar power generation technologies at the beginning of the 21st century is based on a sharp decrease in specific investment in wind generators and photovoltaics. At the same time, the high rates of improvement in these technologies led to the fact that already at the beginning of the third decade of the 20th century, there were signals that the lower limits of the unit cost of such generation had been reached.

The current stage of advancement in battery technology, which began at the end of the last century with the development of lithium-ion batteries for portable electronic equipment, two decades later enabled a large-scale transition of passenger vehicles to electric cars. The successful commercialization of next generation batteries has already led to the displacement of traditional motor fuels in Europe and East Asia based on the energy policy mechanisms that indicate the temporal stages of a ban on the production of non-electrified road transport [5, 7].

The formation of prerequisites to the commercialization of hydrogen technologies for the production of synthetic fuels based on hydrogen produced by electrolysis of water (e-fuels – such as “green” hydrogen, ammonia and methanol; biofuels, etc.) is even a more serious factor in the displacement of traditional motor fuel from transport sector. In addition, these technologies open a new stage in the development of interseasonal electric power storage systems in power systems characterized by a significant share of intermittent renewable generation.

A significant factor in the transformation of energy markets is the “revival” of nuclear technology after decades of stagnation caused by three well-known disasters – Three Mile island, Chernobyl, and Fukushima. Against the backdrop of the aggravation of global nuclear energy issues, including the need to dismantle aging and closing nuclear power plants, the organization of a nuclear fuel cycle and non-proliferation of weapons of mass destruction, improved nuclear technologies (safer low-power reactors) were developed and the stage of their commercialization started. The importance of nuclear energy is currently recognized even in the EU [8].

Thus, the development of electrical (RES), hydrogen and nuclear technologies is becoming one of the central factors in the transformation of energy systems, the driving force behind the creation of new markets for carbon-free energy carriers, energy technologies and equipment, and energy supply services.

Energy security

The structure and size of the major energy trade balances for the world’s largest net energy importers as of 2021 is shown in Fig. 1. Four of the six East Asian (EA) economies ranked first, second, fourth and eighth respectively in this list. The desire to improve their energy security in the face of insufficient NRER reserves (in the case of China) or almost their complete absence (Japan, R. Korea, Taiwan) is expressed in the following components of their national energy strategies: firstly, increasing energy efficiency in all sectors of energy consumption; secondly, diversifying the structure and sources of energy imports; thirdly, developing the technologies using synthetic fuels based on renewable energy sources (e-fuels).

Enhancement of energy efficiency and change in the structure of the economy in favor of the service sector and less energy-intensive industries was reflected in the decline in energy consumption in Japan and in the stagnation of final energy consumption in R. Korea and Taiwan. In contrast, energy consumption in China continues to grow, despite the adoption of some measures to increase energy efficiency. The greatest potential for further growth in primary energy consumption however is represented by RES (generation of electricity based on the country’s solar and wind energy resources), as well as the gas market – due to the replacement of coal with gas in the power industry, and conversion of buildings and transport to gas.

On the supply side, the security of supplies and their economic efficiency is ensured by the participation of companies from East Asia (mainly state vertically integrated companies and owners of energy infrastructure in the national domestic markets of their countries) in energy projects abroad, and the organization of imports based on these projects under long-term contracts. Such mechanisms to some extent determine the predictability of the structure of energy supplies and ensure the stability of Russia’s trade and economic relations with the partners from East Asia. Against the backdrop of the sanctions imposed in 2014, Japan and R. Korea began to be wary of new gas projects in Russia. However, even with the situation worsened in 2022, these countries do not plan to withdraw from existing joint ventures, and China has become the largest foreign investor in the Russian LNG industry [9].

The struggle of capital for world energy markets

The emergence of new shale oil producers and the creation of the possibility for exporting LNG from the

United States after the shale revolution led to increased competition in the global oil and natural gas markets. The American energy business found support in the face of the US government, which, through intergovernmental negotiations, is trying to increase the supply of these energy carriers to foreign markets. However, due to relatively high costs, in the context of falling oil prices in 2014 because of an excess oil supply (OPEC + could not change the situation on account of the inconsistency of positions both within the cartel and between the cartel and oil exporters not included in it), and against the background of a decrease in the consumption of petroleum products caused by the global COVID-19 pandemic in 2020, US companies could not strengthen their positions in the oil market.

The lack of economic prerequisites for the growth in the share of US energy exports of hydrocarbons in world markets led to attempts to position these homogeneous goods (light oil and LNG) as those having some additional value according to non-market criteria – for example, as more "reliable," more "environmentally friendly," and so on. Accordingly, the increase in energy exports from the United States to European countries that have abandoned Russian energy resources can be viewed, on the one hand, as the result of the use of political influence tools, and, on the other hand, as protectionism in the formation of sales markets for "their" companies.

The latter circumstance takes on particular weight in the context of chronic underinvestment in oil and gas projects in other countries, which has been observed over the past decade (see the next section). High energy prices in the face of an artificially created shortage of supply allow US business actors not burdened with long-term contracts to receive additional profits not only due to increased sales, but also due to higher prices. In other words, long-term planning and successful implementation of the US geopolitical course to squeeze Russia out of the European hydrocarbon markets created favorable opportunities (based on the most efficient use of financial instruments) for the development of the shale industry and related sectors of the economy of this country.

Additional business interests associated with the production and use of shale oil and gas include positive effects for the local and national economy. These are the development and operation of fields, the transportation of oil and gas condensate by rail and road, the re-equipment of previously built terminals for receiving LNG into LNG export plants, the development of an industry for the production of equipment for building LNG infrastructure. Huge investments were made in the financial, consulting and political sectors of the US economy to prepare and create international institutions for LNG trading, primarily pricing mechanisms.

The international financial and industrial capital plans to carry out activities similar in scope and scale when implementing the policy of "energy transition" at the global level. At least since the G-20 summit in Osaka (2019), political consolidation has been carried out to maximize the coverage of nation states subordinate to transnational corporations and financial capital in order to transition to a "new technological order of the economy" based on hydrogen technologies. A directive accelerated introduction of "carbon-free" energy technologies (renewable energy and hydrogen energy, transport electrification, small modular nuclear reactors) is expected for this community, with the help of the institutions of the "energy transition" and the "fourth technological revolution." Thus, international capital organizes channels for large-scale investments: "Industries helping the world shift to net-zero emissions could be worth $10.3 trillion to the global economy by 2050, sustainable development consultancy Arup and economics advisory firm Oxford Economics said in a report" [10].

Geopolitical factors in the transformation of world energy

The main geopolitical factor associated with the challenges of energy infrastructure development is the current relative inaccessibility of hydrocarbon resources and critical materials. The latter are particularly acute for the technologies of "green" "carbon-free" energy. Relative inaccessibility refers to the ratio of reserves and resources that can be disposed of by national/private and transnational mining companies. In essence, this is the problem of the distribution of natural resource rent among world economic and geopolitical actors.

The growth in specific energy consumption by developing economies (such as India, China, the countries of Southeast Asia, Africa) indicates the importance of the problems of energy inequality and energy inaccessibility, which are necessary to solve for the socio-economic development of these countries.

The statements and unilateral measures of some governments in the field of carbon-free energy development, which is promoted as the basis for achieving climate goals, are becoming an instrument of political influence on international energy markets. A vivid manifestation of the surge in the political narrative on "fighting climate change" was the emotional speech of 16-year-old Greta Thunberg at the UN Climate Change Action Summit in 2019, within the framework of the UN General Assembly. This activist announced the beginning of an environmental catastrophe due to the inaction of politicians who do not take decisive measures to reduce greenhouse gas emissions from the rostrum of the highest international body.

An important issue of international energy cooperation remains the adequacy of investments and the existing capacity of the infrastructure for transporting energy carriers, both universal and specialized (pipelines, power lines, tankers). Solving this problem is significantly influenced by the uncertainty and ambiguity of the processes of formation of new geopolitical coalitions and institutions of energy cooperation. The latter include consideration of such factors as the provision of transit goods flows (including shipping through the sea straits), the level of energy security (including the problem of maritime terrorism / piracy), pricing (spot and long-term contracts), which together affect the viability and efficiency of investment projects in the energy sector.

The desire to avoid a situation of monopsony in the gas market in the segment of pipeline supplies is a factor pushing Russia to look for mechanisms to maintain its presence in the European market (the creation of a gas hub in Turkey, swap supplies, and others are being discussed). The strategic objective of Russia in the field of cooperation with China and Mongolia, which do not refuse to import Russian energy resources, is to deepen it in the context of technological and investment partnership. This direction will allow Russia to act in the reformatted energy markets in developing countries not only as an exporter of energy resources with low added value, but also as an investor, contractor and supplier of equipment and services for end energy consumers.

As the role of renewable energy in providing primary energy increases and the "energy transition" deepens, the concept of energy imports, and, accordingly, the definition of the energy security of the economy, is going to be significantly transformed. "The concept of *an energy superpower* will change its content. This will not be a "custodian" and "producer" of large volumes of fossil fuels, but a manufacturer and developer of equipment and technologies for a new [carbon-free] energy industry" [11].

East Asian energy security policy

Unlike the EU countries, since the beginning of the conflict in Ukraine, the EA countries have been pursuing a significantly more "cautious" policy in relation to the import of Russian energy resources, not yet supporting a complete rejection of it. Thus, Senior Research Fellow Assistant Director of the Institute of Energy Economics of Japan (IEEI) I. Kutani gives the following assessment of the current situation: "We should not ignore the fact that, for a large proportion, improving people's standards of living and developing industry are top priorities, and climate change measures are merely side issues. *European policy to end dependency on Russia have strengthened this view*… The outcome of the war between Russia and Ukraine is unclear. Given this unavoidable external factor, we should consider how best to increase future profits and competitiveness amid the given environment." [12].

The chairman and CEO of the IEEI Tatsuya Terazawa, speaking about the need for "de-Russianization" of the energy sector, gives the opinion of Japanese experts on the timing of achieving carbon neutrality: "the decarbonization process cannot be completed in the short nor even in the medium term" [13], which implicitly but firmly links together the problems of energy security, NRER trade, and geopolitical processes.

Although Japan and the Republic of Korea have stopped technical and scientific cooperation with some Russian companies and institutions, because of their connection with the defense industry of the Russian Federation, these countries currently do not completely refuse to import Russian energy resources and participate in existing joint ventures in the energy sector.

China has political disagreements with some Western countries and is likely to continue to strengthen its relations with Russia as a geopolitical partner, while ensuring an acceptable level of prices for its energy imports. Chinese Foreign Minister Wang Yi, speaking at a symposium on Chinese diplomacy in December 2022, noted the following: "Throughout the year, China and Russia have firmly supported each other in upholding fundamental interests; our political and strategic mutual trust has further strengthened … [Relations between China and Russia] are free from interference or attempts to sow discord between the two countries and are immune to changes in the international environment" [14].

Thus, the EA countries will continue cooperation with Russia in the energy sector, but its nature will change. Japan and R. Korea, at least in the medium term, will not look for places in the Russian energy sector to invest their capital [15, 16].

III. Example of the World Gas Market

The gas market is one of the most illustrative examples of the ongoing transformation of commodity and financial flows related to energy. This has many explanations. First, the global gas market is just emerging, as the three largest regional markets in the west and east of Eurasia are merging against the backdrop of the rapid pace of China's gasification. Secondly, the United States began to use the so-called "shale revolution" as a tool for solving its geopolitical and socio-economic problems.

The financial and political tandem of the United States and large companies of LNG importing countries creates opportunities for building a logistics infrastructure and related institutions (which will provide arbitrage LNG supplies and mechanisms for related services). In this case, both the Atlantic (western Eurasia, mainly the pipeline gas market with a large share of Russia on it) and the Pacific (the world's largest center of LNG consumption in the east of Eurasia, where China surpassed Japan in terms of imports, and where Russia started to supply pipeline gas as well) regional markets prove interrelated.

The desire of developed countries to diversify the structure of imports and reduce import dependence through the development of renewable energy, supported by the goals of "fighting climate change," became a key factor in underinvestment in the oil and gas, and coal industries. Thus, whereas by 2020 world oil consumption decreased by 5.6% compared to 2015, the investments in the oil industry declined by more than 40% (see Fig. 2); similarly in the coal industry, where consumption fell by 2.5% and investment by 16.2%. At the same time, investment

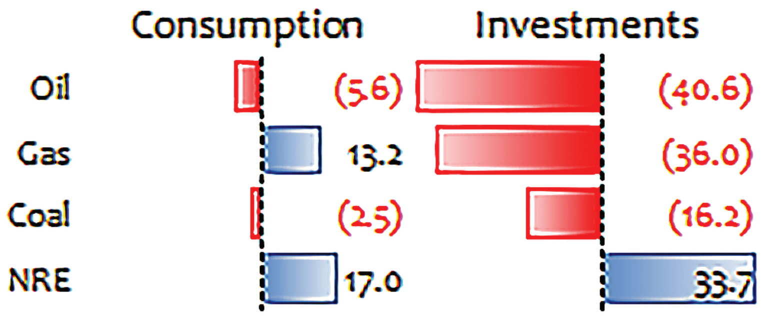

Fig. 2. Growth in energy consumption and investments in energy in the world in 2015-2020, %. Source: estimation based on [17].

in renewable energy grew at a faster rate than renewable energy consumption.

Paradoxically, even in the gas industry, where consumption grew by 13.2% (slightly less than the 17% increase in renewable energy consumption), investment fell by 36%. It is noteworthy that in the period of 2015–2020, most of the gas liquefaction capacities, for which final investment decisions were made, were in projects in the United States [18]. In the field of pricing in the gas market, some importers (primarily some European countries and the United States) pursued a policy of promoting trade based on short-term contracts and peg to prices in gas hubs [18], which did not help reduce uncertainty and stimulate investment in new projects.

The stagnation of demand for energy resources in developed countries, against the backdrop of statements about the abandonment of NRER, became one of the key factors in the formation of a trend (which emerged in 2018) towards a decrease in world prices for these goods. This trend was reinforced in 2020 by the global economic downturn caused by the impact of the COVID-19 pandemic. At the same time, already in 2021, oil and gas prices began to increase, due to the recovery in demand in the face of limited production capacity.

In 2022, Western countries introduced new packages of sanctions against Russia. The new restrictions entailed some technical, organizational, financial, and logistical difficulties, which manifested themselves in the maintenance and repair of imported equipment in Russia, in delays in payments under foreign trade contracts, and an increase in the cost of chartering tankers. In an attempt to reduce the oil and gas revenues of the federal budget of Russia, mechanisms were introduced to limit the price of hydrocarbons exported by Russia. In May 2022, the European Commission published a plan to reduce energy imports from Russia and create a new European energy infrastructure – REPowerEU. The plan includes an increase in LNG imports from the US and Canada, as well as pipeline gas and LNG imports from Norway. It proposes strengthening cooperation between the EU and Azerbaijan (in terms of expanding the Southern Gas Corridor) and establishing an energy dialogue with the countries of the Middle East, North and East Africa, and Australia.

A striking and intensely hushed up geopolitical event in 2022 was the terrorist attack on the main underwater gas pipeline systems Nord Stream-1 and Nord Stream-2. Four months have passed but nobody has named either the perpetrators or the beneficiaries of this largest act of terrorism on the offshore energy infrastructure.

A highly unusual circumstance in the European market is the fact that since autumn 2021, gas prices and their volatility have settled at significantly higher levels than in East Asia. Prices continue to be maintained at such levels to ensure the attractiveness of this market for LNG exporters in the face of a rapid reduction in pipeline gas supplies from Russia. Previously uncompetitive LNG from the US is becoming a key source of gas supplies to the EU. In turn, the EU generates an important steady stream of profits for the United States, attaching an additional factor of political influence based on ensuring "energy security." Whereas in 2021 the United States exported 34 billion m^3 of natural gas to European countries (35% of the total volume of LNG exports from the United States), in the first half of 2022 these figures amounted to 39 billion m^3 and 68%, respectively [19].

At the same time, Asian buyers are also feeling the rise in energy prices. According to the speech by IEA Executive Director F. Birol at the opening of the 43rd IAEE Conference on August 1, 2022 in Tokyo, "this is the first global energy crisis." For the countries of Europe, the main objective during this crisis is to ensure the physical volume of hydrocarbon supplies in the face of infrastructural and institutional restrictions imposed by the EU itself. For Asian countries, the key objective is to maintain an acceptable price level in the context of the growing demand from China. In such a situation, an important factor in the development of the global gas market is the increase in pipeline gas supplies from Russia to China (there is a growing volume of gas exports to China through the Power of Siberia gas pipeline); the project of a gas pipeline to

Table 1. Russia's Energy Exports in 2020

Regional Energy Markets	Quantity, Mt	Value, bn USD
Coal & Coke		
Atlantic	89.5	5.3
South Asia	11.3	0.9
Pacific	112.8	7.1
Oil & Petroleum Products		
Atlantic	253.5	76.9
South Asia	9.6	2.9
Pacific	118.2	38.3
Natural Gas		
Atlantic	147.8	n.a.
South Asia	–	n.a.
Pacific	10.2	n.a.
Electricity		
Atlantic	–	3.7
South Asia	–	4.4
Pacific	–	..

Note: ".." – less than 100 thousand USD; n.a. – not available; "–" equals to zero.
Sources: [22].

China through Mongolia (with a capacity of 50 billion m^3 per year) and a project for the supply of 10 billion m^3 of gas from Sakhalin Island (under the contract signed with China in early February 2022) continues to be worked out [20, 21].

Summing up the analysis of the current stage of the global gas market development, we conclude that its architecture is being rebuilt (Building Back Better) under the significant influence of the political line of world actors, the beginning of which (influence) was laid long before the aggravation of the geopolitical situation in 2022.

IV. Energy Transport Infrastructure

Russia is the world's largest energy exporter. Table I shows the scale of energy exports in 2020 from Russia to three main markets: the Atlantic (mainly representing the countries of the west of Eurasia), the Pacific (the core of which is the countries of East Asia), and the South Asian (which unites energy importers from South and Middle (Central) Asia).

The prerequisites for a new infrastructure for energy export from Russia were in place even before 2022. The narrowing of the capacity of European energy markets and Russia's orientation towards the markets of the Asia-Pacific countries and India were enshrined in the Energy Strategy of the Russian Federation for the period up to 2035 (adopted in June 2020) and some sectoral programs. The current geopolitical situation dictates the need for an accelerated reorientation of energy exports from Russia from western to eastern and southern directions. Such abrupt changes adversely affect both Russia (increasing transportation distances in competitive markets leads to lower rental income) and importers (due to rising energy prices).

In the currently emerging situation, the countries of Western Eurasia, the United States, and some other energy importers will almost completely abandon imports from Russia in the next few years. In these circumstances, the potential of the energy infrastructure created in Russia and oriented to the export of almost 500 million tons of NRER per year, will have to find its customers in other markets.

First of all, the development impulse should be received by the economy of Russia itself, which can form more capacious domestic markets (for example, for natural gas). There will be an increase in the production of energy-intensive products (mainly intended for foreign markets, up to the highest possible processing), whose localized technological chains start from the Russian mining industry.

In addition, Russia will look for new buyers of its traditional energy carriers in already developed markets, increase the volume of NRER exports to the countries of Asia, Africa, and Latin America. To ensure these flows, it will be necessary to develop not only a new infrastructure for transporting energy carriers, but also to establish institutions for international energy cooperation to provide the creation and operation of such an infrastructure.

Russia is once again faced with the problem of providing maritime access to markets, since the use of long-distance water transport has a significant economic advantage over the NRER transportation by land. This time, the Northern Sea Route should play a key role. To do this, it is necessary to ensure integration between the NRER transportation infrastructure from the eastern and Arctic regions of Russia with the newly created logistics hubs on the Russian shores of the Arctic and Pacific Oceans.

Despite the geographic proximity of Japan and the Republic of Korea to Russia, the creation of a specialized export energy infrastructure (pipeline systems and power lines) between them will probably not be implemented due to the influence of the geopolitical factor. The NRER export from Russia to the Pacific and South Asian markets will have to be carried out on the basis of the infrastructure of sea (and aeronautic, if it is created in the future) freight transport.

Implementation of the "energy transition" will require the creation of a new transport infrastructure for the "green" energy. At the same time, the "green" hydrogen transportation by any means of transport is cost- and energy-ineffective: a) a high level of costs for creation and operation of the necessary technological infrastructure, b) significant energy losses during hydrogen transformation from a gaseous state to a liquid state and vice versa, or during transformation into other types of energy carriers or hydrogen-containing substances [23, 24].

One of the possible technological solutions for transporting RES energy over long distances is the construction of international electrical networks based on high voltage direct current (HVDC) power lines. There are already projects for such international energy interconnections in the NEA region, for example, "Asian super grid" [25, 26]. The involvement of hydrogen technologies will likely give a second wind to such discussions, which will make it possible to create an international electro-hydrogen system that is significantly more resistant to changes in RES energy flows and to the risks of supply interruption.

Due to technological problems, hydrogen consumption will be concentrated near the places of its production, and its large-scale transportation over long distances will become possible (after 2050) only in the case of a breakthrough development of hydrogen technologies and a decrease in their cost. A possible option for a mutually beneficial solution to the problem of stimulating the development of hydrogen and renewable energy technologies may be the use of special financial instruments and the creation of new institutions for international energy cooperation based on "green" certificates for electricity and hydrogen.

The price ceiling mechanism for Russian oil introduced by the EU, the G7 countries and Australia is ambiguous in terms of preventing price increases on the world market. Importers will be able to put price pressure on other suppliers, who, in an attempt to prevent falling prices, may begin to limit the volume of supplies. In this regard, the reduction in the oil production quota adopted in October 2022 by the OPEC+ cartel [27] should not be viewed as an act of solidarity for fear that the precedent with the imposition of sanctions may be repeated, but as a measure, the introduction of which is dictated by the economic interests of exporters of crude hydrocarbons.

The influence of all considered factors are superimposed in time, and they are interconnected. Thus, by now, a bifurcation point has formed in the development of global and regional energy markets, which will have the most serious impact on the further development of Russia, and its energy transport infrastructure in particular.

Prospects for the development of international energy infrastructure in the NEA region

The strategic problem for Russia is not building new export logistics chains, but the ability of its economy to ensure the technological development of energy and related industries. In the context of a situation close to monopsony in the energy markets, pressure from energy importers to lower prices can be offset by an increase in the production and export of energy equipment and energy services. For example, in the case of trilateral cooperation between Russia, Mongolia and China on the conversion of Mongolia to gas, it is possible to form packages linking the import of LNG or natural gas with the supply of relevant equipment and services.

In the long term, the main factor of uncertainty in energy markets is related to how stable the new geopolitical architecture, which is still being formed, will turn out to be. Plans to create a gas hub in Turkey are a confirmation of this circumstance. Economically, the situation on the market is far from optimal, and after the end of the military conflict in Ukraine, we can expect the establishment of working trade and economic relations between Russia and European countries.

Since projects related to the creation of a new energy infrastructure are characterized by capital intensity and long payback periods, the duration and scale of changes can be indirectly judged by the Final Investment Decisions (FID) taken by "Western" investors, which make it possible to replace the import of Russian energy resources.

The energy infrastructure in the NEA region will continue to develop, regardless of the pace of implementation of the "energy transition" policy. China needs to reduce its dependence on coal. Japan, the Republic of Korea and Taiwan are likely to be forced to increase their imports of increasingly "green" energy carriers from "friendly" countries, and not from Russia. However, the very fact of the availability of world-class energy resources in Russia creates conditions not only and not so much for their monetization (both NRER and RES), but for the socio-economic development of the country.

The implementation of the emerging opportunities in the transforming energy markets calls for the creation of new institutions for international energy cooperation, including institutions for financing energy infrastructure facilities and mechanisms for bilateral and multilateral energy cooperation.

V. New Institutions for Energy Markets

The main objective of the forthcoming transformation of new export energy markets for Russia is to establish new, efficient institutions for energy cooperation – both in the NEA region and in the world markets as a whole. The significance of these institutions lies in the fact that they are mandatory for the functioning of the transport infrastructure, through which energy resources are physically transported from exporters to importers. The quality of market institutions determines the financial efficiency of the energy transport infrastructure, not to mention the prospects for its further development or the creation of new types of energy transport systems.

The existing institutions of the NRER markets, which have already transformed, in connection with the geopolitically determined refusal of the countries of the western part of Eurasia to import Russian NRER, should primarily include those associated with the immobile infrastructure of specialized energy transport systems, i.e., pipeline and electric power ones. Institutions designed for the trade in energy resources by sea and air transport (mobile infrastructure based on reloading logistics hub ports), due to their almost global nature, will still have to facilitate the unhindered access of energy resources to all markets where they have consumers. Consequently, efficient international institutions for trade in energy carriers, which are transported using the international maritime and air infrastructure, become vital for Russia. Such institutions provide mechanisms for guarantees, insurance, pricing, transit, re-export, certification, and other tools for energy trading in physical and financial markets.

In the context of the political coalitions formed and the multipolarity of the globalization process, the transformation and/or creation of new institutions vital for Russia (representing "hard" mechanisms for ensuring international energy cooperation) requires significant acceleration of the use of "soft" mechanisms for strengthening mutual trust of partners in the international arena [28].

Maritime transportation of NRER (hydrocarbons, coal, enriched uranium) from Russia to new importers in the Atlantic and South Asian markets requires free passage of the Danish straits, Black Sea straits, Malayan straits, the Suez Canal, and exit from the Russian Arctic to the Pacific Ocean through the Bering Strait. In addition to smooth passage of these critical sea lanes, Russia needs non-discriminatory pricing mechanisms for Russian energy, as well as low transaction costs. The mutual correspondence of such institutions and facilities of developing transport infrastructure should fully cover the entire logistics supply chain – from export terminals, through transit and main routes (both with and without a linear, immobile infrastructure), to unloading and processing of import documents, transfer of energy carriers and energy services to importers, and receiving payment by Russian exporters in full.

The institutions of technical and financial regulation of the processes of energy resources transportation are of particular importance for new energy markets in the NEA region such as the markets for electricity and hydrogen energy carriers. For example, the problem of creating an international energy interconnection "[East] Asian energy ring" has been discussed for several decades [29, 30]. The main obstacle to the implementation of this project is the lack of guarantees of compliance with the national requirements of the participants in the field of energy security, that is, the absence of basic regional institutions for energy cooperation.

In turn, due to huge energy losses during the renewable energy transportation over long distances, the hydrogen carrier market in NEA at the first stages of its development (for several decades after 2030) will bring about an additional need for natural gas in the gas market, supplemented by the necessity to create a new market for CO_2 sequestration services and the institutions for trade in green certificates for hydrogen. With the development of the electric power interconnection of the NEA countries, hydrogen will also be used as a renewable energy storage device to supply fuel to peak sources and to supply local hydrogen carriers markets.

Russia can participate in the creation of a regional market for green certificates for electricity and hydrogen. This will not only contribute to the achievement of climate goals but will also solve the problems of the lack of effective technologies for long-range hydrogen transportation, stimulate domestic consumers of green energy, and support the development of hydrogen technologies. Under such a scheme, on the side of buyers of certificates, hydrogen consumption increases and a market for carbon capture, storage, and utilization (CCS (carbon capture and storage), CCUS (carbon capture, utilization, and storage)) is created, and on the side of sellers of certificates, the development of renewable energy generation and the use of hydrogen technologies are encouraged.

VI. Conclusion

The paper describes the main groups of factors influencing the modern processes of transformation of energy markets. The growing influence of the geopolitical factor, the importance of institutions of international energy cooperation, the need to factor in the relationship between economic development and the transformation of energy infrastructure both at the national and international levels are indicated. The main attention is paid to the NEA region, as one of the most significant for Russia in the forthcoming period of diversification of buyers of energy resources exported from the country. The reorientation of energy exports from the Atlantic to the Pacific and South Asian markets is connected both with objective reasons (stagnation of energy consumption in Europe and its rapid growth in China) and with the EU policy of voluntary abandonment of Russian energy resources.

The effects of geopolitical factors will manifest themselves in the political consolidation of the new poles of globalization, with a corresponding transformation of the institutions of energy cooperation and the international infrastructure for the transportation of energy carriers. Along with prompt measures to establish a new infrastructure to export energy resources from Russia, the strategy of Russian energy business actors should be to strengthen foreign economic relations with the countries of the Asia-Pacific region and southern Eurasia. Such relations should be based on a balance of interests, which implies the intensification of the development of the technological and industrial potential of the Russian Federation.

The accelerated development of export of energy-intensive products, the commercialization of domestic energy and hydrogen technologies, and their subsequent export should become important areas for improving Russia's trade balance. Such a vector of expansion of energy markets is dictated by the inevitability of the transition of the world energy sector to renewable energy sources and the globalization of energy supply systems.

A proposal has been put forward that Russia can initiate the creation of a regional market for green certificates for hydrogen, which will help solve the problem of technical and economic inefficiency of long-distance transportation of hydrogen carriers.

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

Oleg Baldynov gained the Bachelor's degree in Finance in 2015 and Master's Degree in Innovation Management in 2017 from Irkutsk National Research Technical University. Russia. From 2017 to 2021, he was a Ph.D. student at MESI SB RAS. His research interests include renewable energy sources, hydrogen energy and energy transmission.

Darya Maksakova joined MESI SB RAS in 2016, after receiving the Bachelor's degree in International Economics from Baikal State University, Russia. In 2018, she received the Master's degree in Finance from the same university. Now she is a junior researcher and a Ph.D. student at MESI SB RAS. Her research interests include energy economics and energy modelling tools.

Key Defining Features of the Electric Power Industry in Asian Regions of Russia in Light of Decarbonization Efforts

G.G. Lachkov*

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

Abstract — **The article examines key defining features of the electric power industry of Asian regions of Russia in light of decarbonization efforts and does this through a case study of integrated power systems of Siberia and the East. We analyze the main characteristics of these integrated power systems, including the mix of installed capacity of power plants, of electricity generation and consumption, and of the fuel thermal power plants burn. On the basis of this analysis, we conclude that the mix of generating capacity of the considered electric power systems falls short of being perfect from the standpoint of decarbonization efforts and that there is a need to convert some of the existing thermal power plants to natural gas combustion and prioritize natural gas combustion when designing new ones.**

Index Terms: **power system, percentage contribution, hydropower plant, thermal power plant, coal, gas, fuel oil.**

I. Introduction

The climate agenda and the decarbonization policy closely related to it are relevant not only abroad [1], but also in this country [2]. This is especially important for integrated power systems (IPSs) of Siberia and the East, which are the largest consumers of coal as their fuel.

II. Subject of Study

The IPS of Siberia is one of the largest integrated systems of the Unified Energy System (UES) of Russia. The IPS of Siberia serves electricity consumers in the Altai, Krasnoyarsk, and Zabaykalsky territories, Irkutsk, Novosibirsk, Omsk, Tomsk, Chita, and Kemerovo regions, as well as the Republics of Altai, Buryatia, Khakassia, and Tyva. The total area covered by the IPS of Siberia is 4 944.3 thousand km^2. More than 19 million people live in the cities and towns there. The electric power complex of the integrated system consists of 118 power plants with a total installed capacity of 52.1 GW. Of these, hydropower plants (HPP) account for 25.3 GW or 48.5%, thermal power plants account for 26.5 GW or 50.9%, and solar power plants account for 0.3 GW or 0.6% (Table 1) [3]. The annual electric power generation by power plants of the IPS of Siberia in 2020 was 207 billion kWh, including: TPPs – 89 billion kWh or 43%, HPPs – 118 billion kWh or 56.9%, SPP – 0.3 billion kWh or 0.1%, and the annual electricity consumption of the integrated power system was 209 billion kWh (Tables 1 and 2) [3].

The main power grid of the IPS of Siberia is formed on the basis of 110, 220, 500 and 1 150 kV power transmission lines with a total length of about 103 thousand km.

The Norilsk power supply system in the north of the Krasnoyarsk territory operates independently of the IPS of Siberia due to its geographical remoteness.

The IPS of the East is a peripheral integrated power system of the country, recently incorporated into the UES of Russia. The IPS of the East is connected to the UES of Siberia and borders the power system of China. The IPS of the East serves electricity consumers located in five federal subjects of the Russian Federation: the Amur region, Primorsky and Khabarovsk territories, the Jewish autonomous region, and the Republic of Sakha (Yakutia). The total area covered by the IPS of the East is 4 457.4 thousand km^2. There are 5 million people living in cities and towns in this area. The integrated power system of the East is formed by 40 power plants with unit capacity of 5 MW and above, 653 110–500 kV power transmission lines with a total length of about 34 000 km. The total installed capacity of power plants of the IPS of the East as of 01.01.2021 was 11.1 GW. TPPs (6.5 GW or 58.5%), which have a limited control range, dominate in the mix of generating capacity. HPPs account for 41.5%, or 4.6 GW (Table 1) [3]. Annual electric power generation by the power plants of IPS of the East in 2020 was 43.9 billion kWh, including: TPPs – 26.9 billion kWh or 61.4%, HPPs – 17 billion kWh or 38.6%, and the annual electricity consumption of the integrated power system was 40.7 billion kWh (Tables 2 and 3) [3].

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

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Table 1. Installed Capacity Mix of Power Plants as of 01.01.2021

Power system	Total, MW	TPP		HPP		SPP	
		MW	%	MW	%	MW	%
IPS of Siberia	52 139.94	26 537.96	50.90	25 301.78	48.53	300.20	0.57
IPS of the East	11 116.09	6 498.59	58.46	4 617.50	41.54	-	-

Table 2. Power Consumption and Maximum Load

Power system	Million kWh	%	MW
Republic of Altai and Altai territory	10 391.3	4.96	1 756
Republic of Buryatia	5 510.6	2.63	932
Zabaykalsky territory	8 192.5	3.91	1 290
Irkutsk region	55 980.5	26.74	8 326
Kemerovo region	31 293.3	14.95	4 335
Krasnoyarsk territory and the Republic of Tyva	47 490.9	22.68	6 891
Novosibirsk region	15 963.5	7.62	2 887
Omsk region	10 350.4	4.94	1 694
Tomsk region	7 607.8	3.63	1 237
Republic of Khakassia	16 588.0	7.92	2 132
Republic of Altai and Altai territory	10 391.3	4.96	1 756
TOTAL IPS of Siberia	209 368.7	100	30 852*
Amur region	9 124.3	22.43	1 470
Primorsky territory	13 535.8	33.26	2 411
Khabarovsk territory and Jewish autonomous region	10 541.1	25.90	1 816
Republic of Sakha (Yakutia)	7 493.2	18.41	1 318
TOTAL IPS of the East	40 694.5	100	6 701*

* Combined maximum value

Table 3. Power generation in 2020

Metric	IPS of Siberia		IPS of the East	
	million	%	million	%
Power generation,	207 014.2	100	43 899.4	100
of which: TPP	88 997.7	42.99	26 940.0	61.37
HPP	117 739.6	56.88	16 959.4	38.63
SPP	276.9	0.13	-	-

The main generating sources are located in the northwestern part of the IPS of the East, while the main consumption areas are in the southeast. The IPS of the East has one of the highest shares of the public utility load in the UES of Russia – about 25%.

For geographical and technological reasons, the power systems of the four subjects of the Russian Federation that make up the Far Eastern Federal District operate independently of the UES of Russia. These are the power systems of Kamchatka territory, Sakhalin region, Magadan region, and Chukotka autonomous district. In Khabarovsk Krau, the Nikolayevsky power district operates independently of the IPS of the East.

The Siberian and Eastern EPSs have export-oriented interconnections with neighboring countries. The Mongolian power system operates in parallel with the IPS of Siberia through a 220 kV double-circuit transmission line from the power system of Buryatiya. The IPS of the East is connected to the power system of China via 220 and 500 kV transmission lines through a DC link, it also enables AC operation in the «islanded mode» [4].

III. Analysis of Key Defining Features of IPSs of Siberia and the East

The large spatial extent of the IPS of Siberia and IPS of the East and the harsh natural and climatic conditions in the regions they cover result in higher capital intensity and operating costs, as well as long construction periods for power plants and power grid facilities.

The actual power losses in the power grids of PJSC «Rosseti Siberia» by 2020 amounted to 4 264.21 million kWh or 7.28% of the amount supplied to the grid [5], whereas, for example, the actual power losses in power grids of PJSC «Rosseti North-West» by 2020 amounted to 2,066 million kWh or 6.22% of the amount supplied to the grid [6].

The long fall and winter period in these regions leads to large amounts of heat produced at CHPPs, and accordingly, large amounts of fuel burned and large amounts of harmful emissions.

The highest electricity consumption and the highest maximum electricity load in the IPS of Siberia are observed in the Irkutsk region, the Krasnoyarsk territory, and the Republic of Khakassia, which is explained by the presence of major aluminum smelters in these regions. In the IPS of the East, the highest level of electricity consumption and maximum electricity load are observed in Primorsky and

Table 4. The share of the IPS of Siberia and the IPS of the East in the UES of Russia

Power system	Installed capacity of power plants, MW/%	Power generation, billion kWh/%	Power consumption, billion kWh/%	Combined maximum value of load, MW/%
UES of Russia	245 313 / 100	1 047.03 / 100	1 033.72 / 100	151 962 / 100
IPS of Siberia	52 140 / 21.3	20 701 / 19.8	20 937 / 20.3	28 486 / 18.7
IPS of the East	11 116 / 4.5	43.90 / 4.2	40.69 / 3.9	6 520 / 4.3
UES of Russia	245 313 / 100	1 047.03 / 100	1 033.72 / 100	151 962 / 100

Khabarovsk territories as the most industrially developed regions.

The share the IPS of Siberia and the IPS of the East in the UES of Russia as measured by key metrics (installed capacity of power plants, the combined maximum electric load, generation and consumption of electricity), as of 01.01.2021, is summed up in the Table 4, compiled based on the data in [3].

As shown in Table 4, the share of the IPS of Siberia and IPS of the East in the UES of Russia as measured by key metrics is about 20% and 4%, respectively. At the same time, the IPS of the East and the IPS of Siberia are characterized by higher growth rates of demand for electric power than the average for the UES of Russia. The average annual growth rate to 2028 is projected at 4.2% and 1.6%, respectively, and 1.1% – for the UES of Russia [4].

A feature of the IPS of Siberia and IPS of the East that make them stand apart from electric power systems of the European part of the country is the large share of HPPs in the installed capacity mix: 48.5% and 41.5%, respectively.

The largest HPPs of the country operate as part of the IPS of Siberia: Sayano-Shushenskaya HPP (6 721 MW), Krasnoyarskaya HPP (6 000 MW), Bratskaya HPP (4 500 MW), Ust-Ilimskaya HPP (3 840 MW), and Boguchanskaya HPP (2 997 MW). The IPS of the East includes major HPPs as well: Zeiskaya (1 330 MW) and Bureyskaya (2 010 MW).

A large share of HPPs provides carbon-free output, high maneuverability of these IPSs, and together with TPPs, running on cheap local coal, allows maintaining relatively low electricity tariffs in the respective regions (Irkutsk region, Krasnoyarsk territory, Republic of Khakassia).

However, along with a large share of HPPs, the IPS of Siberia and IPS of the East are characterized by a large number of lignite-fired thermal power plants.

The following major coal-fired TPPs operate as part of the IPS of Siberia: Novosibirsk TPP-5 (1 200 MW), Tom'-Usinskaya SDPP [State District Power Plant] (1 345 MW), Belovskaya SDPP (1 260 MW), Berezovskaya SDPP (2 400 MW), Krasnoyarskaya SDPP-2 (1 250 MW), Nazarovskaya SDPP (1 308 MW), Irkutskaya CHPP-10 (1 110 MW), Gusinoozerskaya TPP (1 130 MW), and Kharanorskaya SDPP (665 MW). There are also large coal-fired TPPs in the IPS of Siberia: Neryungrinskaya SDPP (618 MW), Khabarovskaya CHPP-3 (720 MW) In recent years, power generation units at Khabarovsk CHPP-3 have been undergoing conversion to natural gas combustion , and Primorskaya SDPP (1 467 MW).

Analysis of statistical information shows that coal accounts for 85.6% of the mix of the fuel burned by TPPs of the IPS of Siberia, while gas accounts for 14.0%, and fuel oil for the rest. In the mix of fuel burned by TPPs of the IPS of the East, coal accounts for 62.3%, gas for 34.9%, and petroleum fuel for the rest (Fig. 1).

On the one hand, this explains a relatively high average specific fuel consumption by Siberian and Far Eastern TPPs, which in the IPS of Siberia is 350 g c.e./kWh, and in the IPS of the East it is 390 g c.e./kWh (for comparison, in the IPS of the European Russia the value of this metric is 290 g c.e./kWh).

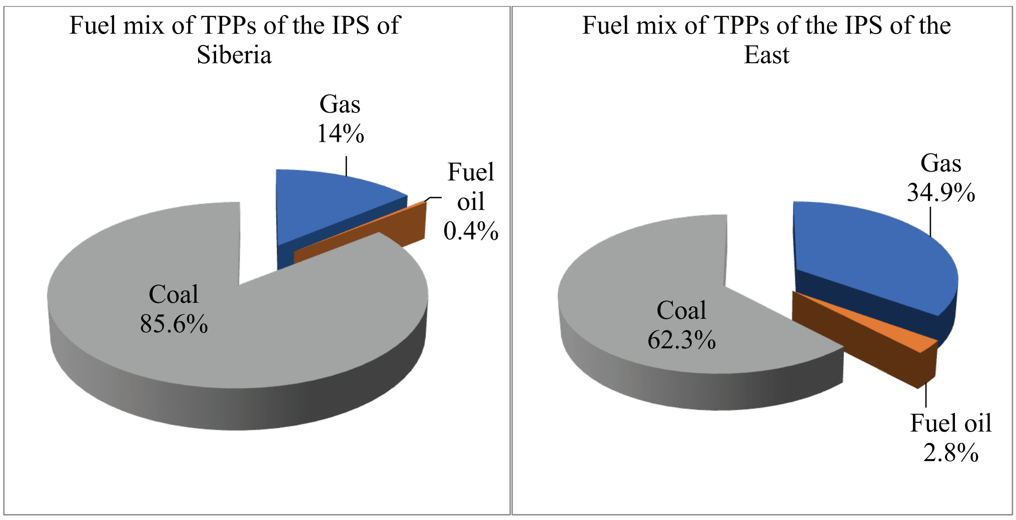

Fig. 1. Mix of fuel burned by TPPs, %.

On the other hand, this puts stress on the natural environment of the adjacent areas due to large amounts of harmful emissions, which increase significantly during low-water periods as a result of a decrease in electricity generation by HPPs and a corresponding increase in generation by TPPs. A striking example of this situation is the «black sky» effect in Krasnoyarsk. Krasnoyarsk is included in the federal project «Clean Air» of the national project «Ecology» along with the cities of Bratsk, Norilsk, Chita, Gusinoozersk, Selenginsk, Ulan-Ude, Kyzyl, Abakan, Petrovsk-Zabaikalsky, Achinsk, Lesosibirsk, Minusinsk, Ussuriisk, Komsomolsk-on-Amur, Chegdomyn, Angarsk, Zima, Irkutsk, Svirsk, Usolye-Sibirskoye, Cheremkhovo, Shelekhov, Yuzhno-Sakhalinsk [7].

IV. Conclusion

The above considerations allow us to arrive at the following conclusions:

- IPSs of Siberia and the East are large and important components of the UES of Russia, with a share of about 20% and 4%, respectively, as measured by key metrics;

- The large spatial extent of the IPS of Siberia and the IPS of the East and the harsh natural and climatic conditions in the regions they cover result in higher capital intensity and operating costs, as well as long construction periods for power plants and power grid facilities;

- the proximity of the integrated power systems of Mongolia and China and the availability of interconnections with these power systems underpin the export prospects of the IPS of Siberia and the IPS of the East, which is of most relevance in the current political and economic environment;

- a large share of HPPs in the generating capacity mix of the IPS of Siberia and the IPS of the East provides carbon-free output, high maneuverability of these IPSs, and along with TPPs that run on cheap local coal, allows one maintaining relatively low electricity tariffs in the respective regions (Irkutsk region, Krasnoyarsk territory, Republic of Khakassia);

- the availability of a large number of coal-fired TPPs in the IPS of Siberia and the IPS of the East, combined with the long heating season, result in large amounts of harmful emissions and a lot of stress put on the natural environment in the regions they cover, especially in cities where coal-fired TPPs are located. Along with the modernization and improvement of the environmental performance of the boiler equipment of these TPPs and the use of renewable energy sources, a radical solution to this problem should be the conversion of existing coal-fired TPPs to natural gas (where technically possible) and prioritizing natural gas combustion when designing new ones.

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Georgiy G. Lachkov is a Senior Researcher at the Department of Complex and Regional Problems of Energy. He holds a Ph.D. in Engineering. He is the author of 55 published research papers. His research interests include the study of problems of expansion planning of the electric power industry and gasification of regions of Russia.

Energy Future of the Russian Far East: Low-Carbon Development Potential

O.V. Dyomina[1,*], R.V. Gulidov[2]

[1] Economic Research Institute of Far Eastern Branch of the Russian Academy of Sciences, Khabarovsk, Russia
[2] Federal Autonomous Scientific Institution «Eastern State Planning Center», Khabarovsk, Russia

***Abstract* — The paper discusses the current and future-oriented models of development of the energy sector of the Russian Far East. We demonstrate that the current model is aimed at maximizing the external rent and resource rent, and it is characterized by a low priority of the environmental policy and actually ignores the global trend of the energy transition. We assess the risks of sticking to the current model and "no action taken" development of the energy sector. We review institutional conditions and identify barriers to the development of low- and zero-carbon technologies in the current model. The future-oriented model aims to preserve the advantages of the current model and complement it with high-tech production facilities in the energy sector along with the transformation of the economy and energy in line with the energy transition trends. It is nowadays common to distinguish between two main groups of technologies that are part of the future-oriented model: hydrogen technologies and renewable energy. By focusing on the former, we analyze the conditions for the development of hydrogen technologies as applied to the subjects of the Far Eastern Federal District and identify competitive advantages and limiting factors.**

***Index Terms*: energy transition, hydrogen technology, renewable energy sources (RES), institutional conditions, energy sector, the Russian Far East.**

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

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I. Introduction

Against the current background of the strengthening of the global climate agenda, the Government of the Russian Federation has declared the goal of achieving carbon neutrality of the country by 2060. Given the great social importance of energy supply, the high inertia inherent in industries of the energy sector, the speed and the possibility of achieving the established benchmark in Russia in principle will depend on the quality of institutions and resources that can be provided as part of state support. Given the large scale of the country and the managerial complexity of the task, it seems reasonable to focus on one of major territorial entities at the first stage, where it would be possible to put to test key managerial solutions to effectively support and stimulate the development of low- and zero-carbon energy sources.

In our opinion, the Russian Far East is one of the most promising testing grounds for applying new technological and institutional solutions to the energy sector. First, the development of this aggregated region has been recognized as a national priority, which is already reflected in a broad portfolio of institutional innovations in the economy. Second, a number of issues have accumulated in the region's energy sector, which are already in conflict with the tasks of accelerated socio-economic development of this macroregion and call for addressing them. Third, the Russian Far East remains an outlet for Russian energy resources targeting APAC markets. On the one hand, this imposes strict requirements on the standards of organization of production, logistics, and service to maintain its competitive edge in the markets of importing countries. On the other hand, it provides ample opportunities for increasing (or at least maintaining) the scale of energy resource production (and transit) in the long term.

The purpose of this study is to assess from the strategic standpoint the low-carbon development potential of the energy sector of the Russian Far East in the context of the

Table 1. Specific Consumption and Power Grid Losses in the Russian Far East and the Russian Federation as a Whole (in Coal Equivalent Terms)

Metric	Russian Far East	Russia
Actual consumption per unit of production, kg/MWh (in coal equivalent terms)	393.6	298.8
Actual consumption per unit of production, kg/Gcal (in coal equivalent terms)	161.5	156.8
Electricity losses in grids, % of electricity generated	11.9	9.2
Heat losses in networks, % of heat produced	14.7	8.8

Source: compiled by the authors based on the data in [18, 20].

global "green" energy transition. The first part describes the specifics of the implementation of state policy to improve energy efficiency and the development of renewable energy sources (RES) in the macroregion. It also identifies barriers to the development of low- and zero-carbon technologies. The second part of the article examines the institutional conditions for the establishment and development of a new model for the development of the energy sector in the Russian Far East. The study concludes with a comparison of key parameters of the current and future-oriented models of development of the energy sector of the macroregion. Conclusions are made on the challenges to be faced in the transition from one model to the other.

II. Literature Review

A large body of research published in this country and abroad has been devoted to analyzing the issues of the energy transition. The process of the energy transition itself is complex, cross-disciplinary, and involves many aspects. Oftentimes, the energy transition is seen in the broader context of the environmental agenda ("sustainable development") and the transition to a green economy. Published research on this subject mainly deals with the analysis of future trajectories of greenhouse gas emissions depending on scenario conditions [1–5].

A feature unique to the current energy transition is multiple technological breakthroughs that back the transition to new energy carriers. As a rule, studies on this subject discuss technologies that are basic for the actual implementation of the energy transition: RES, technologies for improving energy efficiency and development of energy saving, industrial-grade energy storage, dissemination of electric vehicles, technologies of CO2 sequestration, use and disposal, hydrogen energy. The fundamental role of RES dominates the views on the development of energy transition trends [6].

The significant role of the energy sector in Russia's economy necessitates an assessment of changes in its contribution to the economy under the influence of energy transition trends, including from the standpoint of prospects for entering new markets, risks of losing traditional market niches, the threat of technological backwardness of the country, etc. [7–10]. Scholars in the field are unanimous in that the current model of economic and energy sector development in Russia has exhausted itself and cannot ensure the country's accelerated development, while global trends in energy transition present not only a challenge for Russia's economy, which is based on the production and exports of energy sector products, but also new opportunities.

III. The Current Model of the Russian Far East Energy Sector in the Context of the Energy Transition

For many decades, the problem of high energy intensity of the national economy has received little attention in this country [8]. The state policy of increasing energy efficiency and energy saving started to intensify in 2008, when the President of the Russian Federation set a goal of reducing the energy intensity of the country's GDP in 2020 by at least 40% compared to 2007. The legal basis for implementation of this policy was provided by Federal Law No. 261-FZ of November 23, 2009 "On Energy Saving and Enhancing Energy Efficiency and on Amendments to Certain Legislative Acts of the Russian Federation". In 2014, the federal state program "Energy Efficiency and Energy Development," which includes the subprogram "Energy Saving and Energy Efficiency Enhancement," was adopted. However, four years later, in 2018, this subprogram was phased out, and the reference to energy efficiency disappeared from the name of the state program. Thus, the issue of high energy intensity of the economy and the need to enhance its energy efficiency was once again excluded from the priorities of the state policy. Since 2019, no specialized state program (subprogram) aimed at improving energy efficiency in Russia has been implemented.

It should be noted that some measures and initiatives to improve energy performance are carried out by corporations as part of the modernization of their production facilities based on the principles of commercial feasibility. In particular, this includes projects to modernize Russian refineries, including two in the Russian Far East. Despite considerable capital investment and improved production specifications, the indicators of consumption (in coal equivalent terms) per unit of output for the Russian Far Eastern refineries are still lower than the national average (Russia – 59.2 kg c.e., Far Eastern Federal District – 71.9 kg c.e.).

Another example is the state program to modernize Russia's thermal power industry, which included 6 thermal power plants (TPPs) of the Russian Far East with a total electric power capacity of about 2 GW, and a thermal capacity of over 2 500 Gcal/h. The modernization program assumes improvement in fuel consumption specifications. In 2023–2027 the program envisages the construction of the 2nd phase of Yakutskaya TPP-2, Khabarovskaya TPP-4, and Artemovskaya TPP-2, the modernization of Vladivostokskaya TPP-2, the expansion of Neryungrinskaya TPP and Partizanskaya TPP. As of today, thermal power plants in the Russian Far East are noticeably inferior to the national average in terms of energy efficiency, and power and heating networks are characterized by a higher level of losses (Table 1).

Another key element of the energy transition is renewables. Since 2013, Russia has been implementing individual measures of state support, differentiated by segments of the electricity market. The actual effectiveness of these measures leaves much to be desired. Russia lags far behind the leading countries in the scale of RES development and the amount of state support provided by them. As of 01.01.2022, the share of renewables in the installed capacity of the Unified National Power System of the country was only 1.6%, in the amount of electricity generated – 0.5% [11].

The current system of RES support in Russia is aimed at addressing two main issues: the development of own RES generation technologies and the establishment of production of corresponding equipment with deliveries to domestic and foreign markets. Accordingly, support measures focus on financing the construction of generating capacity rather than incentivizing green electricity sales as in most advanced countries [12].

The wholesale electricity (capacity) market enjoys the most favorable conditions in terms of state support. With the exception of the Republic of Buryatia and Trans-Baikal territory, which are included in the 2nd price zone of the wholesale market, the remaining regions of the Russian Far East cannot take advantage of state support measures for the development of RES operating in this type of market. More modest measures that are effective in retail markets also do not cover the entire macroregion: they are available only to the southern regions and parts of the Republic of Sakha (Yakutia) that are included in the Integrated Power System (IPS) of the East. In geographically isolated power systems (Sakhalin, Kamchatka, Magadan region, Chukotka autonomous district, and most of Yakutia) these measures prove ineffective. There it is only possible to claim state support provided for the modernization of inefficient generation facilities using the mechanism of energy service contracts.

These features of state support determined the spatial distribution of RES facilities in the macroregion. The most development of RES has taken place in the Republic of Buryatia and Trans-Baikal territory, where they were introduced as part of the support program for the wholesale market. In addition, significant RES generation capacity is characteristic of the Kamchatka territory, where 3 geothermal power plants (GeoTPP) operate, which, however, were built long before the modern stage of RES development.

In general, it can be stated that for the macroregion of the Russian Far East, with the exception of Yakutia and Buryatia, as well as Trans-Baikal territory, state support for the development of RES facilities is virtually not practiced.

Thus, the main directions of the energy transition, including enhancing energy efficiency, developing energy saving and low- and zero-carbon energy sources in Russia in general and in the Russian Far East in particular, are declarative in nature, the target indicators are very modest, and state support measures are clearly insufficient to stimulate large-scale development in these directions.

For the Russian Far East, we can identify several institutional barriers to improving energy efficiency and the development of low- and zero-carbon sources:

- lack of a unified policy on low-carbon development, including goals, priorities, and directions of development, as well as measures of state support that would take into account the specifics of the Russian Far East;
- the non-competitive nature of the procedures for selecting TPP modernization projects in the macroregion, which does not leave even the theoretical possibility of competition between alternative types of capacity and the existing ones;
- the pervasive dominance of monopolistic market structures that do not encourage cost reduction and efficiency growth at thermal power plants of the Russian Far East;
- different opportunities with respect to access to measures of state support for RES development depending on the geographical location and specifics of the functioning of regional power systems;
- the complexity and inefficiency of the mechanism of participation of municipal institutions in the program of modernization of inefficient generation facilities in isolated areas.

IV. Prerequisites for the Formation of a New Model of Development of the Energy Sector of the Russian Far East

Along with the development of RES, hydrogen technologies are considered another promising area as part of the energy transition [4, 9, 13]. Although Russia is at an early stage of development of such technologies, the government and industry experts of the country are already paying increased attention to this area.

Several fundamental strategic documents have been adopted that have prioritized the development of hydrogen technologies with a focus on foreign markets. Russia's Energy Strategy sets the goal of becoming one of the world leaders in hydrogen production and exports. According to the strategy's targets, hydrogen exports from the country should be 0.2 million tons per year by 2024 and 2 million tons per year by 2035. These targets have been detailed in the Action Plan for Hydrogen Energy Development to 2024. The Vision statement for hydrogen energy development in Russia, adopted last year, sets the guidelines for the

Table 2. Main Characteristics of the Announced Hydrogen Production Projects in the Russian Far East (as of 2021)

Federal subject of the Russian Federation	Product	Annual capacity	Process flow	Initiated by
Republic of Sakha (Yakutia)	NH_3	2026 – 3 million tons 2030 – 6 million tons	Steam conversion with CO_2 capture technology	"Northeast Alliance" Research and Manufacturing Corp.
Sakhalin region	H_2, NH_3	2024 – 30 thousand tons 2030 – 100 thousand tons.	Steam conversion with CO_2 capture technology	SC Rosatom Air Liquide PJSC Gazprom
	H_2	no data	Electrolysis, wind turbines	SC Rosatom
		2024 – 16 thousand tons 2030 – 150 thousand tons.	Electrolysis, wind turbines	H4 Energy
		2025 – 50 thousand tons	Electrolysis, wind turbines	H2 Chistaya Energetika
		2025 – 10 thousand tons	Electrolysis, wind turbines	H2
Magadan region	H_2	2025 – 16 thousand tons	Electrolysis, HPP	H2 Chistaya Energetika
Amur region	H_2	2027 – 110 thousand tons	Electrolysis, HPP	Regional Agency for Investment Promotion
Khabarovsk territory	H_2	2035 – 350 thousand tons.	Electrolysis, tidal turbines	
Kamchatka territory	H_2	2031 – 5 million tons	Electrolysis, tidal turbines	H2 Chistaya Energetika
Trans-Baikal territory	H_2	2023 – 3.2 thousand tons.	Electrolysis, SPP	Unigreen Energy, SKTBE JSC

Source: compiled by the authors based on the data in [4].

Table 3. Characteristics of Factors of Site Location of Hydrogen Production Projects in the Russian Far East (as of 01.01.2022)

Characteristic of site location factors	Republic of Sakha (Yakutia)	Sakhalin region	Amur region	Magadan region	Khabarovsk territory	Kamchatka territory
Installed capacity, incl., MW	3 233.1	1 565.5	4 386.5	1 754.2	2 808.6	758.5
HPP	957.5	1.4	3 660.0	1 327.5	-	47.1
other RES	2.9	14.2	1.3*	0.01	1.2	76.2
CUF, %	36.1	33.4	49.3	19.6	36.6	30.2
Average electricity purchase price, % of the national average	177	242	115	157	117	215
Natural gas reserves, billion cubic meters	2 971.4	1 524.7	-	-	-	7.8
Gas production, billion cubic meters	15.7	32.1	-	-	-	0.3
Water reserves, thousand cubic meters per day.	642	373.5	570.5	393.7	802.2	530.6
Actual water production, thousand cubic meters per day.	84	85	166	12	75	97
Distance to the border with China, thousand km	2.6	2.2	1.4	3.2	1.8	3.5

Note: * PV panels at HPPs

Source: compiled by the authors based on the data in [20, 27].

Table 4. Characteristics of Development Models for the Energy Sector of the Russian Far East

Metric	Current	Future-oriented
Objective function	maximization of external and resource rents	creation of new product niches for energy sector products
Type of rent	resource, external	resource, external, technological
Environmental policy priority	low	high
Hierarchy of interests	dominance of national over regional	balancing regional and national interests
Priority development of energy sector industries	extractive	processing
Linking of energy sector industries to the rest of the economy	poorly integrated into the regional economy	stimulating the development of regional demand for energy sector products
The role of the Russian Far East in the country's development strategy	a resource base and transit area	a platform for the introduction of new technologies and institutions

Source: compiled by the authors.

industry development to 2050 and envisages creation of four territorial clusters: North-West, East, Arctic, and South. In accordance with these documents, it is planned to implement a number of pilot projects in the field of hydrogen energy at nuclear power plants, gas production facilities, and raw material processing plants by 2024. The Comprehensive Program for the Development of the Low-Carbon Hydrogen Energy in the Russian Federation to 2050 is currently being developed [14–15].

Thus, today Russia has the basic institutional prerequisites for the further transformation of the energy sector, including through the development of hydrogen energy as one of the promising areas of low- and zero-carbon economy. The regulatory and legal framework has been largely formed, there are significant reserves of energy resources, including renewable resources, there is idle generating capacity (the installed capacity utilization rate is 51.5% on average in the UES of Russia), and the scientific and technological potential has been consolidated.

All these prerequisites for the creation of hydrogen production facilities are also in place in the Russian Far East. At the beginning of 2022, the total number of prospective investment projects for hydrogen production in Russia exceeded forty. Eleven projects were planned to be located in the Russian Far East macroregion ("Eastern hydrogen cluster"), of which five were in the Sakhalin region (Table 2). It is planned that the development of export-oriented industries will make it possible to optimize the power supply to domestic consumers in isolated and remote communities of the macroregion.

At the same time, zero-carbon ("green") hydrogen production projects are very electricity- and water-intensive, require significant capacities, and focus on the low cost of consumed electricity. Our analysis of the main location factors as applied to the above-mentioned regions, for which projects have been declared, allows us to highlight both advantages and disadvantages of the Russian Far Eastern territories as sites of hydrogen production (Table 3).

The main advantages of the Russian Far East with respect to the location and development of hydrogen production facilities there are its abundant resource base (both in terms of natural gas and water) and the short shipment leg distance to the main markets in the APAC region (primarily China). The downsides include poor RES development, lack of capacity of existing generation facilities, high electricity prices in the macroregion.

It is also important to note the risks involved. The main advantage of the creation of the "Eastern hydrogen cluster" being the proximity to the main hydrogen consumption markets is not immutable. Even though initially Russia's hydrogen energy development strategy considered three potential markets in the APAC region: China, Japan, and the Republic of Korea, in the changed environment, at least in the short and medium term, only China can become such a market. At the same time, China's strategy for the development of hydrogen technologies, unlike Japan and the Republic of Korea, is focused primarily on domestic hydrogen production [17].

V. Results

The outlines of the current model for the development of the energy sector in the Russian Far East were defined in the early 1990s. With the transition from centralized planning to a market economy, the economic system of the macroregion of the Russian Far Eastern was gradually transformed based on making use of its comparative advantages in international (cross-regional) trade. The abundance of natural resources that are in demand in the global market, the geographical proximity to the world's largest economies that are consumers of these resources in the context of low density of economic activity in the aggregated region, small population size, and remoteness from the central regions of the country, have predetermined the structure of the economy and the composition of energy sector industries as we know it today. The energy sector is a major export-oriented segment of the Russian Far East economy. The current model of sector development is focused mainly on maximizing the resource rent from the exports of primary energy resources, the scale of production of which is determined by the demand in global markets and the capacity of mining and transport infrastructure.

The current moment can be considered historic: the economy of the Russian Far East in general and that of the energy sector in particular are at the crossroads of choosing the future development path. Making the most of the opportunities that come with the "green" economy, which open up in connection with the need to achieve the goal of carbon neutrality, may allow to form a different model (paradigm) of development of the energy sector of the Russian Far East thus changing the system of priorities, interests, relationships, and the role of the energy sector in the economy. The key characteristics of the models under consideration are summarized in Table 4.

The future-oriented model is based on the departure from the colonial nature of the development of energy resources of the macroregion and the transition to a more nuanced model of the use of resources that reconciles regional and national interests. In addition, the new model involves the structural transformation of the sector with an increase in the share of processing industries: electricity generation based on RES, hydrogen, gas and oil refining products, gas- and petrochemicals.

In any case, the availability of abundant energy resources will remain a competitive advantage for Russia and the Russian Far East in global markets, hence the traditional specialization of the energy sector will probably be preserved, but it will need to be supplemented with new low- and zero-carbon products. The inertia of development inherent in the energy sector will not allow a forced transition to the future-oriented model. At the same time, it is necessary to accelerate progress in this direction in order to maximize the benefits that come with the green energy transition and mitigate the risks of falling into the "trap" of the "no action taken development if the window of opportunity is not taken advantage of.

VI. Discussion

Our assessments of the risks of development of the Russian Far East's energy sector under the "no action taken" scenario are in line with the claims voiced by those researchers in the field who argue that the energy sector is limited in its ability to serve as a source of funding for the national economy in the long term [8, 10].

In our opinion, the main barriers to the transition to a new, future-oriented model of energy sector development in the macroregion are weak institutions, which is consistent with the results of other studies [18]. The latter is especially critical for Russia, where the main driving force behind the implementation of the "green" energy transition is the state. At the same time, research contributions in the field of assessing the effectiveness of the quality of institutions in the industry-specific energy markets of fuel and energy are extremely scarce. In particular, an attempt was made to assess the effectiveness of institutions in stimulating RES development in Russia [19–21]. It is the study of the quality of institutions in the context of the formation and development of a new model of the Russian Far East energy sector that can become a promising area for further research in order to identify favorable conditions and reduce barriers to the development of a low-carbon economy in the Russian Far East.

These authors' views on the general outline of the future-oriented model for the development of the energy sector of the Russian Far East, which is based on renewable energy and hydrogen technology, align well with the vision of most foreign and Russian experts [4, 5, 9, 17]. Quantitative assessment of possible scenarios of formation and development of a new model of the energy sector of the macroregion of the Russian Far East can be carried out using simulations and will be a logical continuation of the present study.

VII. Conclusion

The current model for the development of the energy sector in the Russian Far East fails to ensure the accelerated development of the macroregion's economy. Sticking to this model preserves the technological backwardness of the sector and is accompanied by an increasing conflict between the logic of accelerated socio-economic development of the macroregion's economy and the energy backbone of this development.

The main constraint for the low-carbon development of the Russian Far East energy sector is the institutional environment, which must be transformed on a par with the adopted approaches to economic development. The energy sector of the Russian Far East should become a testing ground for the introduction of new technological and institutional solutions.

The regions of the Russian Far East have competitive advantages in creating hydrogen production, but their development is possible only in cooperation with APAC countries.

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Olga Valeryevna Demina is Senior Researcher at the Economic Research Institute, FEB RAS (Khabarovsk, Russia), PhD in Economics. Key scientific interests: regional economics, energy economics, research on the energy sector of the Russian Far East. She has 14 years of experience as a researcher. She published over 110 papers, including 8 articles indexed by Scopus and Web of Science.

Ruslan Vitalievich Gulidov is First Deputy Director of the Federal Autonomous Scientific Institution "Eastern State Planning Center" (Khabarovsk, Russia), PhD in Economics. Key scientific interests: theory and practice of state policy of regional development, sustainable development, economic evaluation of projects, economics of energy and natural resources. He has 13 years of experience as a researcher. He published about 50 research papers, including those indexed by Scopus.

The Fuel and Energy Balance of the Asian Regions of Russia for 2020

R.I. Muzychuk*, B.G. Saneev, A.D. Sokolov

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The Asian regions of Russia play a significant role in the energy sector of the country. Almost 96% of coal and 25% of electricity produced in the country is produced in Asian Russia. More than 50% of this electricity is produced by hydro power plants. The reporting fuel and energy balances (FEBs) are the basis for strategic planning of the energy development of these regions. Specialists of the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS) built the reporting FEBs of the Asian regions for 2020 using the information and reference system for the development of regional FEBs. The FEB made for the Asian regions of Russia give the opportunity to determine the structures of production and consumption of fuel and energy resources in the territory and evaluate the efficiency of their use. The analysis of the FEBs shows the need to improve the energy balance of the Asian regions in terms of changing its structure and increasing energy efficiency and environmental friendliness of fuel use.**

***Index Terms*: energy sector of the Asian regions of Russia, fuel and energy balance, production and consumption of energy resources.**

I. Introduction

The importance of Asian regions in the Russian economy is constantly growing. The main role in the economy of the region is played by the energy sector (oil, gas, coal production) and processing industries, including metallurgical (aluminum and other metals), mining (non-ferrous metal ores), chemical, and timber industries, which depend greatly on the energy sector. Large oil and natural gas fields create the prerequisites for creating powerful oil and gas complexes in Asian regions, which can satisfy not only the regional demand for natural gas, oil, and their products, but also supply excess hydrocarbons for export to Japan, China, Korea, and other countries of Asia-Pacific (APAC) region. The ports of the Far Eastern Federal District (FEFD) have a great importance for the development of Russia's trade with the countries of the Asia-Pacific region.

The Asian regions of Russia are the territories of the federal subjects of the Siberian Federal District (SFD) and the (FEFD) of Russia. They differ in scale and density of population, as well as in the development of the territory. The territory of the Asian regions is 11.3 mln km2 or 66.1% of the country's area, where about 25.1 mln people or 17.2% of the country's population lives. These territories produce 16.1% (more than 15 trn rubles) of the country's gross domestic product [1].

The fuel and energy balances of the regions contain interrelated indices of the quantitative correspondence between the supply of fuel and energy resources and their consumption in the territory. They also indicate the fuel and energy distribution among the energy (electricity, heat, gas, and others) supply systems and energy consumers (groups of consumers), and assess the efficiency of the fuel and energy use [2].

The reporting fuel and energy balances serve as a basis for determining existing trends and conducting an energy-economic analysis of the current state of the energy sector [3]. They are built relying on the relevant reporting forms of Rosstat. Main objective of the balances is to show the availability, structure, and efficiency of the energy use in a certain territory.

II. Methodology

The Melentiev Energy Systems Institute SB RAS (ESI SB RAS) has accumulated extensive experience in the development of regional energy programs, part of which is the FEBs of the territories [4, 5]. The methodological approach is based on the principles of a systems approach, economic and mathematical modeling of the energy sector, and the balance method [6]. Since some forms of statistical reporting were nullified and some were changed, appropriate adjustments were made to the data input procedure of the information and reference system

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

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Table 1. Main Indices of Fuel and Energy Production in Russia, Asian Regions, SFD, and FEFD (as of 2020)

Index	Russian Federation	Asian regions	SFD	FEFD	Share of Asian regions in Russia, %
- Electricity, bn kWh	1 089.7	275.1	206.0	69.1	25.2
- Heat, mln Gcal	1 242.5	269.1	187.5	81.6	21.7
- Coal, mln t	398.1	382.1	306.9	75.2	96.0
- Natural and associated gas, bcm	694.5	58.8	16.8	42.0	8.5
- Oil, mln t	513.1	79.9	45.2	34.7	15.6
- Oil refining, mln t	275.1	54.1	42.6	11.5	19.7

Source: Rosstat data

Table 2. Main Indices of Fuel and Energy Consumption in Russia, Asian Regions, SFD, and FEFD (as of 2020)

Index	Russian Federation	Asian regions	SFD	FEFD	Share of Asian regions in Russia, %
Electricity, bn kWh	1 085.0	272.6	207.0	65.6	25.1
Heat, mln Gcal	1 126.3	235.0	164.8	70.2	20.9
Coal, mln t	167.6	114.8	81.8	33.0	68.5
Natural and associated gas, bcm	476.3	37.4	19.1	18.3	7.9

Source: Rosstat data

[7]. The adoption of the «Procedure for making fuel and energy balances of the subjects of the Russian Federation, municipalities» (Order of the Ministry of Energy of Russia dated October 29, 2021 No. 1169) required changes to the models for building the reporting and forecast fuel and energy balances.

III. Source Data

The energy sector of the Asian regions has a great resource potential, which made it possible to create a large fuel and energy base in these territories. In total, the SFD and the FEFD extract 96% of the country's coal, generate 25.2% of electricity and 21.7% of heat, produce 15.6% of oil and 8.5% of natural gas, and process 19.7% of all oil refined (Table 1).

Asian regions consume 142.3 mln t.c.e. of primary energy resources, which is 18.4% of all primary energy consumed in the country. In 2020, 114.8 mln t of coal was consumed in total, which accounted for 68.5% of the total coal consumption in Russia. Asian regions account for about a quarter of electricity consumed in the country (25.1%), just over a fifth of thermal energy consumption (20.9%), and a very low share of natural gas (7.9%) (Table 2).

In Asian regions of the country, the structure of primary energy consumption is dominated by coal – 54.9% (whereas in Russia on average, the dominant fuel is gas – 71.2%).

IV. Fuel and Energy Balance Research

According to the above methodological approach, the FEB was developed for the Asian regions of Russia for 2020 (Table 3).

In 2020, the energy sector of the Asian Russia produced (extracted) 473.8 mln t.c.e. (tons of coal equivalent) of primary energy. Coal predominates in the primary fuel and energy produced in the Asian regions of Russia (57.2%), oil accounts for 24.1%, natural gas makes up 14.2%, and the share of hydropower and renewable energy resources is 3.7%.

Asian regions imported 55.2 mln t.c.e. of energy resources, of which about 94% is oil.

Energy resources exported from the Asian regions make up 320.7 mln t, including 57% of coal, 27% of oil, 9% of oil products, and 7% of natural gas.

In 2020, the Asian regions of Russia consumed 208.7 mln t.c.e. of primary energy. The structure of primary

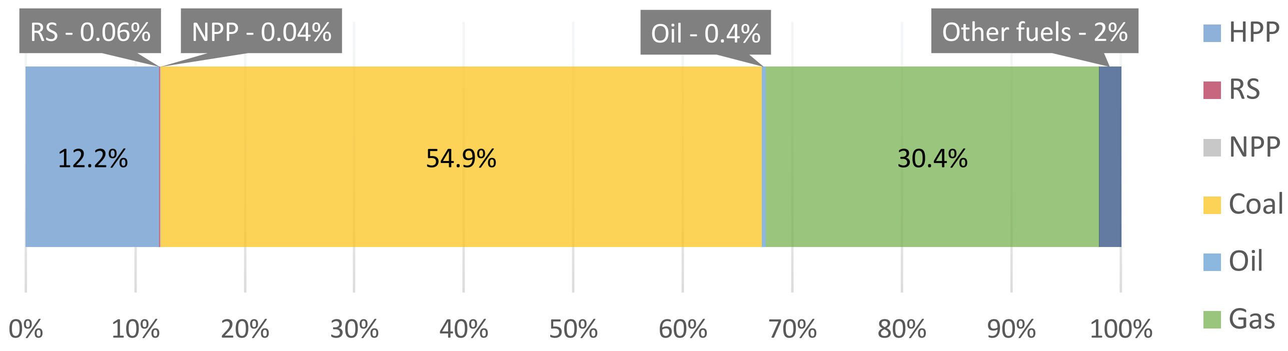

Fig. 1. Structure of primary energy consumption.

Table 3. FEB of the Asian Regions of the Russian Federation for 2020, Thousand t.c.e.

	Coal	Oil and oil products	Natural gas	Other solid fuels	Hydro energy and non-conventional RES	Nuclear energy	Electricity	Heat	Total
Energy production	271.2	114.2	67.9	2.9	17.5	0.06			473.8
Imports	3.3	51.8					0.1		55.2
Exports	–182.7	–114.9	–22.7				–0.4		–320.7
Reserves update	0.8	–0.4							0.4
Primary energy consumption	92.6	50.8	45.2	2.9	17.5	0.06	–0.3		208.7
Production of electricity at HPP, renewable and non-conventional energy sources and NPP					–17.5	–0.03	17.5		0
Thermal power plants	–47	–1.34	–13.7	–1			16.2	20.2	–26.6
Boiler plants	–10.6	–1.9	–4.4	–1.4				16.1	–2.2
Electric boiler plants, heat recovery units, and other heat sources						–0.03	–0.3	2.2	1.9
Coal processing	–14.5								–14.5
Oil refining		–2.4							–2.4
Auxiliaries							–2.1	–2.2	–4.3
Transmission loss		–2.8	–2				–2.7	–4.3	–11.8
Final consumption of energy resources	20.5	42.4	25.1	0.5			28.3	32	148.8

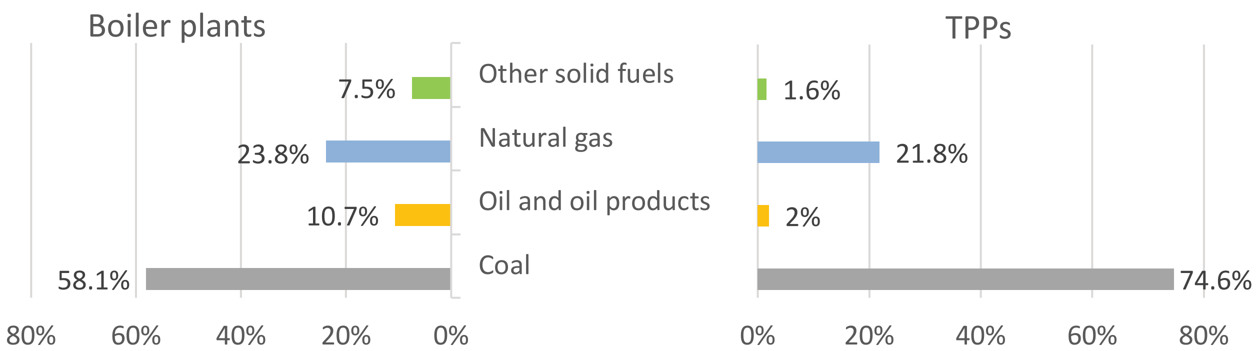

Fig. 2. Structure of fuel consumption at boiler plants and TPPs in the Asian regions of Russia.

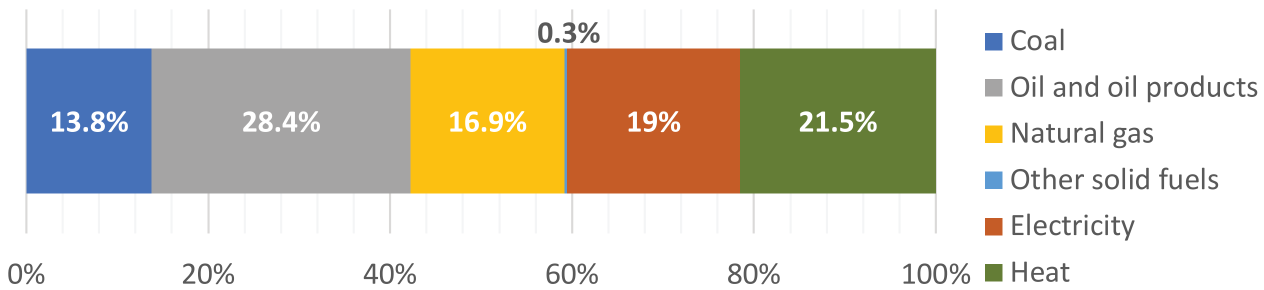

Fig. 3. Structure of final energy consumption in the Asian regions of Russia.

energy consumption is shown in Figure 1. The share of coal in the primary energy consumption is 54.9%, that of natural gas is 30.4%, and the proportion of energy from HPPs is 12.2%. For comparison, in the structure of primary energy consumption in Russia as a whole, coal accounts for 16%, natural gas makes up 54%, and the share of oil is 20%.

In 2020, 52.5 mln t.c.e. of electric and thermal energy was produced from primary energy resources. Conversion of primary energy to produce 16.2 mln t.c.e. of electric energy and 36.3 mln t.c.e. of thermal energy required 81.3 mln t.c.e. of fuel and energy in total. The production of electricity at HPPs, unconventional renewable energy sources, and nuclear power plants in 2020 amounted to 17.5 mln t.c.e.

In 2020, coal was the main fuel for the production of electricity and heat in the Asian regions of Russia (Fig. 2).

The share of coal in fuel consumption by boiler plants was 58.2% and that by TPPs – 74.6%.

Final energy consumption in 2020 amounted to 148.8 mln t.c.e., its the structure is shown in Fig. 3. The share of oil products in the final energy consumption is 28.4%, most of this volume falls on the transport needs. In addition, the share of heat (21.5%) and electricity (19%) is significant, the share of natural gas accounts for 16.9%, and the proportion of coal is 13.8%.

V. Conclusion

The FEB analysis for the Asian regions has indicated a high share of mined coal and a significant share of hydropower. It has also revealed the predominance of coal and a low share of gas in the fuel balance of thermal power plants and boiler plants. These factors stress the need to improve the FEB of the Asian regions of Russia in terms of changing its structure, increasing energy efficiency, and environmental friendliness of fuel use. These improvements will contribute to solving the economy decarbonization problem in the Asian regions of Russia.

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Roman Muzychuk entered MESI SB RAS as an engineer and a Ph.D. student in 2005, after receiving an engineering degree from Irkutsk State Technical University, Russia. In 2019, he received a master's degree in electric power and electrical engineering from Irkutsk National Research Technical University, Russia. Now he is a junior researcher at MESI SB RAS. His research interests include the study of the current state and modeling of energy development based on fuel and energy balances.

Boris Saneev is the Head of the research area "Complex Energy Problems and Regional Energy Policy" at the Melentiev Energy Systems Institute, the Siberian Branch of the Russian Academy of Sciences (MESI SB RAS). He holds the degree of Doctor of Engineering. His research interests include the issues of economic and energy development, energy cooperation between Russia and the Northeast Asian countries.

Alexander Sokolov received D. Sc. degree in engineering from MESI SB RAS in 2006. Currently, he is a chief researcher and the head of the Laboratory of the Energy Sector of Siberia and the Far East at MESI SB RAS. His research interests include the studies and modeling of the development prospects of the energy sector industries.

Gas Industry in the Economic Space of the Russian Far East: Expectations and Reality

O.V. Dyomina[1,*], N.G. Dzhurka[1,2]

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

Abstract — **The study outlines the evolution undergone by the gas industry in the Russian Far East and reviews the main features of its resource base, transport infrastructure, and processing facilities. We analyze the goals of the Eastern Gas Program and its results achieved. We reveal that for two decades, the development of the industry was carried out in an extensive way and was subordinated to the pursuit of national interests. We consider three configurations of the gas industry in the region. The configurations are related in such a way that to arrive at the next configuration the preceding one is complemented by production facilities representing the next link of the process chain. The gas industry in its first configuration includes natural gas production and transport companies; in the second configuration - gas processing facilities; in the third configuration - gas chemical facilities. Based on the analysis of structural shifts, we show that the gas industry in the first configuration underwent development in the region at an advanced pace but remained an enclave in the structure of the economy. Estimates of the effects of sectoral superstructures in the format of the second and third configurations are projections, since the projects to build the Amur Gas Processing Plant and the Amur Gas Chemical Complex are still underway. We used an input-output model to obtain estimates of regional GRP growth rate in the case of development of these industries. It was found that the emergence of gas processing in the region's economy will increase the GRP by 11.2% compared to 2015, and the emergence of gas processing and gas chemical industries will provide a total increase in the GRP by 13.9%. According to the results of calculations based on the dynamic model of economic interactions FrEEDM, given that all process lines of the Amur Gas Processing Plant are put into operation, the above increase in the GRP can be achieved by 2030.**

Index Terms: **analysis of structural shifts, Eastern Gas Program, gas processing, gas chemical industry, the Russian Far East, natural gas production, model of economic interactions.**

I. Introduction

The industries of the energy sector are among the basic industries of the Russian Far East economy. Coal mining has been historically important for the region, while hydrocarbons have been used at scale only in the last two decades due. The latter is due to the depletion of the resource base in traditional mining areas and the formation of a niche for Russian energy resources in the markets of Asia-Pacific countries. To maintain its leading position in global energy markets, it is important for Russia to develop the gas industry at an accelerated pace. We have previously attempted to obtain estimates of the effects of individual projects in the gas industry of the Russian Far East, but today there is a need and opportunity to go further and generalize these estimates as part of a system-wide analysis of the role of the gas industry in the region's economy in terms of the planned and achieved results.

Estimates of the effects of the development of the gas industry of the Russian Far East are made for its three configurations. The configurations are related in such a way that to arrive at the next configuration the preceding one is complemented by production facilities representing the next link of the process chain. The gas industry in its first configuration includes natural gas production and transport facilities; in the second configuration - a gas processing plant is added to the resource base and transport infrastructure; in the third configuration - a gas chemical complex is assumed to be built. To date, the real effects can be estimated only for the first configuration, as gas processing and gas chemical projects are still underway. With this in mind the study is carried out in three stages.

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

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The first stage outlines the projected configurations of the gas industry and describes the dynamics of the industry over the past two decades of its active development. The second stage, as part of the analysis of structural shifts, compares the industry dynamics of individual regions of the Russian Far East with the industry dynamics of the national economy and economy of its nearest environment. Based on this comparison we draw conclusions about changes in the degree of involvement of the gas industry in the structural links as part of cross-regional and cross-industry interactions. At the third stage, we make projections of the effects of establishment of gas processing and gas chemical industries in the region on the basis of an input-output model and a dynamic model of economic interactions.

II. Literature review

The problem of measuring the economic effects of energy sector development (especially the development of the oil and gas industries), as well as that of determining the vector of the development path of the energy sector itself, has produced a substantial body of published research. Among the key issues discussed as part of this field of research are the following: whether the energy sector is a driver of economic growth or acts as its limitation [1-5], how efficient are the energy sector industries in comparison with other industries of the economy [4; 6], what is the nature of the relationship between economic growth and energy consumption [1; 4; 7]. At the same time, most empirical studies in this field are focused on obtaining estimates of the effects of individual major projects in the oil and gas industries as well as their impact on the dynamics of regional and/or national macroeconomic metrics [8-12].

As concerns the Russian Far East, there have been studies tracing the history of the gas industry, the specifics of its current functioning [13; 14], and estimates of the prospective contribution of projects for development of the gas processing plant [11] and gas chemical plant [12]. In addition, an attempt was made to assess the performance of the Eastern Gas Program, where a comparative analysis of the results achieved with the planned performance indicators of the program was carried out, and the factors that led to these discrepancies were identified [15].

The present study is stands apart from the existing ones in that it presents a comprehensive approach to assessing the effects of creating the gas industry in the region. According to this approach, first, both the level of development of the industry itself and its contribution to the regional economy are assessed; second, we analyze the entire array of projects already completed in the gas industry of the Russian Far East and those in progress; third, alternative configurations of the gas industry, combining the main stages of the gas processing chain are described; fourth, we assess the results of the industry development obtained to date, as well as prospective results expected in connection with the introduction of additional industry superstructures in the form of production facility complexes of gas processing and gas chemistry.

III. Research methods

In this paper we conduct a comprehensive analysis of major investment projects in the gas industry of the Russian Far East. As for the already implemented projects, we estimate their effects based on the shift-share analysis method. In this study we use a spatial version of the method proposed in [16], which is compatible with the classical version. On the basis of the three identities, we construct estimates of three pairs of industry and competitive effects, characterizing the standing of the gas industry of a particular region in the national, macro-regional, and local economies:

$$g_i = G + (G_i - G) + (g_i - G_i), \quad (1)$$

$$g_i = \hat{g} + (\hat{g}_i - \hat{g}) + (g_i - \hat{g}_i), \quad (2)$$

$$g_i = \hat{g} + (g_i - g) + (g - \hat{g}), \quad (3)$$

where G, $\hat{g}$, g are the growth rates of the national economy, the neighborhood economy of the region (the neighborhood includes regions sharing a border with the region in question) and the region's economy itself; G_i, $\hat{g}_i$, g_i are the growth rates of the gas industry in the national economy, in the economy of the neighborhood, and in the region's economy itself; $G_i - G$, $\hat{g}_i - \hat{g}$, $g_i - g$ are industry-mix effect, spatial industry-mix effect, and regional industry mix-effect, respectively; $g_i - G_i$, $g_i - \hat{g}_i$, $g - \hat{g}$ are competitive effect, spatial competitive effect (at the industry level), spatial competitive effect (at the level of the entire economy) effects, respectively.

Estimates of the structural shifts at the national level (identity (1)) indicate whether the task of advanced development of the gas industry in the Russian Far East has been completed. Estimates of the cross-regional (macro-regional) level (identity (2)) - indicate whether there was an increase in the degree of connectivity of the economic space of the Russian Far East. Estimates of the regional level (identity (3)) indicate whether the industry obtained the status of the «regional growth driver» and whether its degree of involvement in the structural links of the Russian Far Eastern economies has changed. The calculations use data on the average annual number of employees.

As for the projects that are currently underway, and this refers primarily to projects for the construction of gas processing and gas chemical complexes, their prospective effects are assessed in terms of the concept of iterative cross-industry modeling based on the multipliers of the input-output model. The input-output model is expanded by the inclusion in the base year model of information on technologies and products of gas processing. We assume 2015 as the baseline year, after which the investment phase for the gas processing project began. A social accounting matrix is constructed for 2015, which is then transformed as informed by the data on the production and investment program for the creation of gas processing and gas chemical

Table 1. Characteristics of the Natural Gas Resource Base in the Russian Far East

Metric	Sakhalin region	Republic of Sakha (Yakutia)	Kamchatka territory	Chukotka autonomous district
Number of hydrocarbon deposits, pcs.	63 onshore and 18 offshore deposits in the Sea of Okhotsk	40	4	2
Gas reserves*, bcm	1,524.7	2,971.4	7.8	9.4
Gas resources, bcm	236.5	10,796.9	693.2	283.9
Production volume in 2019, bcm	31.5	4.1	0.4	0.06
Production growth rate in 2012-2019, times	1.9	2.1	1.1	1.9

Source: Subsoil Use. Mineral and raw material base // Department of Subsoil Use in the Far Eastern Federal District https://dvfo.rosnedra.gov.ru/page/425.html

Note: * total reserves of categories A, B, C1, and C2.

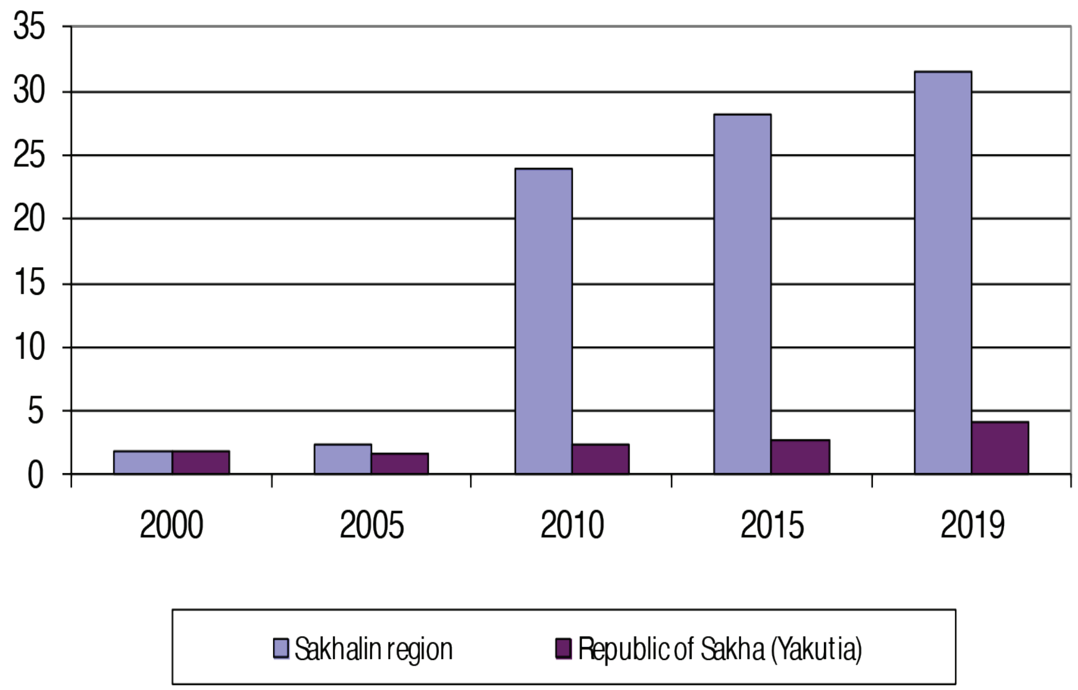

Fig. 1. Dynamics of natural gas production in the Republic of Sakha (Yakutia) and the Sakhalin Region, 2000-2019, bcm.

complexes in the region. For gas processing, we carry out additional calculations of economic effects based on the FrEEDM (Far Eastern Economic Dynamic Model) model of economic interactions described in [17].

IV. Gas industry in the Russian Far East: major investment projects of the 2000s.

Recoverable oil and gas reserves have been discovered in the Sakhalin region (including the shelf of the Sea of Okhotsk), Kamchatka territory, Chukotka autonomous district, Khabarovsk territory, and the Republic of Sakha (Yakutia). The Russian Far East accounts for about 7% in the stock of Russian gas reserves and about 6% in the stock of unproven reserves. The region is characterized by a low degree of exploration (21%) and a low degree of reserve depletion (6%). Both of the indicators attest to the high potential of new large deposits and the prospects for increasing production in the region.

For a long time, the rich resource base of the Russian Far East remained unsolicited with respect to natural gas resources. We can highlight the following factors that hinder the development of the industry: low capacity of intraregional demand (the demand is 5-7 times lower than the potential production volume), limited scope of geological studies of the area, lack of necessary transport infrastructure, high costs of production and transport, multi-component composition of natural gas in the Republic of Sakha (Yakutia).

Table 2. Trunk Gas Transport Systems in the Russian Far East

Characteristic	Sakhalin		Kamchatka	Sakha
	Trans-Sakhalin pipeline system	Sakhalin – Khabarovsk – Vladivostok	Sobolevo – Petropavlovsk-Kamchatsky	The Power of Siberia
Year of commissioning	2008	2011	2010	2019 (Stage 1)
Throughput capacity, bcm	15	5.5	0.75	61, inclusive of the following 38 (exports)
Length, km	800	1 800	392	3 200
Resource base	offshore fields in the Sea of Okhotsk	fields of the Sakhalin island and the shelf deposits of the Sea of Okhotsk	Kshukskoye GCF, Nizhne-Kvakchikskoye GCF	Chayandinskoye OGCF, Kovyktinskoye GCF
Consumers	LNG plant (exports to APAC countries)	consumers in Khabarovsk territory, Primorsky territory, and Sakhalin region; prospective exports to APAC countries	energy facilities of the Kamchatka region	Amur GPP, exports to China

Table 3. Gas Processing Plants in the Russian Far East

Characteristic	Sakhalin Gas Production Center	Yakutsk Gas Production Center		
	Sakhalin LNG plant	Yakutsk GPP	Amur GPP	Amur GCC
Year of commissioning	2009	1999	2021 (2 process lines)	___ (2020 - start of construction)
Design capacity	10.4 million tons	40 thousand tons	42 billion cubic meters of natural gas per year	2.7 million tons
Products	LNG	methane, LPG, gasoline, propane-butane	helium, ethane, propane, butane, pentane-hexane fraction	polyethylene, polypropylene
Resource base	Sakhalin-1 and Sakhalin-2 project fields	Srednevilyuiskoye GCF and Mastakh GCF	Chayandinskoye OGCF, Kovyktinskoye GCF	ethane, methane, propane, and butane of the Amur GPP
Consumers	exports to APAC countries	Yakutskaya SDPP, domestic consumers within the republic	regional consumers, exports	regional consumers, exports

Source: compiled by the authors based on Golubeva I.A., Rodina E.V. Yakutsk gas processing plant (Sakhatransneftegaz JSC) // Neftepererabotka i nefrekhimiya. 2017. No. 4. Pp. 37-40; Yakutsk gas processing plant // Sakhatransneftegaz JSC, URL: http://aostng.ru/about/structure/47/ (access date: 04.07.2022); Amur gas processing plant // Gazprom PJSC, URL: https://www.gazprom.ru/projects/amur-gpp/ (access date: 04.07.2022); Amur gas chemical complex (AGCC), URL: https://amur-gcc.ru/?ysclid=l7k9jqstqm513234110 (access date: 04.07.2022).

The development of the region's gas industry required large capital investment outlays and access to state-of-the-art technology, as well as a guaranteed demand volume, which, in general, only international cooperation provides. With this in mind, the Eastern Gas Program (hereinafter referred to as the Program) was adopted in 2007, combining gas production, transport, and processing projects in the Russian Far East and Eastern Siberia. The program is aimed at achieving two main goals: accelerated development of the eastern regions of the country on the basis of natural gas resources and consolidation and expansion of the niche of Russian gas in APAC markets. The program is divided into several stages, covering the time period to 2030. As part of the program, it was planned to create three gas production centers in the Russian Far East: Sakhalin, Yakutia, and Kamchatka.

Gas is currently produced in four subjects of the Russian Federation located in the Russian Far East. Two main gas production centers have been formed in the region: the Republic of Sakha (Yakutia) and the Sakhalin region, which account for about 98% of free gas reserves (Table 1).

The dynamics of gas production in the region over the past two decades were mainly determined by the development of the Sakhalin center, primarily by the commissioning of the LNG plant in 2009, which provided the necessary infrastructure for gas exports (Fig. 1).

The increase in gas production in the Republic of

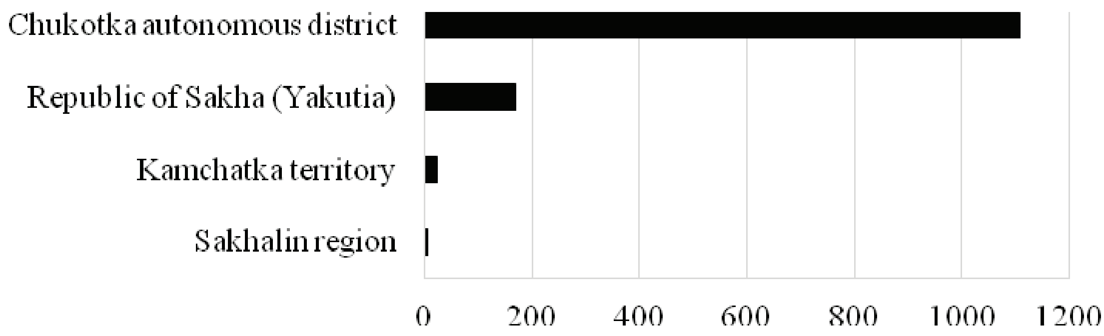

Fig. 2. Competitive effects in the gas industry of the Russian Far East in 2012-2019, %.

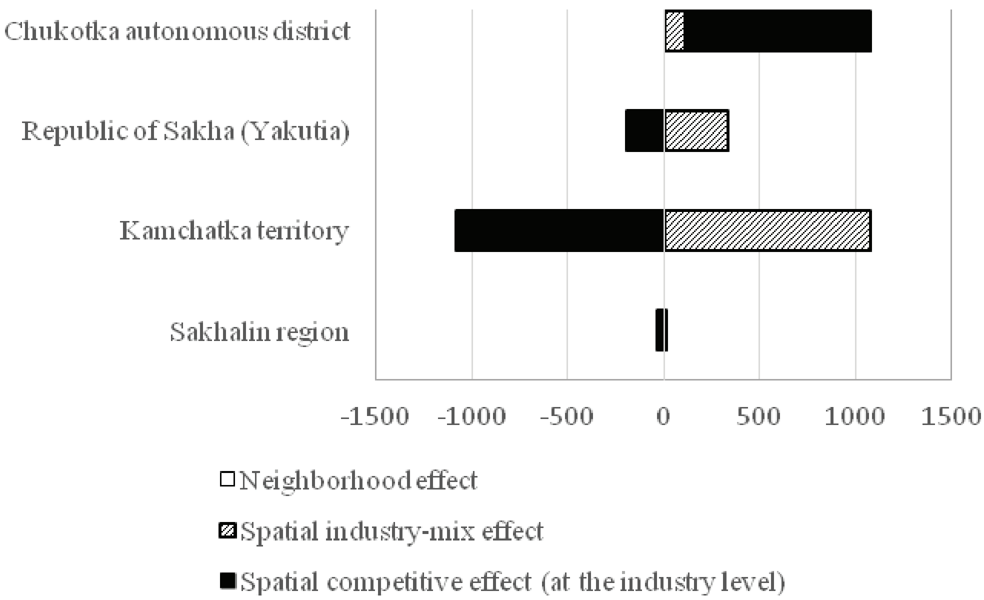

Fig. 3. Estimates of structural shifts in the gas industry of the Russian Far East in 2012–2019 (cross-regional/macro-regional level), %.

Sakha (Yakutia) in 2008-2019 was due to the increase in associated gas extraction as oil production increased and the «Eastern Siberia - Pacific Ocean» oil pipeline was commissioned. Starting from 2019, the growth of gas production in the republic was caused by fulfillment of obligations under the long-term project of gas supplies to China and commissioning of the Power of Siberia GTS.

Gas producers in the Chukotka autonomous district and Kamchatka territory focus exclusively on meeting the demand of domestic consumers. At the same time, there is a shortage of resources in the Kamchatka center.

There is no unified gas supply system in the Russian Far East. To date, only separate local gas transport systems have been created: 1) gas supply pipelines for gasification of individual settlements and industrial enterprises «Zapadno-Ozernoye GCF - Anadyr» in the Chukotka autonomous district; 2) four local gas transport systems operating in a closed and technologically independent manner in the Republic of Sakha (Yakutia), such as «Kyzyl-Syr - Mastakh - Berge - Yakutsk» and «Mirny - Aikhal - Udachny»; 3) the trunk gas transmission system of the Kamchatka gas production center («Sobolevo - Petropavlovsk-Kamchatsky»); 4) trunk gas transmission systems of the Sakhalin gas production center: «Sakhalin - Khabarovsk - Vladivostok» and Trans-Sakhalin pipeline system, 5) trunk gas transmission system of the Yakutsk gas production center «Power of Siberia» Stage 1 (Table 2).

The underdeveloped transport infrastructure still restricts the development of the gas industry in the Russian Far East, including delays in the commissioning of gas

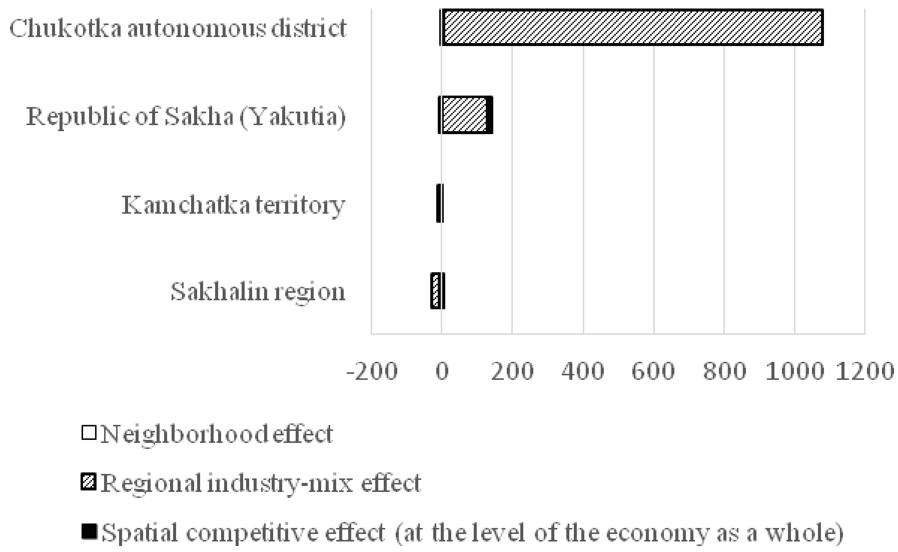

Fig. 4. Estimates of structural shifts in the gas industry of the Russian Far East in 2012-2019 (regional level), %.

processing facilities and the implementation of the region's gasification program.

Between 2012 and 2019, the bulk of projects in the gas industry related to development of the resource and transport infrastructure were implemented, but projects in the gas processing segment as of 2022 are still at various stages of construction.

The gas processing industry in the eastern regions is represented by two operating plants: the Yakutsk gas processing plant and the Sakhalin liquefied natural gas (LNG) plant, as well as two interconnected plants that are currently under construction: the Amur Gas Processing Plant and the Amur Gas Chemical Complex (Table 3). The gas processing facilities (Amur Gas Processing Plant and Amur Gas Chemical Complex) are scheduled to reach their design capacity in 2024-2025.

Yakutsk GPP products are consumed within the Republic of Sakha (Yakutia), while all LNG products from the Sakhalin LNG plant are exported under long-term contracts. The main purpose of the Amur GPP is to extract important components from natural gas. The plant is an important link in the process of supplying natural gas to China via the Power of Siberia gas transmission system. The plant's products are intended both for the domestic market and for the global market (helium and sales gas (methane)). The Amur Gas Chemical Complex (a joint project of SIBUR and Sinopec) is envisioned as the main consumer of the Amur GPP products (ethane and LPG), while the plant itself is focused on the markets of APAC countries, primarily China.

In general, it can be noted that the development of the gas industry in the Russian Far East in the first two decades followed a trajectory of extensive growth. Priority was given to projects of expanding the resource base and building transport infrastructure, which was subordinate to the goal of increasing natural gas exports to APAC countries. At the same time, the region is still characterized by a high potential for increasing physical volumes of natural gas exports.

V. Research findings

VI. Estimates of structural shifts in the gas industry in the Russian Far East

Since the main projects to develop the resource base and transport infrastructure in the Russian Far Eastern gas industry were completed by 2012, the calculations used data on the average annual number of employees from 2012 to 2019. During the period under review, employment in the gas industry of the Russian Far East increased by 24.0%. Estimates of structural shifts obtained at the national level confirm the special status of the gas industry of the Russian Far East in the national economy. Competitive effects in this case (60.5%) are not only positive but also dominate in relation to the national (-4.4%) and industry-mix (-32.1%) effects.

The spatial structure of the competitive effects is presented in Figure 2 (regions are ordered here from top to bottom in descending order of the growth rate of employment in the extractive industries).

The projected spatial distribution of economic activity within the gas industry generally coincides with the actual one. The variation in the values of competitive effects depends on the degree of completion of projects in different regions of the Russian Far East. For example, the high value of the growth rate of the average annual number of employees in the gas industry obtained for the Chukotka autonomous district is nothing but the effect of a low baseline. As stated above, the natural gas extracted in the district is used exclusively for domestic needs. Until 2017, the volume of gas production and consumption in the region was insignificant (about 30 million m^3), but, starting from 2018, it increased due to the launch of the coal-to-gas switching of the Anadyrskaya CHPP.

Estimates of structural shifts obtained for the gas industry of the Russian Far East at the cross-regional and regional levels are shown in Figs. 3 and 4.

Positive values of spatial industry-mix effects in the regions of the Russian Far East indicate the complementarity of projects in the gas industry. In the case of the Kamchatka territory and Chukotka autonomous district, this also indicates a certain increase in the degree of space connectivity due to the implementation of gasification programs. Nevertheless, we cannot speak about the realization of the potential for generating spatial externalities in this case, because for all regions of the Russian Far East (with the exception of the Chukotka autonomous district) the spatial industry-mix effect and spatial competitive effect have different signs. Negative values of spatial competitive effects indicate that the regions of the Russian Far East lose out in cross-regional competition (primarily to the regions of Siberia).

In accordance with the results of the analysis of structural shifts at the regional level, the dynamics of the gas industry are almost unaffected by the overall competitiveness of regional economies (the overall spatial competitive effects in this case are very low). As a rule, the gas industry develops faster than others (the exception here is the gas industry of the Sakhalin region, which is inferior in terms of development rates, primarily to the region's oil industry), while remaining a kind of enclave in the economies of the regions.

Thus, the scale of support for the gas industry in the Russian Far East was sufficient to produce positive and significant competitive effects in it, overriding the impact of negative shocks that destabilize the national economy. But how these incentives will «work» in the future largely depends on the nature of structural links within the gas processing and gas chemical industry, which is new for the region, the results of the creation of which in the period under review remained imperceptible.

VII. Assessment of prospective economic effects of creating a gas processing and gas chemical complex in the Russian Far East

The gas processing and gas chemical industries are new to the Russian Far East and change the established system of economic relations, primarily within the energy sector itself. In general, the process flow of obtaining products of the industry is as follows: energy resource (Stage 1) → primary processing products (Stage 2) → basic monomers (Stage 3) → polymers (Stage 4). Accordingly, it is expedient to assess the economic effects of creating the gas industry under two scenarios: the first scenario assumes the gas industry, combining 1 and 2 stages of the process flow; the second scenario - the industry, combining 1 to 4 stages of the process flow. The core of the new industry is formed by the Amur Gas Processing Plant and the Amur Gas Chemical Complex. The Amur Gas Chemical Complex is supposed to produce basic monomers and polymers, with monomers as intermediate products that are used within the production process.

The emergence of gas processing and gas chemistry in the economy of the Russian Far East will boost the demand for products and services of the existing industries in the region, including capital asset-forming industries, but will not entail changes in the structure of their costs. According to balance estimates, the emergence of gas processing in the region's economy will increase the GRP by 11.2% compared to 2015, and the emergence of gas processing and gas chemistry will provide a total increase in the GRP by 13.9%. The largest increases in gross output are planned in the gas production, oil refining, and electric power industries. At the same time, the capacity reserves of the industries supplying resources for the new complex of industries are sufficient to ensure the above growth of the GRP of the Russian Far East.

According to the results of calculations based on the FrEEDM model, provided that all production lines of the Amur GPP are put into operation, the above increase in the GRP can be achieved by 2030. The effects of the creation of gas processing are already expected during the investment phase. At the same time, due to the reproduction structure of capital investment, it will be impossible to claim the adequate transformation of this investment into growth rates of regional aggregated performance indicators; by 2030 the value of the investment multiplier will not exceed unity.

The products of the gas-processing complex will essentially match the low degrees of processing and will be exported, as a result of which the effects of the operational phase, produced by technological changes, are almost twice as low as the effects of the investment phase.

VIII. Discussion

The research findings presented in this paper are consistent with the results of other studies with respect to confirming the low efficiency of energy projects from the standpoint of stimulating regional economic dynamics [6; 11; 12; 18; 19].

Despite the spatial complementarity of gas production projects, calculations have provided no evidence for the existence of spatial externalities in the gas industry of the

Russian Far East. The losing out of the Russian Far East regions in cross-regional competition to Siberian regions observed by the authors aligns well with the results obtained by the experts of the Higher School of Economics in their analysis of the economic specialization of the regions [20]. According to NIU HSE estimates, for Sakhalin region and the Republic of Sakha (Yakutia. For the republic, in addition to the local importance, we also noted the importance of the industry on a national scale.) production and transport of hydrocarbons are of local importance, for the Kamchatka territory and Chukotka autonomous district they are not industries of their specialization, while for the Irkutsk region and Krasnoyarsk territory they are industries of specialization of national importance.

IX. Conclusion

The scale of support for the gas industry in the Russian Far East was sufficient to produce positive and significant competition effects in it, overriding the impact of negative shocks that destabilize the national economy. In the structure of the economies of the Russian Far East regions, the gas industry tends to develop at a faster pace than other industries, while remaining a kind of enclave.

Projects to develop gas processing and the establishment of the gas chemical industry are associated with a steady increase in the GRP of the Russian Far East, but the investment multipliers of these projects by 2030 fail to reach unity. Due to the fact that the products of the gas-processing complex will correspond to low degrees of processing and will be exported, the extent of close economic interactions does not change much within the economic space of the Russian Far East, .

Thus, the accelerated development of the gas industry in the considered configurations (without/with processing facilities) in general does not translate into the development of the Russian Far Eastern economy itself. Our analysis showed that the projects currently being implemented in the region's gas industry are subordinate to the objectives of the national economy and do not solve the problem of forming a unified economic space in the Russian Far East that would be characterized by the closeness of economic interactions.

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Olga Valeryevna Demina – Senior Researcher at the Economic Research Institute, FEB RAS (Khabarovsk, Russia),
PhD in Economics. Key scientific interests: regional economics, energy economics, research on the energy sector of the
Russian Far East. She has 14 years of experience as a researcher. She published over 110 papers, including 8 articles
indexed by Scopus and Web of Science.

Natalya Gennadyevna Dzhurka – Senior Researcher at the Economic Research Institute, FEB RAS (Khabarovsk),
Institute of Economics RAS (Moscow), PhD in Economics. Key scientific interests: regional economics, economic and
mathematical modeling. She has 13 years of experience as a researcher. She published over 50 papers, including 6
articles indexed by Scopus and Web of Science.

Transforming Structure of Generating Capacities in the Eastern Arctic with Large-Scale Development of Resources

I.Yu. Ivanova*, A.K. Izhbuldin, T.F. Tuguzova, V.A. Shakirov

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The paper presents estimates of the electric power required for the implementation of projects for the development of deposits of mineral resources in the Eastern Arctic. The creation of new industrial load centers or expansion of existing ones will call for significant changes in the energy infrastructure. The estimates presented indicate that the demand for electricity for promising projects in the Taimyr-Turukhan zone is commensurate with current consumption; in the North Yakutsk zone, the demand exceeds the consumption by almost 6 times, and in the Chukotka zone, it is larger by more than 3 times. The paper considers changes in the structure of generating capacities in the territorial zones of the Eastern Arctic for two possible development scenarios: the creation of a low-capacity nuclear power industry and the development of an Arctic liquefied natural gas infrastructure. The provided types of energy sources are rational and substantiated by the conducted modeling studies.**

***Index Terms*: centralized and autonomous power supply, promising projects, power consumption, low power nuclear power plants, liquefied natural gas.**

I. Introduction

The strategic priorities and main objectives of the state policy in the Arctic are defined in the state program documents, where a significant number of projects for the development of mineral resources are declared as priority areas [1, 2]. Given the focal nature of the development of the territory, the implementation of these projects is impossible without the expansion of transport and industrial infrastructure. The demand for electricity in the Eastern Arctic is 6 billion kWh only for priority projects with a high degree of exploration of mineral reserves included in the state balance sheet [3]. According to our estimates, the power consumption in these territories can more than double due to the projects that were developed in 2017–2020.

The absence of the necessary industrial infrastructure and, primarily, free generating capacities is a serious limitation for the large-scale development of the resources of the eastern Arctic. The implementation of the projects for the development of mineral resources will require a significant expansion of existing electricity sources and construction of new ones.

The Eastern Arctic territories are isolated from the Unified Energy System of the Russian Federation, and most of the projects are located in the decentralized power supply zone, therefore, the central objective is to substantiate feasible power supply schemes for Arctic projects. The study presented in the paper aims mainly to assess the possible transformations in the structure of generating capacities for each of the territorial zones of the Eastern Arctic in comparison with the current state.

II. Current Structure of Generating Capacities

The zones of the Eastern Arctic (Taimyr-Turukhan zone, North-Yakutsk zone, and Chukotka zone) differ significantly in the level of energy infrastructure development. The total capacity of power plants in the Arctic areas of the Krasnoyarsk Territory, the Republic of Sakha (Yakutia), and the Chukotka Autonomous District is currently 3 178 MW [4].

The energy supply in these areas is represented by five isolated energy areas: two in the Taimyr-Turukhan zone and three in the Chukotka zone, which is a result of historical industrial and economic development. The North Yakutsk zone consists of 13 districts where consumers are supplied with electricity from autonomous energy sources. Remoteness and lack of necessary transport infrastructure have led to the energy isolation.

More than 80% of the total capacity of power plants in the Eastern Arctic operates in the Taimyr-Turukhan zone. The energy structure of this zone is as follows: the

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

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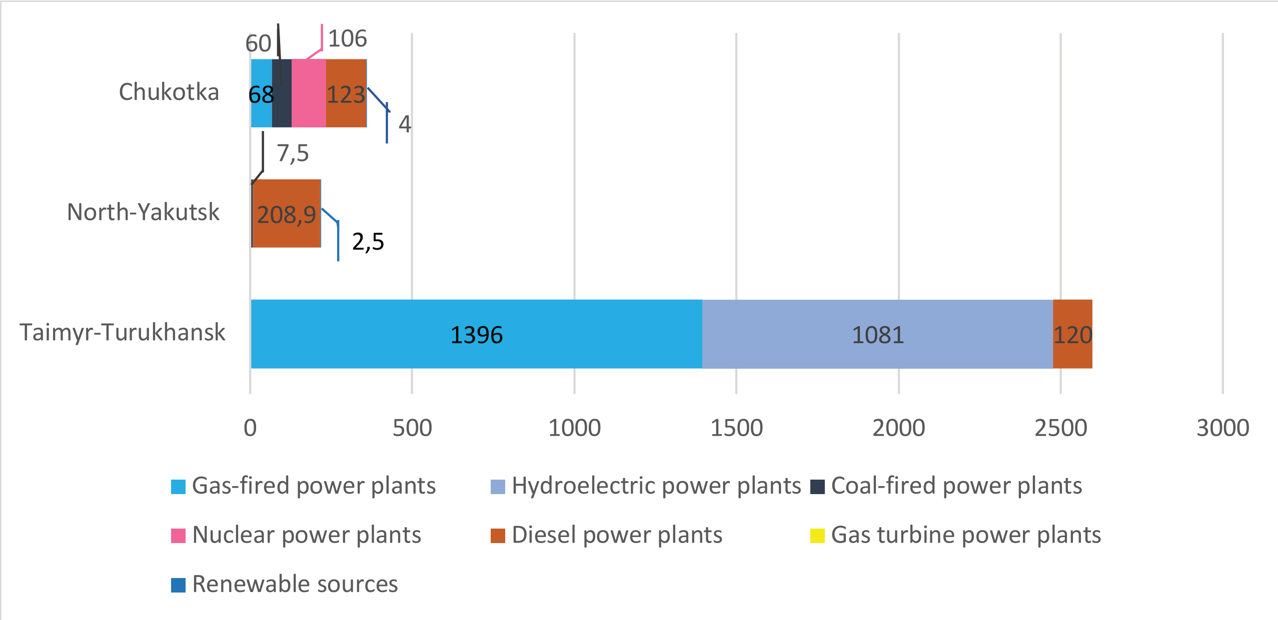

Fig. 1. The structure of the installed capacity of power plants in the Eastern Arctic (Based on the forms of Rosstat "Information on the heat and electricity production by generation facilities (power plants)" for 2019, given data from companies and expert assessments of the authors).

gas-fired power plants of the Norilsk and Vankor energy areas account for about 53%, the Ust-Khantayskaya hydro power plant (HPP) and the Kureyskaya HPP make up more than 40%, and the proportion of diesel power plants is 5% only (Fig. 1).

The Vankor energy area has electrical connections with the Northern energy area of the Tyumen energy system, which is part of the Unified National Electric Grid of Russia. Since 2015, the Vankor energy area has been included in the Krasnoyarsk energy system.

Centralized power supply in the territory of the Chukotka Autonomous Area is provided in three isolated load centers: Anadyr, Egvekinot, and Chaun-Bilibinsky. In the capacity structure in this zone, diesel power plants and nuclear power plants account for 30% each, given the decommissioning of one unit at the Bilibino NPP in 2019 and the commissioning of the floating nuclear power plant "Akademician Lomonosov." Almost 20% is provided by coal-fired power plants (Chaunskaya and Egvekinotskaya) and another 20% – by the Anadyr power plants (Anadyr TPP and Anadyr gas-fired TPP) burning natural gas from the Zapadno-Ozernoye field.

In the capacity structure of power plants in the North Yakutsk zone, utility power plants of JSC Sakhaenergo account for 80%. Relatively large power plants of LLC Yakutsk Generating Company operate at the Verkhnyaya Muna and Ebelyakh diamond deposits.

Due to the vast territory and poor development of the Eastern Arctic of Russia, decentralized energy supply is widespread. Almost 40% of the capacity of autonomous utility power plants in the Asian regions of the Russian Federation operates here. The main problems are complex logistics and seasonality of fuel delivery [4, 5].

III Promising projects for the development of mineral resources

The priority projects in the Eastern Arctic involve the development of the following deposits and fields:

- in the Taimyr-Turukhan zone: Chernogorskoe and Norilsk-1 deposits (rare-earth metals); Suzunskoe, Tagulskoe and Lodochnoe fields of the Vankor area (oil and gas); Syradasay and Malaya Lemberova deposits (coking coal); Popigai deposit (diamond); Payakhskoe field (oil) [6–8];
- in the North Yakutsk zone: Tomtor deposit (rare-earth metals); Ruchey Tirekhtyakh deposit (placer tin); Verkhne-Munskoye deposit (diamond); Kyuchus deposit (gold ore); Prognoz deposit (silver); West Anabar area field (oil and gas) [7, 8];
- in the Chukotka zone: Kekura and Klen deposits (ore gold); Peshchanka deposit (copper); Pyrkakay stockworks (tin and tungsten); Amaam and Alkatvaam deposits of the Bering coal basin (coking coal) [8–10].

The total demand of these projects for power is estimated at 13.7 billion kWh/year [3]. At the same time, the comparison between the growth in demand for electricity and the current indicators of generation in these zones indicates that in the Taimyr-Turukhan zone, the growth in demand is commensurate with generation; in the North Yakutsk zone, it exceeds 5.8 times; in the Chukotka zone, it exceeds 3.3 times. The need for electric power in the projects in the Eastern Arctic is more than 2.5 GW [3].

IV Research methods

The paper proposes a new methodological multi-stage approach developed to conduct feasibility study of energy supply options for new enterprises to be engaged in the

Table 1. Change in the Installed Capacity of Energy Sources, MW

State/Scenario	Gas-fired TPP	Coal-fired TPP	HPP	DPP	GTPP	Total
Current state	1 396	-	1 081	120	-	2 597
Nuclear scenario	2 841	227	1 081	189	-	4 338
Gas scenario	2 841	227	1 081	120	69	4 338

development of mineral deposits. The main stages of the approach are implemented as a set of simulation economic-mathematical and production-financial models that allow multifactor assessment of the performance of energy supply options for consumers located in off-grid areas [11, 12].

The feasible energy supply options for new enterprises were selected based on the findings of the research that determined:

- the competitiveness conditions for the centralized and autonomous power supply from diesel, thermal, and nuclear power plants [13];
- the competitive prices for liquefied natural gas to replace coal, crude oil in boiler houses, and diesel fuel at power plants [14].

V. Prerequisites for structural changes

The substantiation of feasible power supply schemes for new enterprises to be engaged in the development of promising fields involved building two scenarios for the development of energy infrastructure in the Russian Arctic:

- Creation of the low-capacity nuclear industry;
- Development of a liquefied natural gas infrastructure.

Both nuclear and gas scenarios suggest the same increase in the total installed capacity of energy sources compared to the current state.

The implementation of the most power-intensive projects (100–200 MW) will require the development of generating capacities and power grid infrastructure for the load centers in the Taimyr-Turukhan and Chukotka zones:

- Norilsk load center for Chernogorskoye and Norilsk-1 rare-earth metals deposits;
- Vankor load center for Suzunskoye, Tagulskoye and Lodochnoye oil and gas fields;
- Chaun-Bilibinsky load center for Peshchanka (copper) and Kekura (gold) deposits.

New less power-intensive production facilities (20–30 MW) can be connected to the generation centers if they are located in close proximity to them and the mechanism for equalizing electricity tariffs is maintained in the Far East of Russia [13].

Projects in the North Yakutsk zone can only be focused on autonomous power supply, since centralized power supply from the Yakutsk energy system in this territory is hardly possible even in the long term.

An important point in substantiating a preferable energy supply scheme for the enterprises in new development areas is selection of the type of fuel and its rational logistics. The projects for the extraction of fuel resources will naturally use their resources to supply power to the production facilities. In addition to the above deposits and fields (expansion of the Norilsk and Vankor load centers), it is planned to build power plants that use associated gas to power the enterprises of the Payakhskoye and the West Anabar fields and coal-fired power plants - to develop the Syradasay, Malaya Lemberova, the Amaam and Alkatvaam fields.

Ensuring the efficiency of projects for the development of metal ore deposits encounters the problem of choosing a fuel supply option for autonomous power plants. The studies presented in [14] prove the effectiveness of the use of liquefied natural gas in the coastal regions of the Arctic territories. A similar conclusion for the Arctic territories of the Russian Federation is made in [15]. In this regard, the gas scenario assumes the use of gas turbine power plants when developing the Peshchanka and Kekura deposits (when they are connected to the Chaun-Bilibinsky load center) and the Popigai, Tomtor, Kyuchus, Ruchey Tirekhtyakh, and Pyrkakay stockworks.

The nuclear scenario assumes that there is no liquefied natural gas infrastructure. This scenario also considers construction of low-capacity nuclear power plants in the Chaun-Bilibinsky load center to develop the Peshchanka and Kekura deposits, and in the Verkhoyansk area of the Republic of Sakha (Yakutia) – for Kyuchus deposits. The rest of the enterprises involved in the development of remote hard-to-reach deposits are powered by diesel power plants.

VI. Changes in the structure of generating capacities

Depending on the amount of electrical energy required to implement the projects for the development of deposits and for the creation of infrastructure, the increase in capacity by zone can make up 1.7–2.3 times.

Taimyr-Turukhan zone

Both scenarios envisage a growth in capacity due to a double increase in capacity of gas-fired TPPs and construction of coal-fired TPPs. Construction of nuclear power plants and use of renewable energy sources in this zone are not planned (Table 1).

No significant changes are expected in the capacity structure of energy sources: the share of HPPs will decrease

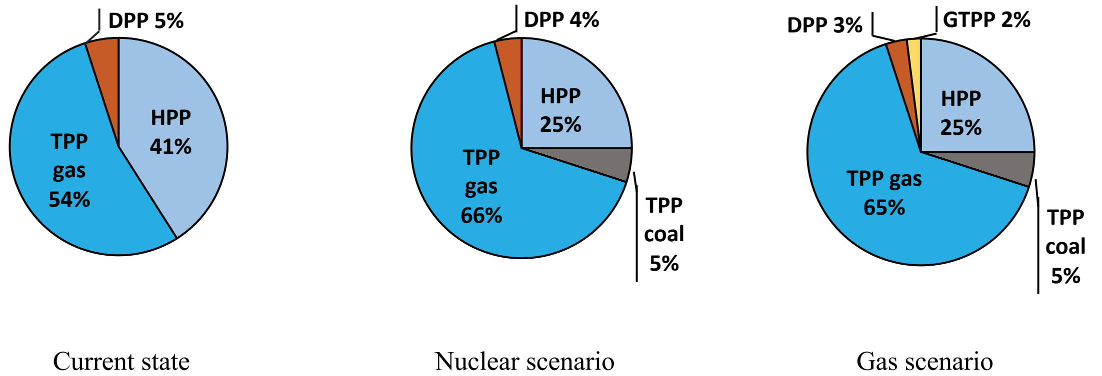

Fig.2. The structure of changes in the installed capacity of energy sources.

Table 2. Change in the Installed Capacity of Energy Sources, MW

State/Scenario	Gas-fired TPP	Coal-fired TPP	NPP	DPP	GTPP	Renewable sources	Total
Current state	-	7.5	-	208.9	-	2.5	218.9
Nuclear scenario	162	8	32	307	-	2.5	511
Gas scenario	162	8	-	259	80	2.5	511

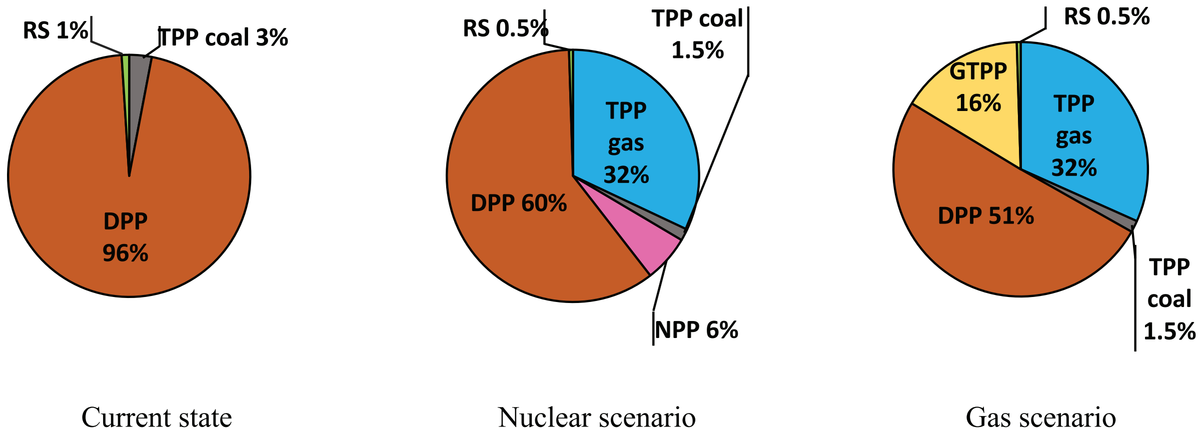

Fig. 3. The structure of changes in the installed capacity of energy sources.

due to an increase in the proportion of gas-fired TPPs and the commissioning of coal-fired TPPs in both scenarios. The share of diesel power plants in the gas scenario will slightly go down due to the commissioning of gas turbine power plants (Fig. 2).

North Yakutsk zone

Both scenarios suggest an increase in the installed capacity due to the commissioning of gas-fired TPPs. The nuclear scenario involves the construction of NPPs to supply energy to Kyuchus field and the commissioning of new diesel capacities. The gas scenario envisages the commissioning of diesel power plants and gas turbine units (Table 2).

The capacity structure of energy sources will change significantly compared to the existing state. In both scenarios, despite the growth in capacity, the share of DPPs declines considerably due to the construction of gas-fired TPPs and NPPs in the nuclear scenario, and the construction of gas turbine plants in the gas scenario (Fig. 3).

Chukotka zone

In both scenarios, the installed capacity of energy sources will increase through construction of coal-fired TPPs and DPPs. In addition, the nuclear scenario suggests the construction of nuclear power plants to meet the demand for power when developing Baimskoye and Kekura deposits. In the gas scenario, an alternative to nuclear thermal power plants (NTPPs) is the construction of gas turbine power plants for power supply to the enterprises of Peshchanka and Kekura deposits, and those in the coastal areas (Table 3).

The capacity of gas-fired TPPs will remain at the current level, the capacity of coal-fired TPPs and DPPs will increase, however, their proportion in the capacity structure will decrease due to the construction of NTPPs in the nuclear scenario, and the commissioning of GTPPs, whose share will be slightly less than 50%, in the gas

Table 3. Change in Installed Capacity of Energy Sources, MW

State/Scenario	Gas-fired TPP	Coal-fired TPP	NTPP	DPP	GTPP	Renewable sources	Total
Current state	68.3	60	106	123	-	4	361
Nuclear scenario	68	121	374	191	-	4	758
Gas scenario	68	121	70	161	334	4	758

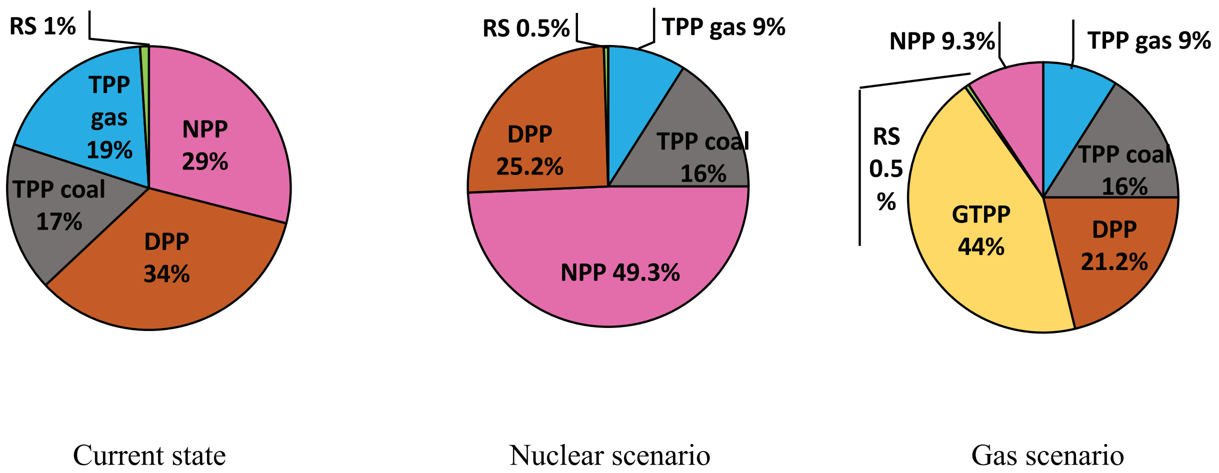

Fig. 4. The structure of changes in the installed capacity of energy sources.

scenario (Fig. 4).

The fuel needs of new generating capacities at the resource development enterprises is estimated at 5–5.6 million t.c.e., of which about 60% falls on projects for the extraction of oil, gas, and coal. The rest of the increase in the demand will be met by the resources delivered from other areas, which will significantly increase the load on the transport system. The complex multi-link seasonal fuel delivery to the areas of the Eastern Arctic and the state of year-round and winter roads are the reasons why the transport infrastructure can become a barrier to the large-scale development of mineral resources. In this regard, the Arctic regions of Russia need a state program for the development of transport and energy infrastructure. The absence of the program calls into question the reality of the economic development of the Arctic [Energy Policy].

VII. Conclusion

The implementation of projects for the development of mineral resources in the Arctic, which are outlined in the state strategic documents, will require the feasibility study of power supply schemes. With this in view, the study should take into account the characteristics of the Eastern Arctic, i.e., partial isolation of the territories from the Unified Energy System of the Russian Federation, the focal nature of development, the absence of established transport and industrial infrastructure.

More than 2.5 GW of additional generating capacity will be required to support projects in the Taimyr-Turukhan, North Yakutsk, and Chukotka zones. The total electricity consumption of the projects is estimated at 13.7 billion kWh/year.

In order to meet the necessary demand of each zone, a separate assessment of possible transformations in the structure of generating capacities was made compared to the current state. A methodological multi-stage approach developed to substantiate the energy supply options was used. The new approach is based on a special set of simulation economic-mathematical and production-financial models.

Two scenarios for the energy infrastructure development are considered: the creation of a low-capacity nuclear power industry and the establishment of a liquefied natural gas infrastructure.

Based on the research findings, the following solutions are presented.

In the Taimyr-Turukhan zone, both scenarios envisage a twofold increase in the capacity of gas-fired TPPs and the construction of coal-fired TPPs. The construction of nuclear power plants and the use of renewable energy sources in this zone are not planned.

In the North Yakutsk zone, the commissioning of gas-fired TPPs will increase the capacity in both scenarios, thereby reducing the share of diesel power plants significantly.

In the Chukotka zone, in both scenarios, an increase in the capacity of energy sources will be achieved through the construction of coal-fired TPPs and DPPs. In addition, the nuclear scenario involves the construction of a nuclear power plant to meet the demand for energy when developing the Peshchanka and Kekura deposits. In the gas scenario, an alternative to NTPPs is the construction of

GTPPs for auxiliary power supply at these deposits.

The demand of new power plants for fuel is estimated at 5–5.6 million t.c.e. Projects for the extraction of fuel resources intended for auxiliary power supply to these plants account for about 60%. Metal ore mining projects in the coastal areas can be supplied with liquefied natural gas, the effectiveness of this energy supply option has been proven by the research.

The large-scale development of mineral resources in the Arctic regions of Russia is impossible without a state program for the development of transport and energy infrastructure.

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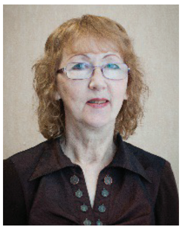
Irina Yu. Ivanova PhD in economics, Head of the Laboratory of energy supply to off-grid consumers, Melentiev Energy Systems Institute (ESI) SB RAS, Irkutsk. Education: Cybernetic faculty of the Irkutsk Polytechnic Institute with two specializations: in Computer-aided Management and Large Energy Systems.
Research area: small-scale energy, the policy of energy supply to consumers in the northern and remote areas, modeling of economic activities of autonomous energy sources.

Alexander K. Izhbuldin Lead specialist of the Laboratory of energy supply to off-grid consumers, Melentiev Energy Systems Institute (ESI) SB RAS, Irkutsk. Education: Irkutsk State Economic Academy.
Research area: development of approaches, methods and models of feasibility study of power supply schemes of consumers, the use of alternative fuels in the Northern and remote areas, as well as in specially protected natural areas.



Tatiana F. Tuguzova PhD in engineering, Senior research fellow of the Laboratory of energy supply to off-grid consumers. Melentiev Energy Systems Institute (ESI) SB RAS, Irkutsk Education: Irkutsk Polytechnic Institute with a degree in Industrial Heat Power Engineering.
Research area: feasibility study on the application of renewable energy sources to supply energy to off-grid consumers, modeling of their joint operation with fossil energy sources.

Vladislav A. Shakirov PhD in engineering, Senior research fellow of the Laboratory of energy supply to off-grid consumers. Melentiev Energy Systems Institute (ESI) SB RAS, Irkutsk Education: Bratsk state university with a degree in Electric power systems and networks.
Research area: assessment of renewable energy potential, hybrid renewable energy systems, multi-attribute decision making.

On Development Prospects of the Energy Industry in the Russian Far North

N.V. Pavlov*, V.V. Lepov, V.E. Zakharov, D.V. Prokhorov

V.P. Larionov Institute of the Physical-Technical Problems of the North of the Siberian Branch of the RAS, Yakutsk, Russia

Abstract — **This paper reviews the research activities of the Energy Department of the IPTPN SB RAS from 2018 to this day with a focus on development prospects of the energy industry in the Far North of the country through a case study of the Republic of Sakha (Yakutia). Systems studies of the energy industry require accumulating a wide array of information that vary in terms of its granularity. We review published research that addressed the issue of how researchers the raw data and what established sources of data are available to facilitate the analysis of energy systems operating in Yakutia. The aim of this study is to outline approaches to enhancing the quality of both fuel supply and modeled projections of the outcomes of integrated heating and cooling systems deployment in the city of Yakutsk. The simulations we performed attested to the availability of a sufficient amount of the waste heat as long as they have been in operation, including the periods of maximum possible cooling load. The values of key economic performance metrics support our claim of economic feasibility of such a project, given sufficient demand for cooling. The study also details recurring failures of one of the components of engineering systems operating in an Arctic village of Yakutia and proposes possible solutions. We conclude that either the design of the boiler or the material of the pipes has to be changed there. This is due to the fact that the pipes fail to operate properly under the extreme operating conditions, since the low ambient temperatures cause the intensification of heat transfer, and a lower temperature of exhaust gases contributes to moisture condensation and corrosion of the pipes. Finally, we outline main directions to be pursued in ensuring environmental protection by the efficient use of fuel and energy resources of Yakutia and detail the methods to be used to this end.**

Index Terms: **Russian Far North regions, energy sector, power supply to isolated and remote communities, environmental Impact assessment of operation of fuel and energy facilities.**

I. Introduction

The Energy Department of the IPTPN SB RAS has been involved in several studies on energy development prospects in the Republic of Sakha (Yakutia) since 2018. This paper attempts to recapitulate the main research findings obtained so far.

II. Main Part

The energy potential of the Republic of Sakha (Yakutia), one of the regions (subjects) of the Russian Federation, is abundant enough to cover the current and future needs of the region multiple times and has a significant impact on the formation of the fuel and energy balance of the Russian Far East and Eastern Siberia, and Russia as a whole.

The large-scale dynamics and structural changes in extraction (production) and consumption of primary energy resources in the RS(Y) date back to the 1980s. A revival of large-scale development and structural change in the energy sector of the Republic began only after the recession during the period of transition from a centrally planned and controlled economy to a market-driven economy at the end of the first decade of the 21st century. It occurred in line with the main anticipated trends laid down in the Energy Strategy of the Republic of Sakha (Yakutia) to 2030 [1–6].

The definition presented above along with the basic principles of the regional energy policy of the Far North of the country are at the core of a hierarchy of tasks for elaborating the vision of future large-scale development of the energy sector of the Republic of Sakha (Yakutia) and the methodological foundations for its development (Fig. 1).

Embracing the development presupposes a solid

* Corresponding author.
E-mail: pavlov_nv@iptpn.ysn.ru

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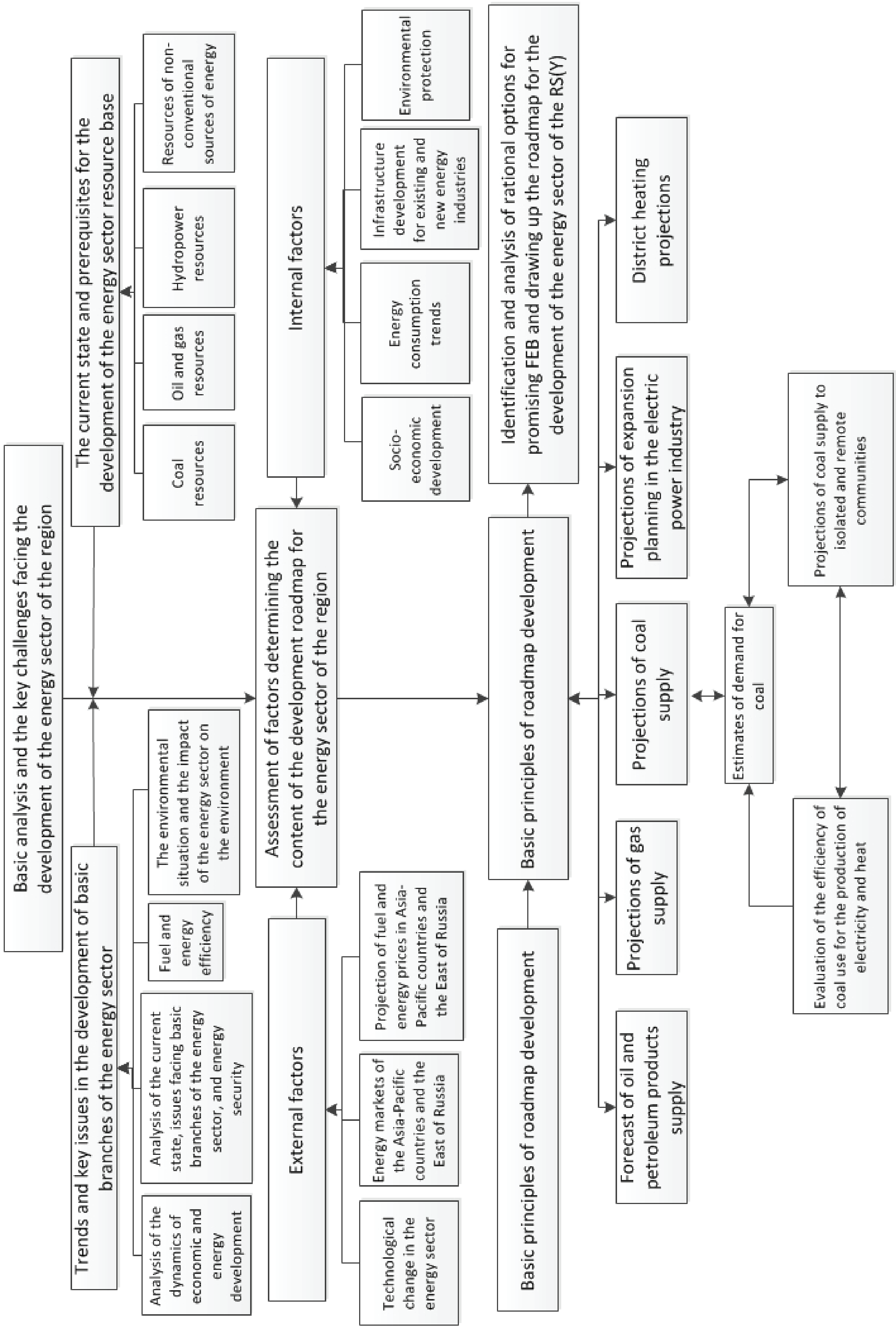

Fig 1. The hierarchy of tasks for developing a roadmap for future development of the regional energy sector and the methodological foundations for its development.

Table 1. The Structure of Key Information Retrieved from the information and Analytical Database on the Operation of the Energy System of the Republic of Sakha (Yakutia), Based on the Results Reported for Years 2016 to 2020

Type of activity of enterprises	Parameter group	Parameters
Heating companies	Heat balance	Production
		Auxiliary consumption
		Heat output
		Net heat output
		including
		public sector entities
		households
		by OKVED (All-Russian Classifier of Types of Economic Activities)
		for on-site production
		Loss due to transmission
	Parameters of heat networks	Length of pipelines, by diameter
		Specifications of pumping equipment
		Equipment health assessment
	Heat source parameters	Specifications of boiler equipment
		Installed capacity
		Type of the main fuel
		Backup fuel type
		Fuel consumption
	Scope of work to repair the heating system	Length of replaced pipelines, by diameter
Power generation companies	Power plant parameters	Actual basic circuit diagrams
		Main parameters of power grid equipment
		Information about generator equipment
		Installed capacity
		Available power
		Maximum load
		Fuel consumption
		Specific fuel consumption
	Electricity balance	Electricity generation
		Auxiliary electricity consumption
		Electricity supply from substation busbars
	Heat balance	Production
		Auxiliary consumption
		Heat output
		Net heat output
		including
		public sector entities
		households
		by OKVED (All-Russian Classifier of Types of Economic Activities)
		for on-site production
Power grid companies	Parameters of electrical networks	Basic circuit diagrams as of the beginning of the year
		Length of power lines, by voltage class
		Transformer power, by voltage class
		List of substations with a voltage of 35 kV and above, with their make, capacity, and number of power transformers indicated
		List of overhead lines with a voltage of 35kV and above, with their parameters (type of towers, make, and conductor cross-section) indicated
		List of power centers with restricted utility connections
		Electricity loss due to transmission

Large consumers	General information	Manufacturing KPIs Annual heat consumption Annual electricity consumption Maximum own load
	Information about own sources of thermal energy	Source type Installed capacity Connected load Specifications of boiler equipment Type of fuel Fuel consumption
	Information about own sources of electricity	Installed capacity Available power Information about generator equipment Connected load Fuel consumption Specific fuel consumption Electricity generation

understanding of the current situation. We regularly analyze key metrics measuring the performance of the energy sector of the Republic of Sakha (Yakutia), both in terms of production and consumption of energy resources and in terms of investment dynamics. To conduct energy studies at the level of entire systems, one has to collect a broad range of information of varying granularity. At the regional level, the degree of data aggregation decreases and, to a greater extent, it is necessary to collect primary information directly from each company that is involved in the energy supply process or is a large consumer. The mode of consumption of fuel and energy resources is influenced to a large degree by both by the operating conditions of the energy system and its structure. The conditions listed above for the collection of information on energy systems justify the need for independent collection and formation of data and analytical information databases of the parameters of investigated objects. The organizational complexity of information collection warrants the effectiveness of collecting data on a broader range of entities than is required for current research. This approach guides the search process allowing for quickly testing working hypotheses on the feasibility of more in-depth studies as they emerge. The information obtained as part of the work carry out includes that from the heating companies that cover more than 90% of the heating load of the municipalities of the republic. Other pieces of information come as the data obtained on the production and consumption of thermal energy by large industrial enterprises that make up more than 80% of the total industrial output. The information on power supply is received from all electricity generation and distribution companies, as well as from suppliers of last resort operating in the republic. The information is also collected about major companies in different sectors of economy that utilize their own electricity sources. Second, we have to face the challenge responding promptly to changing circumstances and enhance our strategic energy planning tools [7].

There is ongoing work to enhance the fuel supply. Despite the expansion of the scope covered by gas supply and a wide coverage of the households by district heating, the firewood still makes up a significant share of the regional energy balance. Firewood continues to be the primary fuel used for heating by the residential sector in rural areas. There are wood-fired boilers that supply heat to social sector consumers and households of the remote and isolated villages in addition to the decentralized sector. Here, the annual consumption of thermal energy is calculated on the basis of actual data for a region of the republic and the amount of firewood consumed for heating in those parts of the residential sector that are unconnected to any form of energy supply. A projection of the consumption of firewood by households to 2030 has been made according to the estimates provided above.

The technologies to produce and burn high-quality fuels from wood and agricultural waste could also be a contributing factor. Such technologies are the only available option for certain consumers. Today and almost up to the 1980-90s of the last century the firewood was used as main fuel for heating. In most municipalities, wood stocks have been severely depleted. The rate of deforestation has been higher than the reforestation rate up until now. Regular wildfires also contribute to a significant extent to the depletion of reserves. The production of wood pellets to cover the same heat load can reduce deforestation by two times due to a fuller use of wood. This also comes with a significantly higher energy efficiency of automated pellet boilers compared to wood harvesting and combustion in conventional wood-burning furnaces, according to preliminary estimates.

The performance of the coal supply system could be improved by introducing the coal grading and beneficiation process flows at local mining companies. Introduction of modern transport technologies and improvement of the coal metering system may also prove relevant. A case in point is the use of flexible intermediate bulk containers (big bags) for coal bagging which makes it possible to eliminate a notable deterioration of the quality and mechanical losses that otherwise come with a complex coal supply chain, and to form an accurate metering system for transportation of coal purchased [8].

Energy development trends are currently leading towards the integration of energy of various types in a single complex. We consider the issues of justification of development of the Russian energy sector as those coupled with the new vector of development of its one specific component, most notably the introduction of integrated heating and cooling systems. The introduction of integrated heating and cooling systems, according to a preliminary evaluation, can significantly reduce the total electricity demand of consumers in Yakutsk by as much as 20%. Provisional estimates indicate that the project could prove economically feasible, even under current market conditions, if there is sufficient demand for cooling. In this article, a comparative evaluation of energy efficiency is carried out with respect only to potential energy savings. The relevance of introducing the technology of integrated heating and cooling systems has been confirmed by the results of modeling and it is also in line with key global energy trends (including decarbonization and globalization, along with the introduction of CO_2 emission quotas, etc.) [9].

The extreme cold weather characteristic of the Republic of Sakha (Yakutia) requires greater reliability and efficiency of engineering systems during their entire lifespan of operation in local settlements. The duration of the heating season in Yakutia averages 8–9 months per year, and is year-round in some Arctic settlements. Therefore, recurring failures of individual components of engineering systems merit special attention.

The authors analyzed the operation of the air blower pipe of the coal-fired boiler KVm-2.5LB of the boiler plant operated in one of Arctic villages of the Republic of Sakha (Yakutia), and studied several samples of the faulty section of the pipe using optical and electron scanning microscopy. The composition of the metal was identified and the inhomogeneity of mechanical properties was evaluated by micro-hardness distribution analysis. Although the primary microstructural analysis indicated that the pipe steel was subjected to severe overheating, more than twofold thinning of the pipe walls, and the presence of wormholes along with the fact that the pipe was subsequently repeatedly welded, provided evidence supportive of the claim that the fracture was due to corrosion. The calculation of the dew point attested to the unavoidable moisture condensation on the pipe walls due to non-standard low-temperature operating conditions in a wide range of air humidity values during the operation of the boiler. The design of the boiler, or the material of the pipes, therefore, has to be changed due to the fact that they proved inadequate under the extreme operating conditions, since the low ambient temperatures caused an intensification of heat transfer, a decrease in the temperature of the exhaust gases, moisture condensation, and corrosion of the pipe steel [10].

Finally, as for the environmental component, in addition to fieldwork, remote research methods were used for the first time to study certain areas of Southern Yakutia, which was due to their remoteness from industrial centers and inaccessibility of objects of our studies. The interaction of the Elga coal complex, represented as the coal-mining geotechnical system «Coal-mining complex – Natural environment – Human», with natural complexes was studied in line with the geosystem approach. The factors of influence on the components of the natural environment and the directions of their change were identified. The functional, cause-and-effect, and local relations between the subsystems of the geotechnical system were also systematically arranged. We performed assessments of the degree of resilience of landscapes in the area of development to human-induced impact and the change undergoing by such landscapes. We proposed a map of environmental zoning. The map rendered various levels of environmental protection measures specified in a set of documents regulating them. That took into account the extent to which human-induced transformation altered sustainability.

We built a planimetric map with point and non-point features of the Elga coal complex. To this end, GIS technologies were applied. They included satellite imagery for studying natural and man-made systems and the use of unmanned aerial vehicles. The map will allow modeling the spread of pollution from point and nonpoint sources of air, land, and water pollution. Such a map could be used to create a unified model that captures changes in natural environment components and the degree of landscape disturbance within the premises of the facility. Zoning of the disturbed lands of that are licensed for subsoil use at the Elga coal field was carried out, and three centers of human-induced impact, corresponding to various factors of human-induced impact, were identified [11].

We carried out a component analysis of the current state of the natural environment of North-Eastern Yakutia and an assessment of the resilience of natural landscapes to human-induced impact as a necessary basis for developing ways to reduce the consequences of environmental impact during the mineral resource development of the investigated area.

We identified the directions for improvement of the area. They include the integrated use of geoecological research methods based on landscape analysis, which is necessary for assessing the current state, its monitoring, and predicting changes in the natural environment. Another component is the use of geoinformation methods and aerial surveying in order to obtain operational information and do environmental mapping.

Furthermore, we identified the main directions to be pursued for environmental protection in the use of fuel and energy resources in Yakutia.

III. Conclusion

The development prospects of the energy industry in the Republic of Sakha (Yakutia) are related to improving the reliability of energy and fuel supply and making energy consumption more efficient, including through:

- elaboration and timely updating of strategic planning documents for energy development, drawn up so as to take into account the unique features of the Russian Far North;
- development and timely implementation in the energy sector of the products of technological change;
- development of integrated heating and cooling systems;
- application of new cold- and corrosion-resistant materials;
- development of such topologies and operating conditions of power plants that are adequate to the severely continental climate and low temperatures;
- adoption of efficient energy supply schemes based on proper long-view technical and economic comparisons of available options.

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Nikita V. Pavlov, Head of the Energy Department at V.P. Larionov Institute of the Physical-Technical Problems of the North SB RAS, Yakutsk. His research interests include methodology, system modeling, software tools and databases for research, projections and selection of rational directions for the development of the energy in the Russian Far North. He is the author of over 70 research publications, including chapters and sections in 4 edited volumes.

Valeriy V. Lepov, D.Sc. in Engineering, Director of V.P. Larionov Institute of the Physical-Technical Problems of the North SB RAS, Yakutsk. His research interests include fracture mechanics and multi-scale modeling, material science and phase transition, energy and systems approach, history and philosophy of natural sciences and engineering. Valeriy Lepov is the author of over 300 research publications, including 4 patents and 5 monographs.

Vasiliy E. Zakharov, Researcher at the V.P. Larionov Institute of the Physical-Technical Problems of the North SB RAS, Yakutsk. He is the author of over 50 research publications. His research interests include theoretical and applied issues of ensuring regional energy security, problems of long-distance transport, storage and reservation of fuel, theoretical issues of system analysis and strategic planning.

Dmitriy V. Prokhorov, Ph.D, Senior Researcher at the V.P. Larionov Institute of the Physical-Technical Problems of the North SB RAS, Yakutsk. He is the author of over 50 research publications. His research interests include theoretical issues of ensuring the reliability and safety of consumers in the North, renewable energy sources.

Environmental Considerations Related to Generation Facilities in the Regions of the Asian Part of Russia

E.P. Maysuyk*

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The features unique to the operation of energy facilities in the Asian part of Russia influence environmental agenda setting in these regions. The Asian regions account for a large share of Russia's mix of air pollutant emissions and production of coal ash, with boiler houses responsible for a significant part of their amounts. Particulate matter and sulfur oxides dominate the ingredient composition of pollutant emissions, unlike in European Russia. From an environmental point of view, what makes regions of the Asian part of Russia stand apart in a rather egregious way is the large proportion of cities with high levels of air pollution. Of the 37 such cities in the country, 27 are located in Siberia and the Russian Far East. The regions of the Asian part of Russia, due to the predominance of coal in their fuel balances, are characterized by a high share of CO2 emissions from generation facilities. Specific carbon dioxide emissions in the Asian regions are 1.5 times higher than in the European part of the Russian Federation. Given that in the near future it is unlikely for coal to be completely eliminated from fuel balances of the Asian regions, in order to decarbonize Russia's energy sector, a number of strategies of low-carbon development should be developed for these regions.**

***Index Terms*: Energy facilities, coal balance, pollutant emissions, carbon dioxide emissions, decarbonization strategies.**

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

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I. Introduction

The environmental features unique to energy facilities in the Asian regions of Russia are shaped by the mix of pollutant emissions from large and small generation facilities, the ingredient composition of emissions, the volume of fuel consumed and its mix, and the use of treatment equipment. In order to identify such features unique of energy facilities in the Asian regions of Russia we assess their contribution to environmental impacts.

In this study, such environmental assessment was performed for two key metrics: emissions of pollutants into the atmosphere and production of coal ash. Furthermore, we estimated carbon dioxide (CO_2) emissions from TPPs and boiler houses in the context of decarbonization of the economy, including the country's energy sector.

Calculations of emissions from power facilities were made on the basis of data on the consumption of fuel and energy resources by TPPs and boiler houses in Russia in 2020 (statistical reporting form 4-TER), highlighting the Asian regions.

II. Calculation Methods

For quantitative environmental assessments we used the techniques approved in the Russian Federation for calculating gross emissions of air pollutants from TPPs and boiler houses [1–3], as well as methodological guidelines for quantitative assessment of coal ash produced by power facilities [4, 5]. The calculations used data on the quantity and quality of combustible fuels and data on the types of power equipment.

Pollutant emissions were calculated for four main ingredients: particulate matter, sulfur dioxides, nitrogen oxides, and carbon oxides. The calculations assumed that at large coal-fired power houses, both in Russia on average and in the Asian regions of the country, the efficiency of ash capture is not less than 92%. There is

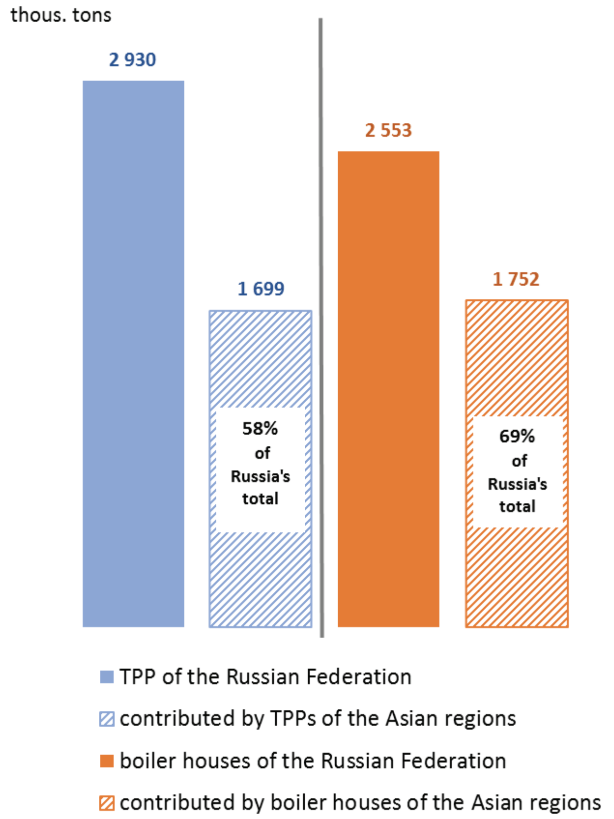

Fig. 1. Estimated emissions of air pollutants from TPPs and boiler houses in Russia and its Asian regions in 2020.

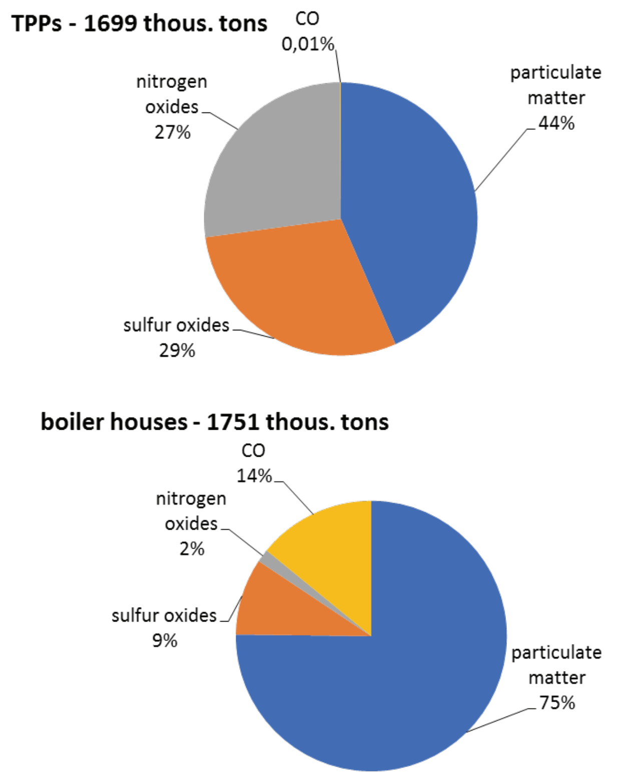

Fig. 2. Ingredient composition of air pollutant emissions from TPPs and boiler houses in the Asian regions of Russia in 2020.

Table 1. Consumption of fuel and energy resources at TPPs and boiler houses in Russia in 2020, thousand tce

Fuel	Generation facilities		Total
	TPP	boiler houses	
Coal	46,053	10,452	56,505
Fuel oil	412,000	1,353	1,765
Natural gas	10,859	3,986	14,845
Total	57,324	15,791	73,115

no reliable information about the efficiency of ash capture at coal-fired boiler houses. According to expert estimates, ash treatment, especially at many small boiler houses, is not provided for or is not carried out properly, and it was assumed to be zero in our calculations.

For quantitative assessment of greenhouse gas emissions from generation facilities, we used the methodological guidelines as per the approved Order of the Ministry of Natural Resources of the Russian Federation No. 300 [6]. The scope of our calculations for combustion of fuels at power facilities covered only carbon dioxide. The calculation was based on the data on the amount of fuel burned and its type (coal, natural gas, fuel oil, etc.), as well as emission factors recommended by both the International Panel on Climate Change (IPCC) and those adopted in this country [6].

III. Quantitative Assessments of the Environmental Performance of Generation Facilities

Data on the amount of consumption of fuel and energy resources at the power facilities of the Asian regions of Russia are presented in Table 1.

On the basis of the techniques referred to above, we performed calculations of air pollutant emissions. The estimated amount of pollutant emissions in 2020 originating from power facilities (TPPs and boiler houses) of the Russian Federation was estimated at 5.5 million tons, of which 63% (or 3.5 million tons) was contributed by the Asian regions of the country (Fig. 1).

Among power facilities located in the Asian regions, the largest amount of emissions came from boiler houses (almost 1.8 million tons), the main pollutant being particulate matter. When compared to European Russia, boiler houses emitted 2.2 times fewer pollutants and 3.3 times fewer particulate matter into the atmosphere. Comparing air emissions from TPPs in the Asian regions, it should be noted that along with particulate matter emissions (40–43% of total emissions) almost 30% were sulfur dioxide emissions, whereas in the case of large houses in the European part of the country the predominant air contaminant was nitrogen oxides (up to 40% of total TPP emissions of the European part of Russia). In the Asian regions of Russia, particulate matter is the main

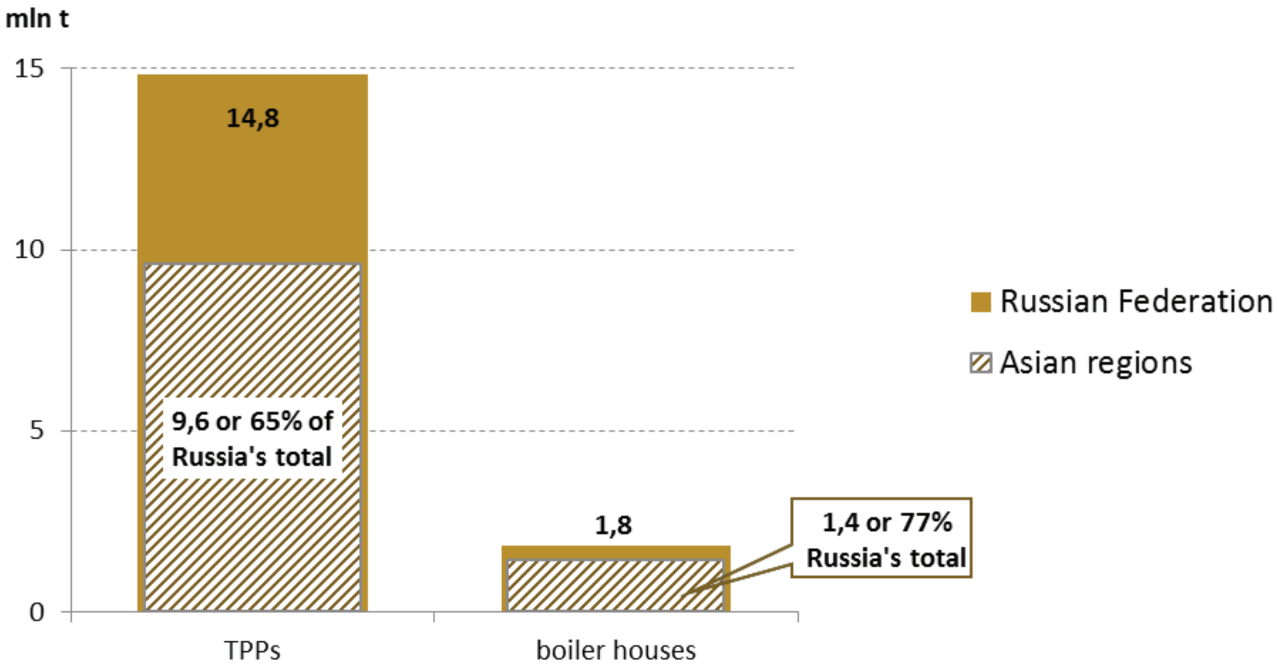

Fig. 3. Estimated amount of coal ash from power facilities in Russia and its Asian regions in 2020.

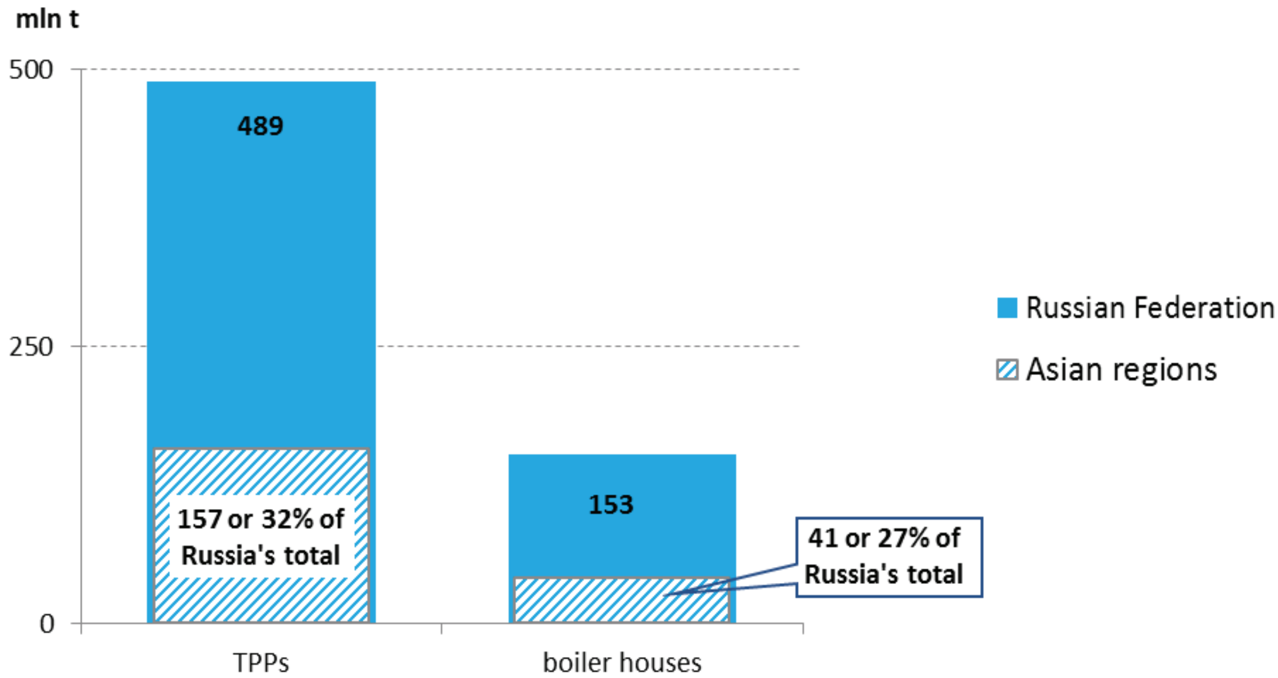

Fig. 4. Estimated amount of carbon dioxide emissions from power facilities in Russia and its Asian regions in 2020.

Table 2. Estimated carbon dioxide emissions from generation facilities in Russia, million tons (as of 2020)

Country, region	Generation facilities		Total
	TPP	boiler houses	
Russia's total, inclusive of the following:	489	153	642
Asian regions	157	41	197
European regions	333	112	445

pollutant from both TPPs and boiler houses. Depending on the type of a generation facility, a significant amount of sulfur oxides (500 thous. tons) and nitrogen oxides (460 thous. tons) came from large TPPs, see Fig. 2.

The environmental assessment performed indicated that the main sources of air pollutant emissions were coal-fired generation facilities, with a significant share of boiler houses, while the volume of coal consumption by TPPs was almost 4 times higher than by boiler houses.

This feature unique to the Asian regions of Russia is related to the considerable amounts of coal consumed by generation facilities. The coal consumed is for the most part lignites, most notably its Kansko-Achinsky, Primorsky, Kharanorsky, and Azeisky varieties. For the purposes of our calculations, their qualitative characteristics were assumed as per the data found in reference books [7–9].

The estimated amount of coal ash generated in Russia as a whole was estimated at 16.6 million tons, of which almost 11 million tons (or 66%) were produced in the Asian regions of the country. The largest contributor was large power facilities – TPPs (Fig. 3) that capture a significant amount of fly ash (as was assumed in the calculations, with the efficiency value being 92%).

The calculated amount of coal ash at TPPs in the Asian regions of the country was almost 2 times higher than their production at TPPs in European Russia and 3.4 times higher, when making a similar comparison, at boiler houses. The resulting environmental assessment for coal ash also characterized the regions of the Asian part of Russia as facing great environmental challenges and highlighted the significant amount of coal used for generation needs.

Based on the amount of fuel used by generation facilities in Russia in 2020, the amount of CO_2 was estimated at 642 million tons, with the Asian regions of the country accounting or 197 million tons of the total amount. In terms of power generation facilities, the mix of carbon dioxide emissions sources was dominated by TPPs in both Russia and the Asian part of the country (Fig. 4).

The contribution of the Asian regions to Russia's total carbon dioxide emissions can be reduced by about half through large-scale gasification of power facilities.

In general, the calculations of CO_2 emissions showed that in the European regions of Russia the share of TPPs was quite high (up to 75%), but this contribution was formed by the consumption of significant amounts of natural gas (94% of all gas in Russia), while in the Asian regions the large contribution of TPPs to carbon dioxide emissions (up to 79%) originated from coal-fired generation, see Table 2.

To analyze the data obtained, it is advisable to compare the specific carbon dioxide emission figures for Asian and European parts of Russia. Taking into account the amount of fuel burned at the power facilities of Russia in 2020, we can see that the specific emission of carbon dioxide in the Asian regions was 2.5 tons of CO_2 / tce, and in the European regions – 1.7 tons of CO_2 / tce. In fact, there were 1.5 times more carbon dioxide emissions per ton of coal equivalent used by power facilities in the Asian regions than in the European regions of the Russian Federation.

Thus, the main causes of greenhouse gas emissions from generation facilities in the Asian regions of the Russian Federation are as follows:

- high share of coal in the fuel and energy balance of the areas in question;
- lack of technology to capture and use greenhouse gases;
- insufficient energy and fuel conservation measures;
- high degree of wear and tear of the generating equipment.

IV. Conclusion

Environmental assessment of the operation of generation facilities in the Asian regions of Russia allowed us to identify their key environment-related features. First of all, it is the predominance of coal in the fuel balance, which generates a significant amount of pollutants (63% of emissions from power facilities in Russia) and carbon dioxide (31% of CO_2 emissions from power facilities in Russia) emitted into the atmosphere. Furthermore, about 60% of all coal ash in Russia is produced there.

Numerous coal-fired boiler houses operating in the Asian regions of the country make a significant contribution to emissions. At the same time, environmental protection equipment at boiler houses is often missing or does not operate properly, thus accounting for almost half of the contribution to total emissions from power generation facilities. In fact, the use of treatment devices at thermal power houses offsets the emissions from four times the fuel consumption compared to boiler houses.

Thus, the environmental features unique to the energy industry of the Asian regions of Russia should also include:

- low level of gasification of boiler houses and power houses;
- high wear and tear of energy equipment and the use of obsolete equipment;
- lack of measures to process the coal before combustion (including thermal processing and gasification of coal);
- lack of ash capturing equipment at boiler houses and gas treatment equipment at large thermal power houses. Given the new challenges posed by

the climate agenda for generation facilities, it is necessary to provide for the following:

- equipment of the facilities with greenhouse gas capture systems;
- burial or re-purposing of carbon dioxide;
- introduction of automated boiler houses;
- increase in the share of energy facilities that run on renewable energy sources;
- implementation of energy-saving measures at all stages of energy production;
- continuous monitoring of the effluence of both pollutants and carbon dioxide into the environment.

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

Prospects for the Use of Wood Fuel in the Context of Low-carbon Energy Development

E.D. Ivantsova*, D.A. Kozyaeva

Siberian Federal University, Krasnoyarsk, Russia

Abstract — **Wood fuel can play an important role as a CO2-neutral alternative as part of the low-carbon energy transition. Furthermore, given the sanctions imposed recently, the development of the domestic market for wood fuel is extremely relevant for the timber industry of Russia as most of the pellets produced were previously exported. The article examines the current parameters of the development of the biofuel market and provides a comparative analysis of various types of fuel in terms of their economic and environmental performance. We also elucidate the key advantages of wood pellets as a fuel alternative to coal and fuel oil. Thus, the production of wood pellets seems to be very promising both in terms of the development of wood industries and in the context of low-carbon energy development. In the course of the study we identified the factors that act as constraints on the growth of the fuel pellet market, the prospects for overcoming them, and the necessary measures of government support for the industry (most notably, subsidy mechanisms and infrastructure development). The key takeaway from this study is that there are undeniable advantages that come with biofuels, in particular, wood pellets, the use of which in Russia is very promising provided that the economic incentives offered by the government to both manufacturers and residential consumers are in place.**

Index Terms: **Biofuels, timber industry, fuel pellets, low-carbon energy, pellets, wood fuel.**

* Corresponding author.
E-mail: eivantsova@sfu-kras.ru

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I. Introduction

The development of the timber industry in Russia in recent years has focused on the reorientation of the industry from the export of raw timber to the production of high value-added products. The corresponding goal was outlined in the Strategy for the Development of the Forest Complex to 2030 [1]. One of the promising areas, in the context of the development of high-tech industries, is biofuels, including wood pellets. At the same time, it would be fair to note that the motivation behind building pellet production facilities is more often associated with the obligations of enterprises to dispose of sawmill and wood-processing residues.

Pellet production in Russia is growing steadily both in absolute terms and as a share of global production and export volumes (Fig. 1). According to the Food and Agriculture Organization of the United Nations, in 2012, Russian pellet production was slightly more than 4% of the world volume, and by 2020 it is already more than 6% of world production and almost 8% of world exports [2].

According to Roslesinforg, Russian manufacturers annually produce about 2.7 million tons of pellets. In 2021, 2.4 million tons of pellets were exported, and about 90% were delivered to European countries [3]. The largest producers in the country are the enterprises of Segezha Group (360 thousand tons per year), Ustyansk Timber Plant (300 thousand tons), "Sawmill 25" (160 thousand tons), "Yenisei DOK" (120 thousand tons). Apart from them, there are dozens of medium-sized enterprises, as well as many small enterprises, but the information on the latter is much more difficult to collect.

In April 2022, exports to Europe began to decline under the sanctions imposed, and on July 10 the period for permitting the imports of wood products to the EU countries under old contracts expired, which seriously affected Russian manufacturers. Many enterprises were forced to stop the production of wood fuel. Against the backdrop of the sharp decline in exports, there is a

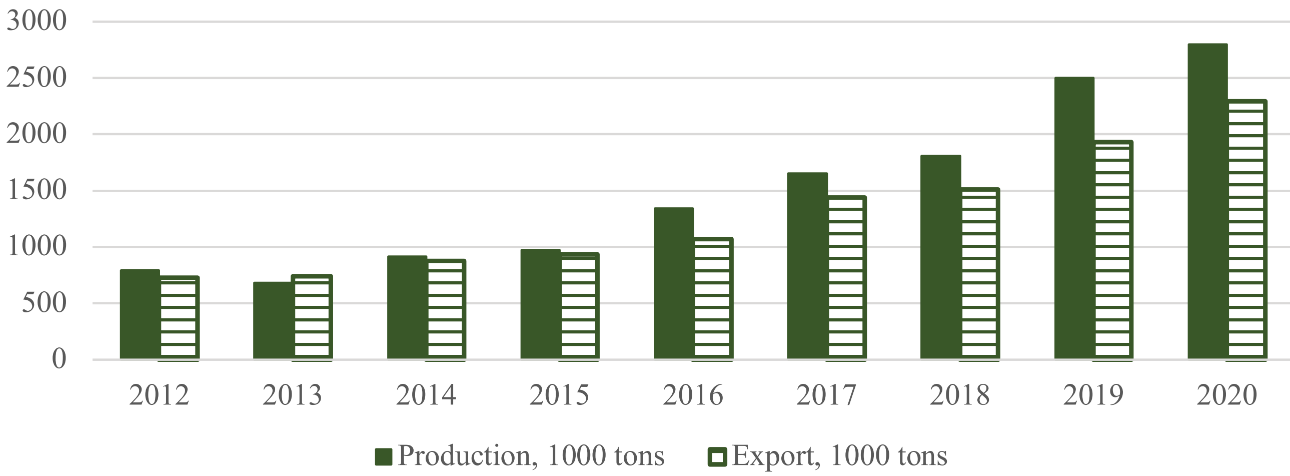

Fig. 1. Volumes of production and export of pellets in Russia in 2012–2020. Source: FAO, 2022.

TABLE 1. Comparison of parameters of Different Types of Fuel

Type of fuel	Heating capacity, kcal/kg	Cost, RUB/t	Ash content, %	Shelf life	Sulfur emissions, %	CO_2 emissions, kg/GJ
Coal	5 100	2 800	4–8	6-8 months	1–3	60
Mazut	9 800	17 000	1,5	5 years	1–2	78
Wood Pellets	4 500	6 400	1	—*	0,1	0*
Firewood	2 500	3 000	0,5	2 years	0	0*

Note: zero carbon dioxide emissions mean that when the product is burned, the amount of CO2 released does not exceed the amount that is formed during natural decomposition, and the amount of other harmful emissions is negligible. If stored properly (in a dry place), the shelf life of wood pellets is unlimited.

reason to believe that the domestic market of Russia has significant growth potential. As part of the measures to implement the Strategy for the Development of the Forest Complex to 2030, it was decided to convert about 30% of environmentally inefficient boiler plants from coal and fuel oil to fuel pellets [4]. The above conditions attest to the relevance of studying the prospects for the development of the pellet market in Russia in the context of the low-carbon agenda. This article investigates the possibilities of using wood pellets in the development of low-carbon energy, provides an overview of published research on the challenges and prospects of biofuel use, analyzes the current state of the domestic pellet market in Russia, and outlines the areas to be addressed by government support for the industry that are a prerequisite for the efficient operation of Russian pellet manufactures.

II. Literature Review

There are numerous studies on the advantages of biofuels over other energy sources. In addition, comparisons were made between the efficiency of using different types of biofuels [5]. There is also another alternative: co-firing of coal with wood pellets [6–8].

Pellet production is beneficial for the timber industry as an additional product category that at the same time allows it to fulfill the obligations to both dispose waste and mitigate climate change. Through a case study of the Finnish forest industry, it has been shown that the sawmill industry should consider introducing new business models for co-production of wood products and biofuels [9].

Speaking of the ways to overcome the restrictions that are currently imposed on Russian pellet producers, one should note the study of region-specific features of the development of low-carbon initiatives. The biofuel market has a fairly high concentration, and the spatial distribution of production is very uneven [10]. Therefore it is advisable to start converting boiler plants to biofuels in those regions where such experience already exists. First of all, these are the regions of the Northwestern and Siberian federal districts.

Furthermore, the transition to biofuels is relevant from the point of view of the climate agenda: in particular, it corresponds to the goals of the Strategy for the Social and Economic Development of Russia with Low Greenhouse Gas Emissions to 2050 [11]. In Russia, the strategies for modernizing the economy in order to move away from the raw material-oriented model and transition to a “green” economy largely coincide [12]. The production of pellets, combining the advantages of using renewable raw materials and a relatively advanced processing, is very promising in this context.

III. Results and Discussion

The main objective of this study is to evaluate the advantages of pellets in comparison with coal and other types of fuel, taking into account the focus on low-carbon development of thermal power engineering. Key comparison parameters and specific scores are presented in Table 1.

Since the specifications of these types of fuel differ significantly depending on the grade, it should be pointed out that the average values re given for lignites of the ZBPK grade (large lumps) as the most commonly used for heating private houses, M-100 fuel oil (GOST 10585-2013), wood pellets, and birch firewood with an average moisture content of 50%. Admittedly, even within the same standard grade, characteristics may vary. Obviously, the cheapest way to generate thermal energy is coal, which is the reason for the predominance of this type of heating. At the same time, coal is inferior to wood fuel both in terms of ash content and emissions of pollutants, as well as in terms of its shelf life. Wood fuel is also carbon-neutral, which is a major advantage in terms of low-carbon energy development. In addition, pellets are very convenient for domestic use when heating private houses: the process of feeding and burning in pellet boilers is automated.

The current state of the domestic pellet market in Russia is characterized, first of all, by the issues related to product sales. In the regions most affected by the EU ban on Russian exports, various support programs are already being implemented related to the reorientation to the domestic market. For example, in the Republic of Karelia, large producers of fuel pellets, including Segezha Group enterprises, previously supplied their products mainly to European countries. In June 2022, the Plan was approved to provide support measures to enterprises of the timber industry complex, within the framework of which it was proposed to use wood pellets in the energy sector of the republic – in particular, to convert to biofuels about 15 boiler plants, which today provide heating to social sector facilities. Representatives of the timber industry enterprises also express their readiness to facilitate such a transition as part of the so-called «Northern delivery». Segezha Group Vice President Nikolay Ivanov estimated the possible supply of wood pellets to the Far North at 250 thousand tons annually, which could ensure full manufacturing capacity utilization of not only the group's enterprises ("Tairiku-Igirma Group" LLC of Segezha Group produces up to 100 thousand tons per year), but also those of other manufacturers of pellets in the regions of Siberia.

There are also known successful cases of conversion of boiler plants to biofuels in the Krasnoyarsk region. For example, in the town of Kodinsk, Kras-Eko JSC is implementing a pilot project to modernize an electric boiler plant with a partial conversion of thermal power production to the use of biofuels. In the Boguchansky district of the region, 10 heat sources were put into operation by Les-service LLC, where boiler equipment was modernized to accommodate the use of wood pellets. Thanks to this, the volume of biofuels used in the region increased by 8 thousand tons of fuel pellets per year. Experts note that the use of wood pellets is 20–30% more economical than conventional coal and fuel oil [13].

The Russian Pellet Union, which unites manufacturers that together account for more than 60% of the production and exports of wood pellets in Russia, notes that the low consumption of fuel pellets in this country is due to the initial orientation of the Russian energy sector towards district heating. Moreover, there is a lack of effective energy-efficiency and resource-saving programs at industrial heating facilities. In addition to the transition of large boiler plants to biofuels, it is necessary to consider the possibility of promoting the use of wood pellets for heating private houses, the members of the Union believe [14]. A promising incentivizing tool could be providing subsidies to households for the purchase of pellet boilers and wood fuel.

A key limitation for the development of the industry is the lack of a national certification system for fuel pellets. In 2022, almost all certificates for pellets previously issued to Russian manufacturers expired, including the FSC (Forest Stewardship Council) and SBP (Sustainable Biomass Program) certificates. Taking into account the indicated growth potential, the domestic market will need the established quality standards for wood pellets, and subsequently the demand for certified products will also build up within the country.

The prospect of a partial reorientation of exports to the markets of Southeast Asia may also be attractive, provided that certain conditions are in place. Japan and the Republic of Korea have previously been major importers of wood pellets from Russian manufacturers. The implementation of plans to increase the share of renewable energy sources in the global energy balance could lead to an increase in their industrial consumption of biofuels. Wood pellets are not exported to China due to the ban on the imports of several types of solid waste into the country, including sawdust and sawdust products. Unfortunately, the Japanese market was closed to Russian pellet exporters due to another package of sanctions adopted, so South Korea remained the only available destination. At the same time, we can expect re-exports of Russian products, since foreign countries facing severe shortages may look for any available ways to procure wood fuel. Russian enterprises are able to meet the demand in this segment, but the lack of infrastructure and the high cost of transport are the key concerns. Thus, a successful reorientation of sales to the countries of the Asian region is possible only with the government support in the form, for example, of subsidizing the transport of pellets and the creation of the necessary infrastructure in the seaports of the Russian Far East.

IV. Conclusion

Wood pellets certainly have a number of advantages over other fuels in the context of low-carbon energy development. CO_2 neutrality, low ash content, and low pollutant emissions speak in favor of the environmental friendliness of this type of biofuels and its ease of use. All these advantages can form the core message to be communicated as part of the promotional campaign for the use wood fuel use by households, and economic support measures will serve as a significant incentive to switch from coal and fuel oil to wood pellets. In the current conditions that prove challenging for the timber industry, government support is urgently needed. Furthermore, simultaneously achieving the goals of the low-carbon development strategy and the strategy for the development of the forest complex by heating up the domestic market for wood pellets is a very attractive prospect.

Despite these benefits, converting boilers to biofuels can take a long time, whereas the industry needs support right now. In addition, the cost it takes to convert a coal-fired boiler to wood fuel is comparable to the cost of building a new boiler. Thus, the relevance of government support for both producers and consumers of wood fuel in the domestic market is extremely high. Among the possible support measures, the most attractive initiatives are state subsidy programs, regulation of tariffs for producers and exporters of wood pellets, as well as the creation and development of the infrastructure necessary for the industry to operate.

Acknowledgements

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Analysis of Carbon Sequestration Potential of Forests of the Asian Russia

E.V. Gubiy

Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences, Irkutsk, Russia

Abstract — **This study provides estimates of the amount of carbon dioxide (CO_2) sequestration and release by managed forests in Siberia and the Russian Far East. The data from "National report of the Russian Federation on the inventory of human-induced emissions by sources and removals by sinks of greenhouse gases not controlled under the Montreal Protocol for 1990–2010" served as input data. We calculated the amounts of CO_2 taken up and released. The net CO_2 flux is the difference between the CO_2 sequestrated and CO_2 released. The sequestration potential of forests depends on the climatic conditions of the area and the species of woody plants growing there. Many forests die every year, and the CO_2 release by forests is caused by clear-cuttings and natural disasters. The highest sequestration rate of forests was observed in Omsk and Irkutsk regions, the lowest – in the Chukotka autonomous district and Magadan region. The largest amounts of CO_2 were sequestrated in the Republic of Sakha (Yakutia) and Krasnoyarsk territory. The highest release rates were observed in the Chukotka autonomous district and the Khabarovsk territory, the lowest – in the Novosibirsk region, Kemerovo region, and Kamchatka territory. We conclude that nearly half of the total CO_2 sequestration by managed forests in Russia was contributed by its Asian regions, with 27.5% by the Siberian Federal District and 20.9% by the Russian Far East.**

Index Terms: **sequestration potential of forests, sequestration of human-induced emissions, carbon dioxide sequestration, managed forests in Russia.**

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

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I. Introduction

In 2015, the Paris Climate Agreement [1] was adopted to strengthen the global response to the threat of climate change by keeping the global average temperature increase to 2°C by 2050 and preferably 1.5°C by 2040. In the future it is planned to build a climate-neutral world. The Agreement also aims to strengthen the ability of countries to cope with the effects of climate change.

As many scholars and politicians believe, it is greenhouse gas emissions that cause global climate change [2]. Therefore, among the key measures aimed at combating climate change within the framework of the Paris Agreement, the Parties to the agreement emphasize the following: the use of renewable energy sources, the development of hydrogen power and smart technologies, a radical reduction in energy losses. However, the principle of carbon neutrality implies not only the reduction in greenhouse gas emissions to zero, but also the possible compensation of emissions by sequestration of greenhouse gases by terrestrial ecosystems, in particular forests [3]. Therefore, another measure that is anything but unimportant is to expand the area of managed forests and significantly reduce the area of wildfires and clear-cutting.

Given the abundant forest resources of the Asian part of Russia, it is through the sequestration potential of the forests that the country can make a significant national contribution to achieving the goal of the Paris Climate Agreement [4]. As part of this study, we estimated the amount of carbon dioxide (CO_2) sequestration and removal as the main component of greenhouse gases by managed forests in Siberia and the Russian Far East by pools (aboveground and belowground portions of live biomass, deadwood, litter, soil). Data on the amount of carbon (C) sequestration and removal by managed forests in Russia by federal districts and subjects from 1990 to 2020 were taken as input data for the study [5, 6]. Based on these data, we calculated the amount of CO_2 sequestration and removal for all subjects of the Siberian and Far Eastern Federal Districts, as well as the net CO_2 flux of managed forests.

Table 1. Sequestration and emissions of greenhouse gases in the LULUCF sector in 2020

Category of land	Greenhouse gas emissions (+) and sequestration (–), million tons co2-eq year-1
Forest lands	– 622.3
Cropland	69.6
Grassland	– 31.8
Wetlands	2.6
Settlements	2.5
Other land	0.9
Harvested wood products	9.2
Indirect emissions from managed land	0.1
Total	– 569.2

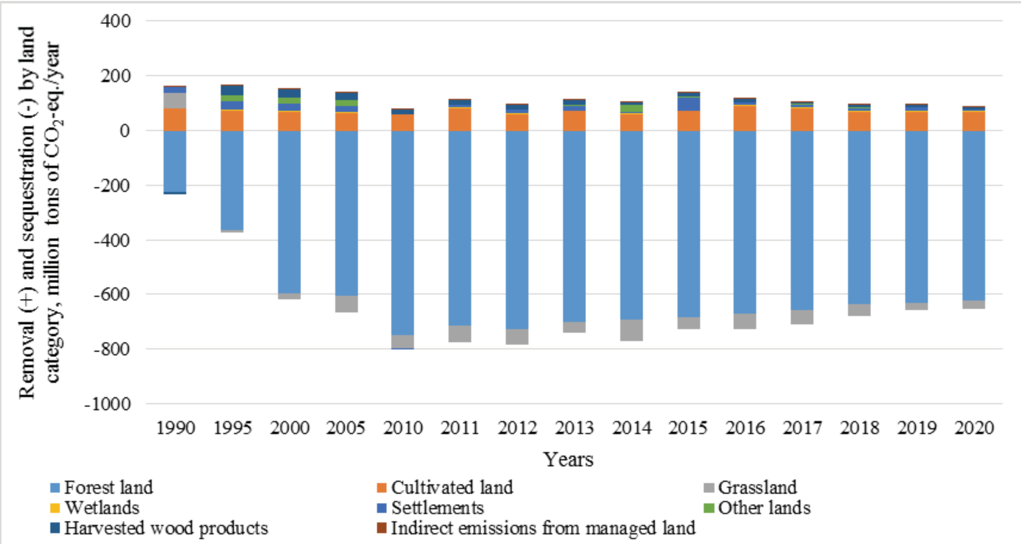

Fig. 1. Greenhouse gas emissions and sequestration in the LULUCF sector.

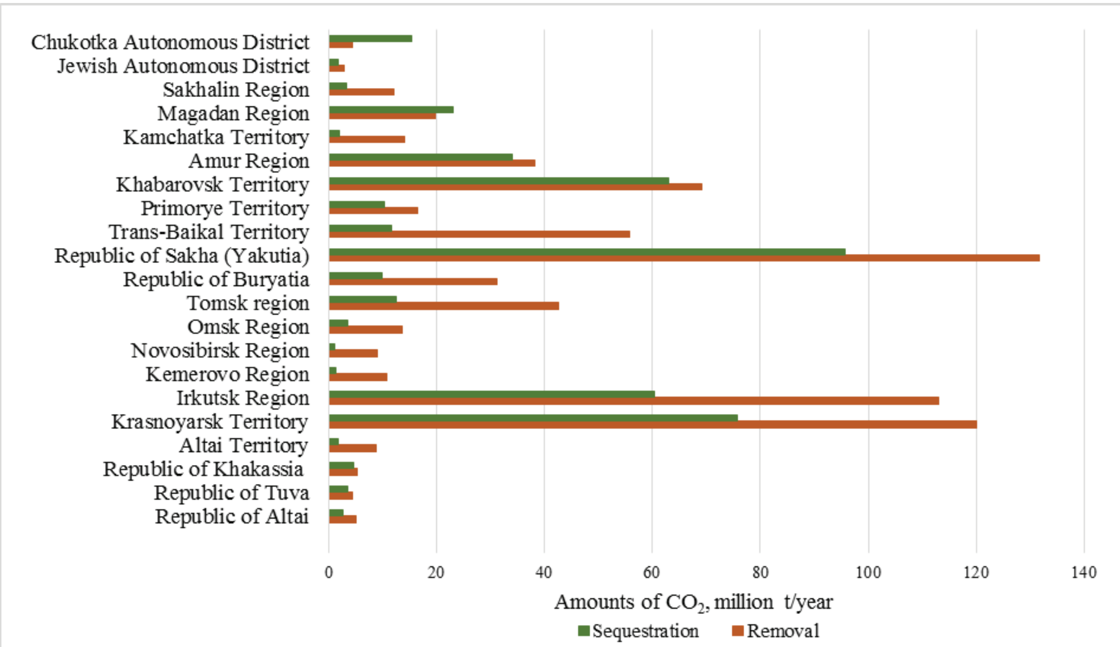

Fig. 2. Amounts of carbon dioxide sequestration and removal by managed forests by subjects of the Siberian and Far Eastern Federal Districts.

II. Methods and Data

The basis of the study was the National report of the Russian Federation on the inventory of human-induced emissions by sources and removals by sinks of greenhouse gases not controlled under the Montreal Protocol for 1990–2010 [5, 6], which was drawn up and submitted in accordance with the obligations of the Russian Federation under the UN Framework Convention on Climate Change and the Kyoto Protocol to the UN Framework Convention on Climate Change.

We processed the data for 1990-2020 on removal and sequestration of greenhouse gases that result from human-induced activities in the course of land use, land-use change, and forestry (LULUCF) [5, 6].

The conversion of C emissions to CO_2 emissions was done by multiplying carbon by a carbon-to-carbon-dioxide conversion factor of 44/12 (molar weights are as follows: C is 12 g/mol, $O_2 = 2 \cdot 16 = 32$ g/mol, $CO_2 = 12 + 2 \cdot 16 = 44$ g/mol, respectively).

III. Contributions of Different Land Categories to Greenhouse Gas Sequestration

According to the principles of the Intergovernmental Panel on Climate Change (IPCC) for national greenhouse gas inventories, there are the following categories of land use in the LULUCF sector (land use, land-use change, and forestry): forest land, cropland, grassland, wetlands, settlements, other land, harvested wood products, indirect emissions from managed land.

The greenhouse gases sinks are forest land as well as grassland. The remaining categories of land are emission sources. Cultivation of agricultural land and logging have the highest emissions associated with these activities (Table 1).

As shown in Table 1, the net flux of greenhouse gases is most dependent on forestry. Accounting for the contribution of all other land categories in 2020 reduced sequestration by as little as 8.5%.

Fig. 1 shows that from 1990 to 2020 the amounts of both sequestration and emissions of greenhouse gases have changed significantly for all categories of land. This is due to the transfer of land from one category to another. For example, the area of managed forests was increased due to the transfer of some of the unmanaged forest land to this category. And it was decreased, among other reasons, due to designating some of managed forests as settlement land. Cropland and grassland are annually transformed into unmanaged forest land when naturally overgrown with shrubs and small woods.

CO_2 is the main cause of climate change. In addition, methane (CH_4) and nitrogen oxide (NO_2) emissions are present in the LULUCF sector, which are mainly caused by wildfires. Their share in the net flux of greenhouse gases over the entire area of Russia is less than 4% [5].

Without having sufficient statistical data on the spatial distribution of lands of each category over the territory of Russia and data on emissions and sequestration of greenhouse gases on lands of different categories, it is the contribution of managed forests as the main sink of CO_2, which will be detailed below.

IV. Contribution of Managed Forests in the Asian Part of Russia to Carbon Dioxide Sequestration

Currently, managed forests in Russia include forest lands of the forest fund (except reserve forests), defense and security lands, protected natural areas (PNA), and urban forests [8]. Combined, they occupy 691.2 million hectares (or 77.1% of the forest lands of the Russian Federation). In [5, 6] the amounts of emissions and sequestration of CO_2 in urban forests was not estimated. Therefore, these metrics will be considered in detail for managed forests of the forest fund, defense and security lands, and protected natural areas (a total of 690 million hectares, or 77.0% of the forest lands of the Russian Federation).

The sequestration potential of forests is related to the climatic features of the area and the species of woody plants that grow there. Carbon dioxide release by managed forests is caused by clear-cutting, destructive fires, and other causes of loss of standing forest cover.

Data on CO_2 sequestration and removal rates by managed forests of each subject of the Siberian and Far Eastern Federal Districts are presented in Table 2. Table 2 shows that the highest sequestration rate of forests was observed in Omsk (2.93 t/ha) and Irkutsk (2.41 t/ha) regions, and the lowest – in the Chukotka autonomous district (0.45 t/ha) and the Magadan region (0.74 t/ha). Among the subjects of the Siberian and Far Eastern Federal Districts, the highest removal rates were observed in the Khabarovsk territory, Chukotka autonomous district, and the Republic of Khakassia – 1.72; 1.58 and 1.51 t/ha, respectively. The lowest emission rates were in Novosibirsk and Kemerovo regions, and the Kamchatka territory – 0.24; 0.26 and 0.28 t/ha, respectively.

The largest amounts of CO_2 were sequestrated and removed by managed forests in the Republic of Sakha (Yakutia), Krasnoyarsk territory, Irkutsk region, and Khabarovsk territory (Fig. 2). This is due to the fact that the area of forests in these subjects of the Russian Federation is the highest.

The net CO_2 flux was calculated as the difference between CO_2 sequestrated and CO_2 removed. Data on the net CO_2 flux of managed forests in the Siberian and Far Eastern federal districts are shown in Fig. 3. The largest contribution to CO_2 sequestration in the eastern part of the country comes from managed forests in the Irkutsk region (56.0 million tons/year), Krasnoyarsk territory (46.3 million tons/year), Trans-Baikal territory (45.9 million tons/year), and the Sakha Republic (Yakutia) (36.7 million tons/year). The negative net flux was observed in two subjects of the Far Eastern Federal District with the least favorable climatic conditions: Chukotka autonomous district (–11.1 million tons per year) and Magadan region

Table 2. CO_2 Sequestration and Removal Rates by Managed Forests in the Siberian and Far Eastern Federal Districts

Federal districts and subjects of the Russian Federation	Area, million hectares	Rate of CO_2 sequestration, t/ha	Rate of CO2 removal, t/ ha
Siberian Federal District	181.9	1.83	0.92
Altai republic	3.9	1.27	0.66
Republic of Tuva	3.5	1.29	1.04
Republic of Khakassia	3.1	1.76	1.51
Altai territory	3.9	2.27	0.44
Krasnoyarsk territory	86.1	1.40	0.88
Irkutsk region	47.0	2.41	1.29
Kemerovo region	5.2	2.09	0.26
Novosibirsk region	4.8	1.89	0.24
Omsk region	4.7	2.93	0.74
Tomsk region	19.6	2.18	0.64
Far Eastern Federal District	265.6	1.49	1.02
Republic of Buryatia	15.9	1.96	0.62
Republic of Sakha (Yakutia)	100.0	1.32	0.96
Trans-Baikal territory	26.3	2.11	0.44
Primorsky territory	10.5	1.57	0.98
Khabarovsk territory	36.5	1.89	1.72
Amur region	24.7	1.55	1.38
Kamchatka territory	7.2	1.96	0.28

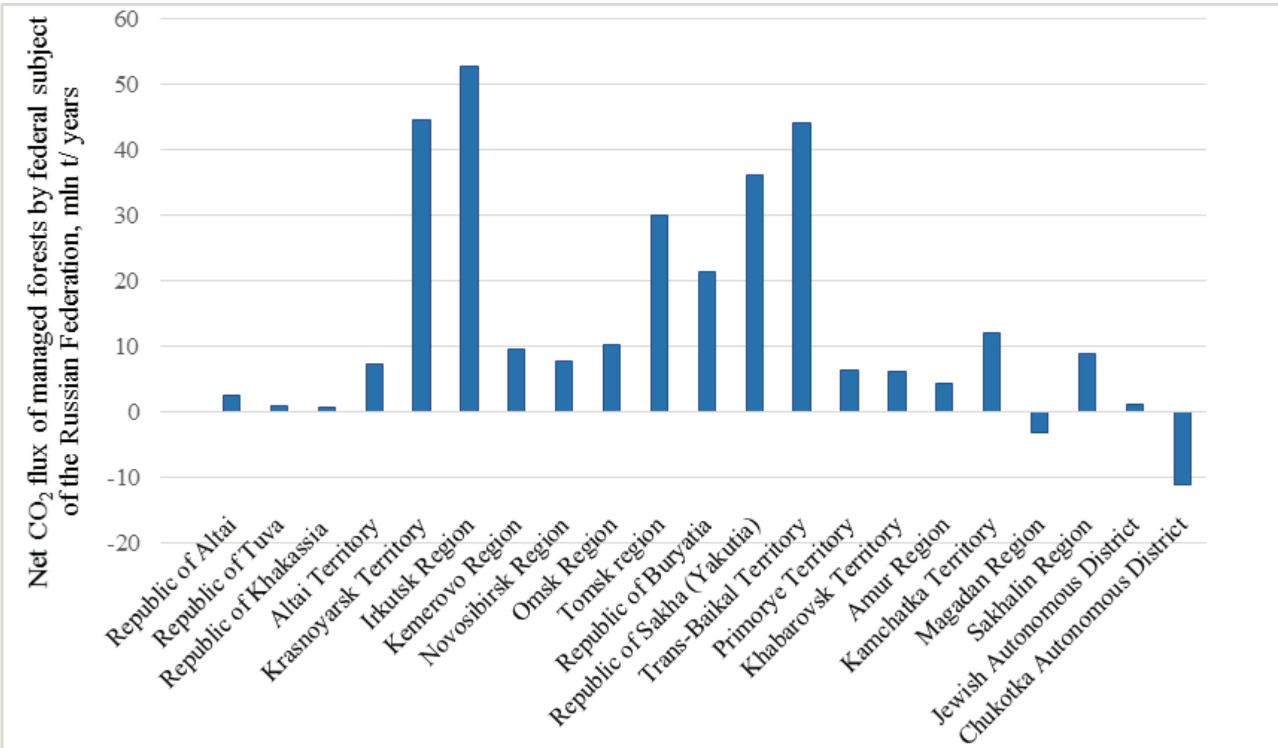

Fig. 3. Amounts of carbon dioxide sequestration and removal by managed forests by subjects of the Siberian and Far Eastern Federal Districts.

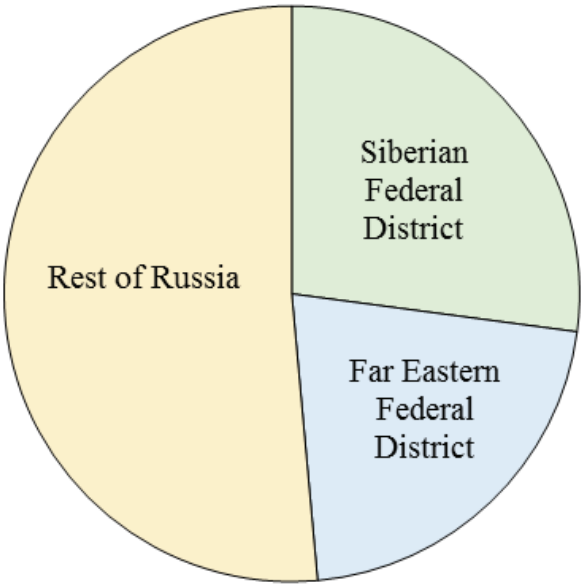

Fig. 4. Contribution to carbon dioxide sequestration by managed forests in the Siberian and Far Eastern Federal Districts.

(–3.2 million tons per year). In almost all federal subjects of the eastern part of the Russian Federation, the net flux of CO_2 of the forest fund accounted for more than 80% of the total net flux of managed forests. The exception was the Primorsky territory, where the net CO_2 flux of the forest fund accounted for 69.4%, and 27.1% was contributed protected natural areas. The net CO_2 flux of defense and security lands accounted for no more than 3.5%.

Overall, almost half of the total contribution to CO_2 sequestration by managed forests in Russia comes from its Asian regions. As can be seen from Fig. 4, the Siberian Federal District accounted for 27.1% and the Far Eastern Federal District for 21.5%.

V. Conclusion

The forest resources of the Asian part of Russia, due to the sequestration potential of forests, can make a significant national contribution to the country's achievement of the goal of the Paris Climate Agreement. The study estimated the amount of sequestration and removal of CO_2 as the main component of greenhouse gases by managed forests in Siberia and the Russian Far East. Since the net flux of greenhouse gases depends to the greatest extent on the sequestration and removal of CO_2 by forests, we studied their amounts by federal districts, and in the case of the Asian part of Russia – also by subjects of the Russian Federation.

The study found out that the contribution of managed forests in the Asian part of Russia accounted for almost half of all CO_2 sequestrated by managed forests in Russia, despite much harsher climatic conditions than in the western part of the country, the main reason for this being large areas of forested land.

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Elena V. Gubiy graduated from Irkutsk State University in 2009 and received her PhD in 2020. She is a Researcher at the Melentiev Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia. Her research interests include bioenergy, biomass, and renewable energy.

The Effect of Energy Generation Mix on Air Quality in the Siberian Regions

E.A. Syrtsova

Siberian Federal University, Krasnoyarsk, Russia

***Abstract* — Production of electricity and heat makes a significant contribution to environmental pollution. The article shows that key factors behind the negative impact of this type of activity on air quality are the power generation mix and the type of fuel used. In order to address environmental issues facing the Siberian regions it is necessary to expand the use of natural gas and introduce the best available technologies of coal combustion at existing thermal power plants in order to reduce emissions of the most hazardous pollutants.**

***Index Terms*: electricity and heat production, fuel combustion, air pollution, urban environmental issues, air quality.**

I. Introduction

As of 2020, 38% of the population of Siberia lived in cities with high and very high levels of air pollution, and in some regions the share of this population exceeded 60% (Table 1).

A significant contribution to air pollution is made by electricity and heat production: the share of pollutant emissions from the activity referred to as «Provision of electricity, gas, and steam» in total emissions in Russia in 2019 was about 17%. At the same time, the sector accounted for 36% of particulate matter emissions, 25% of sulfur dioxide emissions, and 46% of nitrogen oxide emissions. In Siberia, these figures were even higher. Table 2 presents the share of emissions of the most common pollutants from fuel combustion for electricity and heat generation in the total emissions of these substances in the region. The data are presented for 2017: the metric was not calculated for subsequent periods. In some regions, the share of the sector is more than 90% because there are no other large industrial enterprises that are sources of pollution. Furthermore, fuel combustion makes the greatest contribution to emissions of particulate matter and nitrogen oxides, which are most reliably associated with negative impacts on human health.

Thus, a significant share of environmental issues of Siberian cities is associated with the production of electricity and heat. Because this type of activity is an indispensable component of critical infrastructures, it is important to determine which generation parameters contribute to adverse impacts on the environment and can be changed in order to improve the air quality in cities.

II. Literature Review

In terms of adverse impacts on the air quality, the thermal power industry holds a principal place in the energy generation mix. With this in mind, in [2], the authors provided performance metrics of the environmental efficiency of different methods of energy production and calculated the value of the overall comprehensive index of adverse impacts on the environment and human health. Combustion of coal, oil, and gas contributes the largest amount of greenhouse gases and harmful substances emission into the atmosphere. The comprehensive index of adverse impact for coal was 65.2 points, for oil and gas – 26.4 points. For comparison: nuclear power and hydropower scored 16.1 and 16.5 points, respectively. It is also worth noting that there is not only the gap between thermal power and other types of energy generation but also a significant difference in the types of fuel used. When coal is burned, a significant amount of sulfur dioxide, nitrogen oxides, and particulate matter is emitted, which contributes to the formation of acid rain and smog, and have an adverse impact on human health. The role of coal as the main fuel has been well-researched, including from the point of view of the impact on human potential. The authors found that in 2006 the use of coal in power generation prevailed in 6 out of 10 regions of the Russian Federation with the lowest human development index [3]. The type of fuel also affects the eco-intensity metric. Paper [4] demonstrated that the expansion of the electric power industry in Trans-Baikal territory in 2006–2016 falls in the zone of «brown» or

[*] Corresponding author.
E-mail: ekoryakova@sfu-kras.ru

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Table 1. Air Quality in the Regions of Siberia in 2020

Region	Level of air pollution (H – high, VH – very high)	Cities	Share of population living in cities with high and very high levels of air pollution
Altai Republic	-		-
Tuva Republic	VH	Kyzyl	68%
Khakassia Republic	VH	Chernogorsk	69%
	H	Abakan	
Altai Krai	H	Barnaul	48%
Krasnoyarsk Krai	VH	Kansk, Minusinsk, Norilsk	58%
	H	Krasnoyarsk, Lesosibirsk	(Taimyr Autonomous Okrug – 99%)
Irkutsk Oblast	VH	Vikhorevka, Zima, Svirsk, Usolie-Sibirskoe, Cheremkhovo, Shelekhov	70%
	H	Angarsk, Bratsk, Irkutsk	
Kemerovo Oblast	H	Kemerovo, Novokuznetsk	47%
Novosibirsk Oblast	-	-	0%
Omsk Oblast	-	-	0%
Tomsk Oblast	-	-	0%

Source: Yearbook «The state of air pollution in cities in Russia for 2020» [1]

Table 2. Share of Pollutant Emissions from Fuel Combustion for Electricity and Heat Generation in Total Emissions in the Region in 2017, %

	Particulate matter	Sulfur dioxide	Nitrogen oxide	Carbon dioxide
Siberian Federal Okrug	78.0	25.8	74.6	32.1
Altai Republic	92.8	96.0	100.0	96.7
Tuva Republic	94.8	99.6	96.0	98.7
Khakassia Republic	46.6	54.3	74.8	16.7
Altai Krai	77.5	91.4	87.9	69.8
Krasnoyarsk Krai	60.2	4.9	65.7	23.6
Irkutsk Oblast	69.2	90.9	44.7	15.7
Kemerovo Oblast	59.9	66.3	75.0	23.7
Novosibirsk Oblast	79.8	98.0	86.8	63.3
Omsk Oblast	87.2	87.9	84.5	74.3
Tomsk Oblast	31.6	92.5	73.4	18.0

Source: Calculated according to official statistics

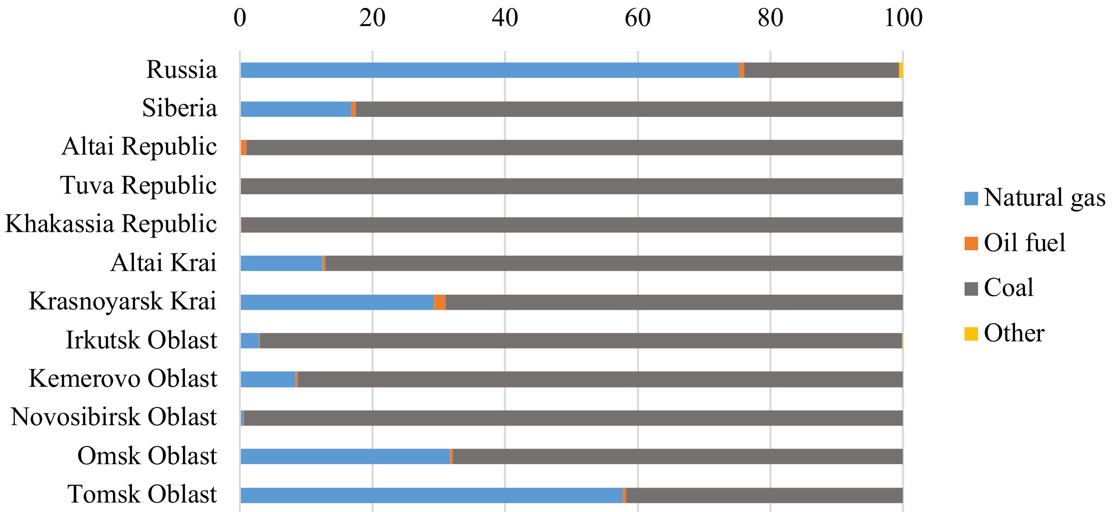

Fig. 1. Structure of electricity generation by types of power plants in 2021, %. Source: Calculated according to official statistics.

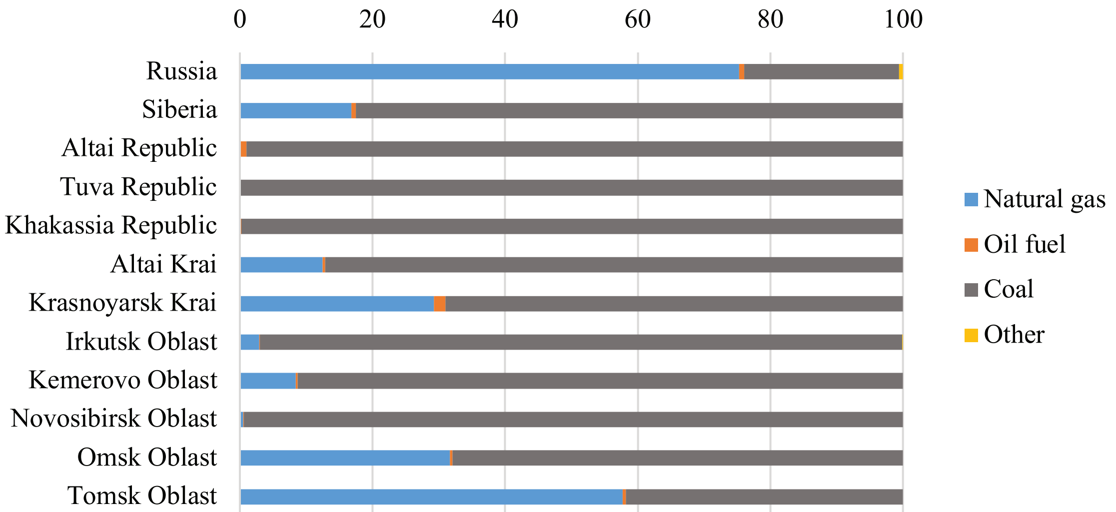

Fig. 2. Fuel consumption at power plants and boiler in 2020 by type of fuel, %. Source: Calculated according to official statistics

«black» growth, i.e., it was characterized by an increase in environmental impacts, while in Russia as a whole, in recent years it has gravitated towards «green» growth. The authors attributed this difference to the fact that in the Trans-Baikal Territory electricity and heat are supplied by coal-fired plants. The need for gradual replacement of coal-fired thermal power plants with more environmentally friendly energy sources was discussed in [5]. It was noted that nuclear power is a promising type of power generation for Siberia due to the availability of enterprises for the production and enrichment of uranium ore, as well as capacities for storing spent fuel.

Obviously, in addition to the type of fuel burned, many other factors, such as the local climate conditions, the location of pollution sources, and the technologies used, contribute to adverse impacts on the atmosphere during the production of heat and electricity. The risks are due to the extreme continental climate with low capability of the atmosphere for self-cleaning and dominant use of coal as the fuel of choice. The proximity of sources of pollution to housing areas has the most negative impact on the air quality in cities and the health of the population [3]. Through a case study of the Irkutsk region, it was shown that one of the reasons for the adverse impact of thermal power plants on the atmosphere is the low level of emission treatment. At the same time, in the case when large CHPPs are equipped with ash collectors, most small boiler plants located in close proximity to the housing and social infrastructure facilities operate without emissions [6]. The possibility of upgrading existing thermal power plants and boiler plants in order to reduce pollutant emissions was discussed in [7]. The authors showed that the innovation-driven development of the energy sector, based on the expansion of the use of natural gas and the use of the best

Table 3. The Main Generating Enterprises of the Krasnoyarsk Territory and Their Contribution to Air Pollution in 2020

№	Eenterprise	Cities and settlements – heat consumers	Location	Share of enterprise emissions in the total emissions of the municipality, %
		Thermal power plants of power companies		
1	Berezovskaya GRES	Sharypovo, Dubinino	Sharypovsky district	90.9
2	Nazarovskaya GRES	Nazarovo	Nazarovo	92.7
3	Krasnoyarskaya CHPP-1	Krasnoyarsk, Berezovka	Krasnoyarsk	13.0
4	Krasnoyarskaya CHPP-2	Krasnoyarsk	Krasnoyarsk	14.1
5	Krasnoyarskaya CHPP-3	Krasnoyarsk	Krasnoyarsk	6.3
6	Krasnoyarskaya GRES -2	Zelenogorsk, Orlovka	Zelenogorsk	19.6
7	Kanskaya CHPP	Kansk	Kansk	16.0
8	Zheleznogorskaya CHPP	Zheleznogorsk, Sosnovoborsk	Sosnovoborsk	N/A
9	Minusinskaya CHPP	Minusinsk, Zeleny Bor	Minusinsk district	80.6
		Power plants of industrial enterprises		
10	CHPP JSC RUSAL-Achinsk	Achinsk	Achinsk	N/A
11	CHPP LLC Teplo-Sbyt-Servis	Kansk	Kansk	N/A
		Norilsk-Taimyr Energy District		
12	Norilskaya CHPP-1	Norilsk	Norilsk	N/A
13	Norilskaya CHPP-2	Talnakh	Norilsk city district	N/A
14	Norilskaya CHPP-3	Kayerkan	Norilsk city district	N/A

Source: compiled from the data presented in the Government Report «On the State and Protection of the Environment in Krasnoyarsk Krai in 2020» [8] and the Program for Expansion Planning of the Krasnoyarsk Territory Electricity Sector for 2022–2026 [9].

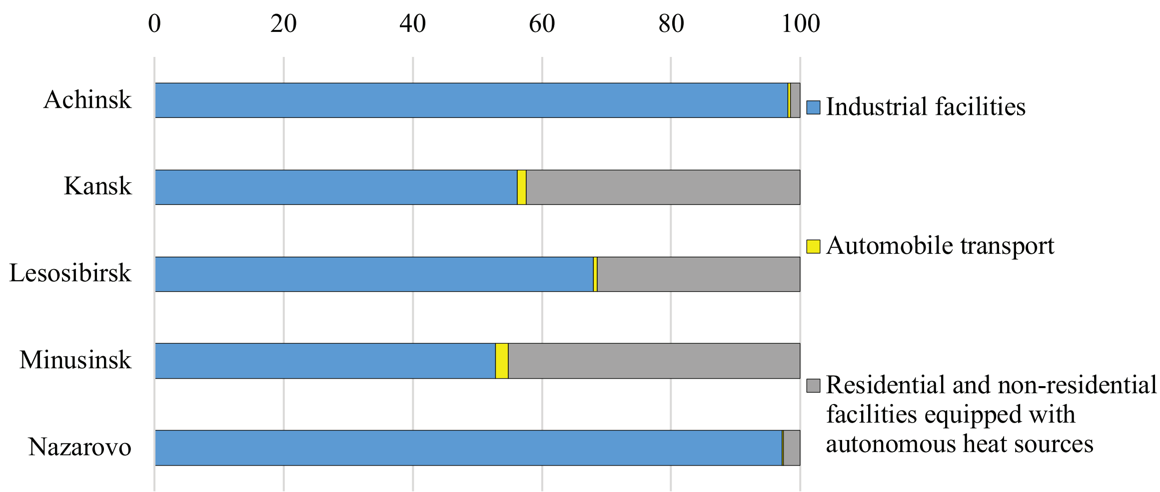

Fig. 3. Atmospheric air pollution in the cities of Krasnoyarsk region by type of objects of pollution, %. Source: Compiled based on the conclusions of the summary estimates of air pollution in the cities of the Krasnoyarsk territory [11].

available coal combustion technologies, will reduce the human-induced environmental impacts.

III. Structure of Energy Generation in the Regions of Siberia

As it stands now, thermal power plants are the basis of Russia's electric power industry, accounting for 60% of all electricity generation in 2021. Nuclear and hydroelectric power plants also make up a significant share: 20% and 19%, respectively. The share of other sources, including solar, wind, and others, is less than 1%. In Siberia, the power generation mix is different: due to the presence of large rivers, hydroelectric power plants generate more than 60% of the electricity in this area. Nuclear power is not developed in Siberia. There are solar power plants in some regions, and in the Republic of Altai they generate most of the electricity – about 77% (Fig. 1).

In most regions of Siberia, thermal power plants form the basis of the sector. In regions where hydroelectric power plants prevail, their capacities are used for the needs of large industrial facilities, and the electricity and heating needs of cities are met by combined heat and power plants. As noted above, the type of fuel used is of particular importance in terms of the impact on air quality. The most environmentally friendly type of fuel for thermal power plants is natural gas, its use prevails in the European part of Russia, whereas Siberia and the Russian Far East use mainly coal (Fig. 2).

As noted above, during coal combustion, a significant amount of sulfur dioxide, nitrogen oxides and particulate matter is emitted. Therefore, the dominant use of coal as a fuel is responsible for the high percentage values of emissions of these pollutants during the generation of electricity and heat in the total emissions in the regions (Table 2).

IV. Impact of Electricity and Heat Production on Air Quality in the Cities of the Krasnoyarsk Territory

In what follows, through a case study of the Krasnoyarsk territory we consider the impact of individual major generating enterprises on air quality. The total amount of pollutant emissions contributed by the activity referred to as «Production and distribution of electricity, gas and water» in 2020 amounted to 188 thousand tons, 27% of emissions in the region. The top six enterprises (Table 3) account for 44% of all emissions into the atmosphere in the industry referred to as «Production and distribution of electricity, gas and water» and 12% of the total emissions in the region [8].

There are 14 thermal power plants in the region that supply heat and electricity to homes in most cities and industrial centers. There are also several facilities that serve industrial consumers. Heat and power plants in the Norilsk-Taimyr Region use natural gas as their fuel, while all other facilities use lignites from Krasnoyarsk territory's coal deposits, which, as has been repeatedly noted, is a negative factor.

As can be seen from Table 3, all thermal power plants have a significant impact on the air quality in the areas where they are located. With the exception of the Berezovskaya GRES and Minusinskaya CHPP, all of them are located in urban areas, which determines the greatest impact on the population of those cities. Here it should be noted that in the mix of heating production in cities, apart from major thermal power plants, an important part is played by boiler plants and individual heat sources, which are usually located directly inside residential buildings. From this point of view, cogeneration plants, even those that are coal-fired, have significant environmental and economic advantages over small boilers: they provide greater reliability of heating, have lower specific fuel consumption, lower specific emissions of pollutants, and are subject to stricter control with respect to emissions.

There are 1 255 boiler plants in Krasnoyarsk Krai that serve as auxiliary sources in heating layouts of large cities and are the main heat sources for the majority of small cities of the Krai. This situation is characteristic of other regions of Siberia as well. The main type of fuel used by boiler plants is coal, and in the case of individual heating sources it is coal and wood. For a number of Siberian cities a program of replacing inefficient boilers and connecting their consumers to CHPPs is currently underway; such measures are planned or already being implemented by the Siberian Generating Company in Krasnoyarsk, Kansk, Nazarovo, Novosibirsk, Kemerovo, Belovo, Abakan, Chernogorsk, Barnaul, Biysk, and Kyzyl. According to the Siberian Generating Company, during the 5 years of the program implementation it was possible to reduce the volume of pollutant emissions by 10 thousand tons per year and to reduce their impact on the urban environment [10].

It is worth noting that accounting for the adverse impact of boilers on air quality is difficult because of the lack of complete data on all boilers and the derelict state of statistics on air emissions at the municipal level - there is simply no usable data on small towns of the region.

Individual heat sources - boilers and stoves, which are used for heating purposes in the residential sector - are an even more challenging component to analyze. In 2021 in the Krasnoyarsk territory there were performed summary estimates of air pollution in several cities of the territory, which included the formation of data on emissions from housing facilities and non-residential premises equipped with autonomous heat sources (AHS).

Figure 3 indicates that in the cities having no major industrial pollutant facilities, autonomous heating sources make a significant contribution to air pollution.

In all surveyed cities AHS facilities contribute to exceedances of maximum permissible concentrations for such substances as nitrogen dioxide, carbon monoxide, dust, and suspended substances [11]. Since the exceedances were recorded within the boundaries of residential areas, it can be argued that AHS emissions have an adverse impact on the health of people living in those areas.

V. Conclusion

A number of factors, including the generation mix and the type of fuel used, contribute to adverse impacts of power generation on air quality. The predominance of coal in the mix of consumed fuel at thermal power plants and boilers increases the contribution of heat generation to air pollution for all major pollutants, including particulate matter and nitrogen oxides, which are most reliably associated with negative effects on human health. For many Siberian cities, the adverse impact is exacerbated by natural and climatic features with unfavorable conditions for dispersion of pollutants.

To address the environmental issues of the Siberian regions, a gradual transition to cleaner energy sources and fuels is necessary. Due to the lack of foreseeable prospects for the development of alternative types of energy, the focus should be on expanding the use of natural gas. In addition, it seems relevant to analyze the current equipment and technologies of coal combustion at existing thermal power plants in order to choose options for their modernization so as to reduce emissions of the most hazardous pollutants.

The power generation mix within individual settlements is also important. Consequently, other key areas of greening in the field of heat production are the continuation of projects to replace small boilers and the transition of the residential sector to more environmentally friendly fuels.

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Ekaterina A. Syrtsova, PhD in Economics, Senior Researcher at the Laboratory for Climate Change and Ecological Development. Key research interests: sustainable development, econometric modeling, urban environmental issues.

Hydrogen Technologies and Prospects for Their Use in the Asian Regions of Russia

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

Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Irkutsk, Russia

***Abstract* — The paper discusses the prerequisites for the development of hydrogen infrastructure and the scope of application of hydrogen technologies in the Asian regions of Russia (ARR). The previous approach to the creation of a hydrogen infrastructure in Russia may be revised due to economic sanctions and the impossibility of technology transfer. The available largest and most efficient resources of crude hydrocarbons and coal (nonrenewable energy resources – (NRER)), as well as the significant potential of renewable energy allow large-scale production of hydrogen in the Asian regions of Russia. There are also preconditions for the use of hydrogen technologies for energy end-users in this territory. The creation of large pilot testing grounds in isolated power systems of the Asian regions of Russia will make it possible to enhance and develop the hydrogen production, storage, and transport technologies to prepare them for delivery to export markets for energy equipment and services.**

***Index Terms*: development of hydrogen infrastructure, hydrogen technologies, ammonia, Asian regions of Russia.**

I. Introduction

The number of pilot and demonstration projects aimed at testing hydrogen technologies has been rapidly increasing in the world in the last decade. The growing social need to protect the environment from anthropogenic impact and the reduction in the cost of energy hydrogen technologies are reasons for their spread. Thus, according to the consulting company Lazard, at the moment, in the case of a large-scale hydrogen production, capital costs for electrolyzers, key components of electrochemical production of hydrogen, lie in the range of 310–920 $/kW for alkaline electrolyzers (AEL) and 460–1190 $/kW for polymer electrolyte membrane (PEM) electrolyzers. According to the forecasts published by the International energy agency (IEA), International renewable energy agency (IRENA) and DNV GL, the cost of all types of electrolyzers may further decrease by 20–70 percent in the period up to 2030–2050 (Table 1) [1–3].

Along with this, the number of mass-produced commercial models, for example, electric vehicles equipped with fuel cells (fuel cell electric vehicle, FCEV) increases. Currently, FCEVs are more expensive than other types of fuel systems of vehicles. However, the economic instruments used in some countries (subsidizing the purchase of zero emission vehicle, reducing transport tax, interest-free loans) and technological progress make it possible to reduce the cost of this technology [4, 5]. As a result, the number of FCEVs increased almost 5 times in the period from 2018 to 2021, and the share of hydrogen cars may reach 6% of the total number of passenger cars and light trucks sold in the world by 2030 [4–6].

The scalability of the fuel cell technology allows its use in other types of vehicles (trains, water and air transport), as well as in the energy supply systems of various scales and purposes – from households to large facilities of metallurgical, chemical, and other energy-intensive industries. Today, Panasonic Corporation produces “Ene-farm” fuel cells for the generation of heat and electricity [7], the “Sunfire” company develops and releases industrial solid oxide electrolyzers and fuel cells [8]. The energy production based on fuel cell can be organized for centralized and distributed isolated power supply. Fuel cells can also be used in mobile electricity generators. Combined cycle gas-turbine (CCGT) plants have become another area for hydrogen energy supply systems. Kawasaki Heavy Industries [9] and Mitsubishi Hitachi Power Systems (MHPS) [10] are leaders in the development of combined cycle and gas turbine plants using hydrogen as fuel. Currently, MHPS has created several gas turbine units operating on a methane-hydrogen mix (20% and 30% H_2), however, Mitsubishi has announced the release of the CCGT running entirely on hydrogen by 2027 [11].

Thus, in fact, the process of commercialization of hy-

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

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TABLE 1. Capital expenditure of electrolyzers, $/kW

The future of hydrogen			Green hydrogen cost reduction: scaling up electrolyzers to meet the 1.5°C climate goal			Hydrogen forecast to 2050 energy transition outlook 2022 (DNV)		
AEL	PEM	SOEC (Solid oxide electrolysis cells)	AEL	PEM	SOEC	AEL	PEM	SOEC
2019/2030			2020/2050			2022/2030		
500–1400/ 400–850	1100–1800/ 650-1500	2800–5600/ 800–2800	1000/ >750	>1500/ >1250	–	1000/ >750	>1500/ >1250	–

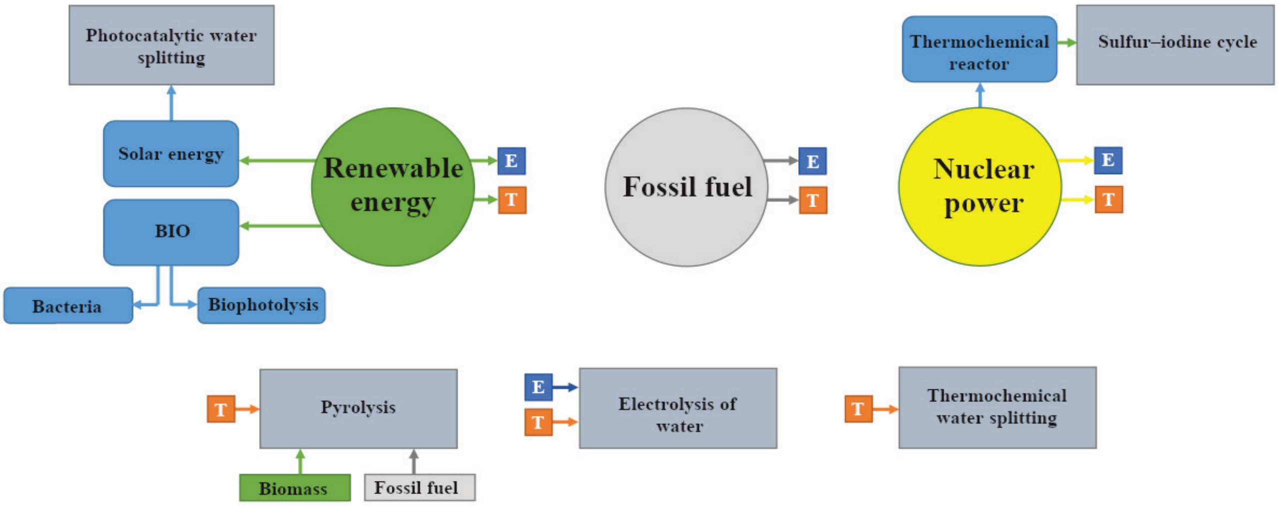

Fig. 1. Hydrogen production methods (T – thermal energy, E – electrical energy).

drogen technologies has begun in the world. Their spread will reduce carbon emissions in the transport sector of the economy, increase the efficiency of existing ones, and create low or carbon-free energy supply systems for different consumer groups, including industrial ones. As a result, the trend in the development of hydrogen technologies can solve several current problems facing the energy sector.

II. Hydrogen Energy Development in Russia

Russia has become the 6th country after Germany, Australia, Norway, Japan and the Republic of Korea, where the development of hydrogen energy is enshrined in program documents and is an integral part of the energy development. The Energy Strategy of the Russian Federation until 2035 and the Hydrogen Energy Development concept establish the creation of hydrogen energy; Russian hydrogen energy roadmap to 2024, The Strategy of Socioeconomic Development of the Russian Federation with a low level of greenhouse Gas Emissions until 2050, and the Transport Strategy of Russia until 2030 with forecast until 2035 touch upon the topic of the hydrogen energy in Russia [12–16]. The data presented in the listed documents show the export orientation of the hydrogen energy, the purpose of which is to build the facilities for the production, storage, and transportation of hydrogen and hydrogen-containing substances and to provide leadership of the Russian Federation as a world hydrogen producer and exporter. According to the Energy Strategy of Russia until 2035, the volume of production is up to 2 million tons by 2035, and the aim of the Hydrogen Energy Development Concept is to produce up to 12 million tons [13]. In the context of a low-carbon paradigm of global energy development, such export volumes have to rely on the hydrogen production by pyrolysis of biomass, methane and other fossil fuels, or by water electrolysis, when renewable energy and/or nuclear energy are used (Fig. 1).

To date, fossil fuel is the main source of hydrogen production, which involves the technologies for gas-steam methane reforming and coal gasification. Steam natural gas reforming will be the main method of producing hydrogen at the initial stage of the hydrogen energy development in the world. Probably, coal gasification will become the second most common method, because the cost of such production is comparable to the technologies of steam reforming in the presence of cheap and suitable quality coal. However, this technological process is characterized by significant energy losses. Both of the mentioned processes are exothermic, which can be used to produce thermal energy. These methods are also characterized by greenhouse gas emissions, which requires the use of carbon capture and storage technologies.

Any generating capacities (RES, thermal condensing and

Table 2. Hydrogen and ammonia production volumes in the Russian Federation, million tons per year

Production method	Asian regions of Russia	Europian regions of Russia	Total
“green” H_2	5.8	1.3	7.1
“non green” H_2	0.1	0.002	0.102
“non green” NH_3	13.4	0.2	13.6

nuclear power plants (NPPs)) can act as sources of electricity in the electrolysis-based hydrogen production. Some studies show that the hydrogen production at the off-peak load hours at hydroelectric power plants (HPPs) and NPPs can improve the efficiency of energy supply systems [17]. At NPP, hydrogen can be produced by low-temperature and high-temperature electrolysis (using solid oxide electrolyzers). In the first case, the operating temperature of the electrolyzers does not exceed 100°C. High-temperature electrolysis requires water preheating to 800–1000°C. In this case, the consumption of electrical energy goes down by about 30%, and the total efficiency can reach 45–50% [18].

The sulfur-iodine cycle of nuclear power plants is one of the most promising methods of large-scale hydrogen production [18]. The Institute of Nuclear and New Energy Technology (China) in 2005 named the research of such a technological path of hydrogen production as one of the priority studies and developed a pilot plant that produces 60 liters of hydrogen per hour. The Japan Atomic Energy Agency developed a laboratory plant for hydrogen production using a continuous closed sulfur-iodine cycle with a capacity of 30 liters of hydrogen per hour in 2019. The researchers aim to reach larger hydrogen production (100 l/h) and achieve a longer period of operability [18].

The electrolysis-based hydrogen production relying on renewable energy does not emit greenhouse gases and has a minimal negative impact on the environment in comparison with other methods of hydrogen production. Currently, the cost of the hydrogen production through electrolysis is higher due to renewable energy than the production of hydrogen by reforming natural gas. However, the trend towards reduction in the cost of equipment and the cost of electricity generated from photovoltaic (PV) and wind (WPP) power plants has been observed in the last decade. It offers the hope for the successful commercialization of green hydrogen production technologies in the future [1, 3, 19].

A wide range of possible methods for producing hydrogen (see Fig. 1) makes it possible to establish its production in various territories, regardless of natural and climatic conditions and the availability of fossil fuel (due to the existing gas, oil and coal infrastructure that allows transporting energy resources anywhere in the world). The resulting “yellow,” “green,” “grey” or hydrogen of another “color” (Yellow hydrogen is hydrogen produced using nuclear energy; green hydrogen is hydrogen produced without CO (electrochemical water splitting, biological hydrogen production, use of biomass); grey hydrogen is hydrogen produced through steam conversion of natural gas; black (brown) hydrogen is hydrogen produced from coal gasification.) will exclude any GHG emission at the stage of its use by end-users. In addition to these factors, hydrogen transportation over long distances is technically difficult due to chemical and physical properties of hydrogen, and the use of hydrogen-containing substances (ammonia, methylcyclohexane) leads to an even greater complication and lengthening of production and technological processes, and a decrease in the total energy efficiency of the energy supply chain - from primary energy resources to useful energy for the final energy consumer. As a result, a significant part of the hydrogen produced will be used near the place of its production in the way that is the cheapest for this area, and its “greening” technologies will be used for consumers who are critically sensitive to this indicator.

This idea can be implemented through the mechanisms to trade in “green” certificates. Similar to the “green” certificates confirming the fact of generating electricity based on renewable energy sources, hydrogen “green” certificates will provide a guarantee of low or zero carbon “origin” of hydrogen. By purchasing such a certificate, the buyer will be able to consume hydrogen produced by any method (see Fig. 1) as “green”. At the same time, the cost of the certificate will have to compensate for the difference in the cost of production between the “green” hydrogen and the hydrogen consumed by this final energy consumer, which is obtained with the carbon monoxide emission, given the transaction costs of the trading system for the “green” hydrogen certificates. As a result, international trade in carbon-free hydrogen will be carried out in the form of the sale of virtual digital “green” certificates, and “former” green hydrogen can be used near its production sites. In other words, the consumption of relatively cheap “green” hydrogen will be concentrated in places of hydrogen production, while “grey” or “blue” (but repainted in “green”) hydrogen will be used in large consumption centers [20].

According to the Ministry of Industry and Trade of the Russian Federation, the main export direction of hydrogen carriers [21] from Russia will be the countries of the European Union and the Asia-Pacific region. At the same time, it is planned that more than 80% of hydrogen and 98.5% of ammonia will be produced on the territory of the ARR (Table 2) [21]. Due to the new economic sanctions imposed in 2022, the estimated production volumes of hydrogen and ammonia may decrease and “green” hydrogen carriers may be consumed domestically.

At the same time, there are only a few projects in Russia aimed at using hydrogen technologies by end consumers:

- The government of the Sakhalin Region, State Atomic Energy Corporation Rosatom, Joint stock company (JSC) Russian Railways, and JSC Transmashholding signed the agreement on cooperation and interaction on the project for building railway communication using hydrogen fuel cell trains and systems to ensure their operation in September 2019 in Vladivostok [22]. Hydrogen passenger train is planned to be based on the railbus RA-3. Operational and financial models were prepared, a feasibility study of the passenger transportation project on Sakhalin Island was developed. The first train is expected by 2024, and their number on the suburban network will increase to 7 in 2025–2030 and to 30 in the more distant future;
- The JSC Rusatom Overseas, PJSC KAMAZ, JSC Development Corporation of Russian Far East and Arctic, and JSC Development Corporation of Sakhalin Region signed a memorandum of understanding, which suggests cooperation in the development and application of hydrogen technologies in the transport sector on Sakhalin Island in September 2021. The parties consider the possibility of joint participation in the project for the creation of a hydrogen fleet, and the organization of zero carbon transport on hydrogen fuel cells in the Sakhalin region [23];
- The PJSC Gazprom and JSC Russian Railways implement joint projects in the field of hydrogen energy. Natural gas extracted from the fields of the Yamalo-Nenets Autonomous District can become a feedstock for the production of hydrogen on site in order to use the produced hydrogen as fuel for locomotives on the "Ob–Karskaya" railway [24];
- The En+ Group company plans to develop and implement a project for building a hydrogen transport infrastructure in the Krasnoyarsk Territory: the first stage suggests the construction of liquefied natural gas refueling stations, and the second stage includes the construction of liquid hydrogen station. The company is also developing cryogenic tank containers for the liquid hydrogen transportation, which are designed to solve the problem of long-distance delivery of hydrogen [25];
- The leading manufacturer and supplier of iron ore products and hot-briquetted iron in Russia, the Metalloinvest company, is implementing a project for the construction of the "Mikhailovsky HBI" plant with the prospect of a full transition to hydrogen. The JSC Rusatom Overseas (a company of the State Corporation ROSATOM) and Air Liquide, a leading producer of industrial gases, signed a memorandum of understanding to explore the possibility of organizing the production of low-carbon hydrogen and introducing hydrogen into the production processes of Metalloinvest company [26, 27].

III. Hydrogen Technologies and Prospects for Their Adoption in the Asian Regions of Russia

Although the number of projects aimed at hydrogen production (33 projects in the Atlas of Hydrogen and Ammonia Projects [21]) is significantly larger than the number of projects related to the use of hydrogen technologies by domestic consumers, there are some prerequisites for their application in Russia:

- The possibility of large-scale production of "grey," "yellow," and "green" hydrogen based on the use of large and cost-effective natural gas and coal resources, which are unused for operational reasons of generating capacities in electric power systems, or idle due to dispatch restrictions on the release of power from nuclear power plants or renewable energy sources (HPPs, WPPs, and PVs);
- The availability of natural and climatic potential for the production of "green" hydrogen based on the creation of renewable energy sources in isolated areas, primarily in the Arctic zone of the country;
- The necessity to test the technologies for hydrogen production, storage, and transport to gain a strong position in the world markets for hydrogen technologies;
- The need to reduce GHG emissions in industry and transport, and to create low-carbon energy and fuel supply systems, primarily for consumers of off-grid energy systems using "green" electricity generation.

The last circumstance is especially important for the ARR, where due to natural and climatic conditions and poorly developed infrastructure, the implementation of energy and fuel supply is complicated. At the same time, the mining industry plays an important role in the territory of Siberia, the Far East, and the Arctic, which is as a rule represented by isolated industrial hubs. The energy supply systems in such decentralized and hard-to-reach places can be established by combining hydrogen technologies with renewable sources and/or small and medium-power nuclear reactors. The combination of these technologies will make it possible to create autonomous carbon-free energy supply systems, which will improve the quality of energy services provided and eliminate dependence on the import of energy carriers.

An example of such a power supply system is the project of the Arctic scientific station "Snezhinka," which is planned to be started in 2024. The station is a fully autonomous complex based on renewable energy and hydrogen technologies. Under the project, hydrogen produced based on renewable energy sources will be used for uninterrupted power supply to the complex together with batteries for seasonal storage of renewable energy [28].

Another possible direction of using hydrogen in the ARR is to reduce emissions in the transport sector of the economy. The continental, sharply continental, and Arctic climate prevails in this territory, which is characterized by a long period of low atmospheric temperature. In these conditions, the use of FCEV is more preferable compared to electric vehicles (battery electric vehicle, BEV). The fuel cell design allows the FCEV to be operated at temperatures up to –40°C. The study of the effect of low temperatures on electric buses revealed that the driving range of the battery electric bus is reduced by 38% at ambient temperatures from 0 °C to –5°C, whereas for FCEV, this indicator was only 23.1% [29, 30].

IV. Conclusions

The last decade has seen an active development of hydrogen technologies, which currently remain more expensive than conventional ones. However, technological progress and financial instruments used in the framework of environmental initiatives can reduce their cost and make them competitive. The rapid expansion of the global FCEV fleet and the use of fuel cells in energy supply will require an increase in hydrogen production, and the creation of the necessary infrastructure, i.e., the systems for hydrogen production, storage, transportation, and distribution.

The availability of enormous fossil energy sources, a large capacity of NPPs, a high potential of increase in the capacity of HPPs, and high technical potential of RES allow large-scale production of hydrogen in the ARR. At the same time, the produced hydrogen can be consumed near the production sites, whereas the export of “green” hydrogen, due to the high cost and technological complexity of hydrogen transport over long distances, will be carried out virtually using the mechanisms of trading in hydrogen “green” certificates that confirm the carbon-free “origin” of a certain amount of hydrogen.

The territory of Asian Russia has prerequisites for the creation of autonomous low or zero carbon energy systems based on hydrogen technologies, which will make it possible to provide testing grounds for the improvement of these technologies, and to decarbonize industrial production, buildings, and transport sector of the economy.

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Oleg Baldynov gained the Bachelor's degree in Finance in 2015 and Master's Degree in Innovation Management in 2017 from Irkutsk National Research Technical University. Russia. From 2017 to 2021, he was a Ph.D. student at MESI SB RAS. His research interests include renewable energy sources, hydrogen energy and energy transmission.

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