Specific features of the decarbonization measures in the energy sector in off-grid remote territories of Russia's eastern regions

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Abstract. The study addresses the specific features of energy systems to formulate the activities for low-carbon energy development in off-grid and remote areas of the East of the Russian Federation. The analysis involved focuses on the quantity, type, capacity of energy sources, electricity and heat generation, type and volume of fuel burned. The ranges of fuel price indicators and economically justified electric and thermal energy rates are identified. Based on the analysis of the energy technologies used, it was concluded that the carbon intensity of the electrical and thermal energy production is high. Liquefied natural gas should be considered as the main alternative fuel for these territories. The most acceptable low-carbon technologies for large industrial consumers are nuclear and hydrogen ones, for municipal customers are those based on renewable energy sources.

1 Introduction

In Russia's eastern regions, the coverage area of the interconnected electric power systems of Siberia and the East is limited to the southern areas. In the northeastern regions, there are five off-grid power systems: in the Krasnoyarsk and Kamchatka Territories, the Sakhalin and Magadan Regions, and in the Chukotka Autonomous Okrug (Figure 1). Due to vast territories, long distances, specificities of industrial development and undeveloped transport infrastructure, almost all constituent entities of the eastern part of the Russian Federation have off-grid territories.

These areas are characterized by a wide variety of climatic and natural conditions, diverse options for transport accessibility. They also vary in terms of scale and structure of final energy consumption and in the technical and economic indicators of energy facilities, systems, complexes, and plants.

Based on a multivariate analysis of diverse information for each entity of the Russian Federation, those having no settlements with off-grid power supply are excluded from further consideration. These are the Altai Territory, the Republic of Khakassia, the Novosibirsk and Omsk Regions, the Republic of Buryatia, and the Jewish Autonomous Region.

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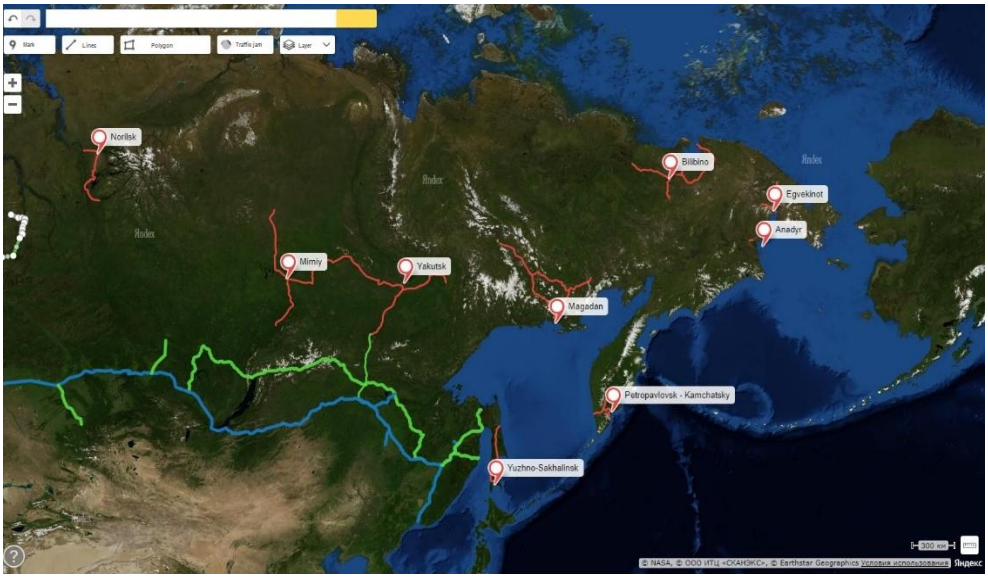

Fig.1. Map-scheme of centralized power supply in the northeastern regions of the Russian Federation.

In general, in 15 entities of Russia's eastern regions, there are 662 off-grid settlements, of which 62% are located in the Far East. According to the results of the 2020 census, 295.6 thousand people live in them, i.e., only 1.8% of the population of the considered entities of the Federation [1, 2].

In the entities of the eastern regions of Russia, the largest number of the population in the off-grid hard-to-reach areas lives in the Republic of Sakha (Yakutia) (143 settlements), in the Khabarovsk Territory (104 settlements), and in the Krasnoyarsk Territory (99 settlements). Almost half (328) of the settlements are small with up to 200 people but only 8.5% of the population lives in them [1], [2].

A distinguishing feature of the eastern regions is that 36% (or 106.1 thousand people) of the total population of the remote territories under consideration live in the Arctic zone, of which 77.1 thousand people live in the countryside. The Arctic zone encompasses northern parts of the Krasnoyarsk Territory and Republic of Sakha (Yakutia), and the entire Chukotka Autonomous Okrug.

2 Characteristics of municipal energy sources

Utility power plants in the off-grid hard-to-reach areas of the eastern regions of the Russian Federation are represented by various types. Diesel power plants (DPP) are the predominant source of power. There are also mini-CHPs and plants based on renewable energy sources (RES): geothermal power plants (GeoPP), mini-hydroelectric power plants, wind farms (WF), and solar power plants (SPP). Such RES-based plants as wind farms, solar power plants, and mini hydroelectric power plants normally operate as part of an integrated system with diesel power plants. Solar power plants are in operation in the Republic of Sakha (Yakutia), in the Kemerovo and Irkutsk Regions; mini-hydro power plants are operating in the Republic of Altai, Kamchatka Territory, and Sakhalin Region; wind farms - in the Republic of Sakha (Yakutia), Kamchatka and Primorsky Territories, and Sakhalin Region; GeoPP - in Kamchatka Territory and the Kuril Islands of the Sakhalin Region.

There are 684 municipal autonomous power plants in the eastern regions of the Russian Federation, with the total installed capacity of 822 MW. Most of them are located in the Far

Eastern District. It is important to highlight that the installed capacity of almost all autonomous power plants, especially in the northern regions, significantly exceeds the maximum load of consumers. This is necessary because power redundancy is crucial in the off-grid northern and remote areas.

The total electricity generation by autonomous municipal power plants is estimated at 1,225 million kWh, fuel consumption – at 405 thousand tce (Tables 1, 2).

Table 1. Overall indices of utility power plants.

Federal District of the Russian Federation	Number of power plants, units	Total installed capacity, MW	Electricity generation, million kWh
Siberian	255	175.3	237.0
Far-Eastern	429	646.4	987.7
Total for the eastern regions,	684	821.7	1224.7
of which in the Arctic zone	165	315.0	433.5

Note: based on [3-7]

In the Arctic zone of the eastern regions, there is 24% of the total number of power plants. The installed capacity of these plants is 38%, electricity production and fuel consumption are 35 and 39% respectively.

Table 2. Fuel consumption at utility power plants, thousand tce.

Federal District of the Russian Federation	Total	including:				
		Diesel	Gasoline	Gas	Oil	Coal
Siberian	87.3	71.4	0.03	-	15.8	-
Far-Eastern	317.8	309.1	0.04	5.8	0.4	2.5
Total for the eastern regions,	405.1	380.5	0.07	5.8	16.2	2.5
of which in the Arctic zone	158.7	140.0	-	-	16.2	2.5

Note: based on [3-7]

Of the total amount of fuel, 94% is diesel, 4% is oil, and 2% is coal. Oil and coal are used only in the Arctic zone, gasoline and gas account for an insignificant share of total consumption.

The thermal energy production utilizes both conventional direct combustion technologies and advanced technologies based on renewable energy sources. Conventional technologies include burning coal, wood, natural gas, and liquid fuels.

There are about 400 utility heat sources in the off-grid remote areas of the eastern regions, with the total installed capacity of 1,704 Gcal/h. Most of them are located in the Republic of Sakha (Yakutia). Their total output is estimated at 2,743 thousand Gcal (Table 3).

Most of the heat sources located in the Arctic zone are also operating in the Republic of Sakha (Yakutia). The share of the Arctic zone in the total installed capacity of heat sources and heat generation is 69.1% and 69.2% respectively.

Table 3. Overall indices for utility boiler houses.

Federal District of the Russian Federation	The number of heat sources, unit	Total installed capacity, Gcal/h	Thermal energy production, thousand Gcal
Siberian	71	257.5	436.6
Far-Eastern	330	1,446	2,306.5
Total for the eastern regions,	401	1,703.5	2,743.1
of which in the Arctic zone	201	1,176.3	1,898.8

The volume of fuel consumed by utility boiler houses is 715 thousand tce, of which 67% in the Arctic zone (Table 4). Coal makes up the largest share (55%) in fuel consumption, oil - 21%, gas - 5%, gas condensate fuel (GCF) - 3%, and firewood - 2%. The Sakhalin Oblast and the Chukotka Autonomous Okrug use diesel fuel to produce thermal energy on a small scale.

Table 4. Fuel consumption at utility boiler houses, thousand tce.

Federal District of the Russian Federation	Total	including:					
		Coal	Wood	Gas	Oil	GCF*	Diesel
Siberian	246,2	132,4	3,7	37,7	72,2	-	-
Far-Eastern	468,4	263,6	10,9	0	74,6	20,9	10,4
Total for the eastern regions,	714,6	396	14,6	37,7	146,8	20,9	10,4
of which in the Arctic zone	480,4	339,8	1,2	37,7		18,1	6,2

Note: * GCF– gas condensate fuel

The highest values of quantity, capacity, production of thermal energy, and fuel consumption are observed in the entities located in the northern areas, including the Arctic zone. More powerful heat sources, including a mini-CHP in the village of Deputatsky, are also located there. Fuel is represented in various types, such as coal, firewood, oil, gas condensate, and diesel fuel. More than half of the fuel consumed is coal, accounting for 55%, while oil represents over 20%.

3 Characteristics of power plants for industrial consumers

A large number of autonomous power plants for industrial use are in operation in off-grid remote areas of the eastern regions of the Russian Federation. The companies engaged in the extraction of mineral raw materials mainly utilize them. The hydrocarbon fields currently being developed in the Krasnoyarsk Territory (Vankorskoye, Yurubcheno-Tokhomskoye), the Irkutsk Region (Verkhnechonskoye, Yarakta, Ichedinskoye, Markovskoye, Dulisminskoye, Danilovskoye, Severo-Danilovskoye), and the Republic of Sakha (Yakutia) (Talakanskoye, Chayandinskoye) are located in remote areas that are not covered by power systems.

In addition, within these territories, there are many gold and silver mining ventures ranging from small artisanal artels to large mining and processing companies. The total capacity of power plants of the industrial consumers in the off-grid hard-to-reach areas of the eastern regions, according to the authors' estimates, is more than 1000 MW. Table 5 provides data on some of them based on the available information [4]-[13].

Table 5. Installed capacity of power plants of industrial consumers.

Constituent entity of the RF	Total installed capacity, MW
Irkutsk Region	289
Tomsk Region	63.0
Krasnoyarsk Region	118.2
The Republic of Sakha (Yakutia)	255.9
Sakhalin Region	14.5
Chukotka Autonomous Okrug	28.7
Total in the eastern regions,	769.3
of which in the Arctic zone	133.6

Note: based on the data from [4]-[13]

4 Prices and rates

The main type of fuel for generating electricity in most settlements located in the remote areas with undeveloped energy and transport infrastructure is diesel.

The price of diesel fuel directly depends on the delivery logistics and in the area at issue, on average, is 60–70 thousand rubles/t for winter diesel fuel and 70–80 thousand rubles/t for arctic diesel fuel [14]. The exception is the territories most remote from oil refineries, or territories with undeveloped transport infrastructure, where prices reach 120-145 thousand rubles/t (Figure 2).

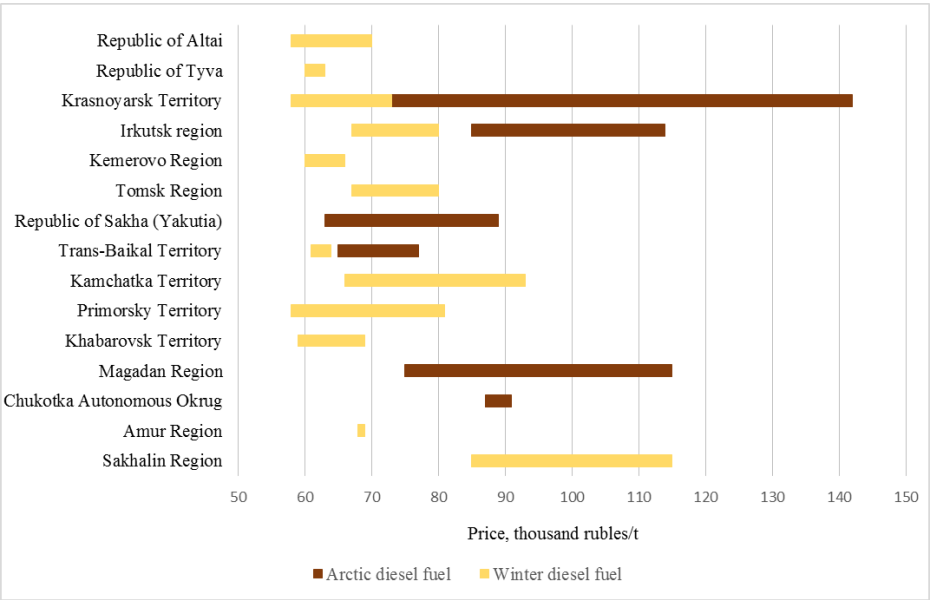

Fig. 2. Diesel price ranges (as of 2022).

Coal is the most common type of fuel for heating in the off-grid remote areas of Russia's eastern regions. Coal prices, depending on the availability of coal mining in the region and its location, change tenfold (Table 6). On average, the price ranges for coal are 2.5–7.0 thousand rubles/t for brown coal and 5.0–10 thousand rubles/t – for hard coal.

The highest prices for brown coal in the Siberian Federal District are in the Krasnoyarsk Territory and the Irkutsk Region. The brown coal price in the Chukotka Autonomous Okrug reaches 30,000 rubles/t. The maximum price of coal in the Siberian Federal District reaches 64 thousand rubles/t in the Arctic zone of the Krasnoyarsk Territory. In the Far Eastern District, the highest coal prices are in the Kamchatka Territory, where almost all coal used by the utilities is imported from the Kemerovo and Sakhalin Regions.

Table 6. Coal price (as of 2022).

Federal District of the RF	Coal price, thousand rubles/t	
	Brown coal	Hard coal
Siberian	1.3 – 12.0	2.4 – 63.7
Far Eastern	1.9 – 30.1	4.0 – 76.3

Other types of fuel are also used for energy production. These are liquefied hydrocarbon gas (LHG), oil, fuel oil, wood fuel, and gasoline.

The price of crude oil varies from 48.5 to 80.0 thousand rubles/t and depends on the distance and complexity of transportation.

LHG is supplied to the Kamchatka and Khabarovsk Territories, the Republic of Sakha (Yakutia). Its price varies from 25 to 45 thousand rubles/t in the Republic of Sakha (Yakutia) and to 130 thousand rubles/t in the Kamchatka and Khabarovsk Territories. The price of local natural gas in the Republic of Sakha (Yakutia) is 5.5 thousand rubles/thousand m^3.

In the remote areas of the Khabarovsk and Primorsky Territories, and the Sakhalin Region, wood fuel is widely used for heating. The price varies from 1.5 to 3 thousand rubles/m^3.

In all the territories under consideration, the highest prices are observed in the Arctic zone, especially in the Arctic areas of the Krasnoyarsk Territory. The prices in the western part of Siberia are lower.

The fuel component is prevailing in economically justified electric energy rates in the considered territories and can reach 85%. Therefore, economically justified rates directly depend on fuel prices and their maximum value is 100-120 rubles/kWh (Figure 3).

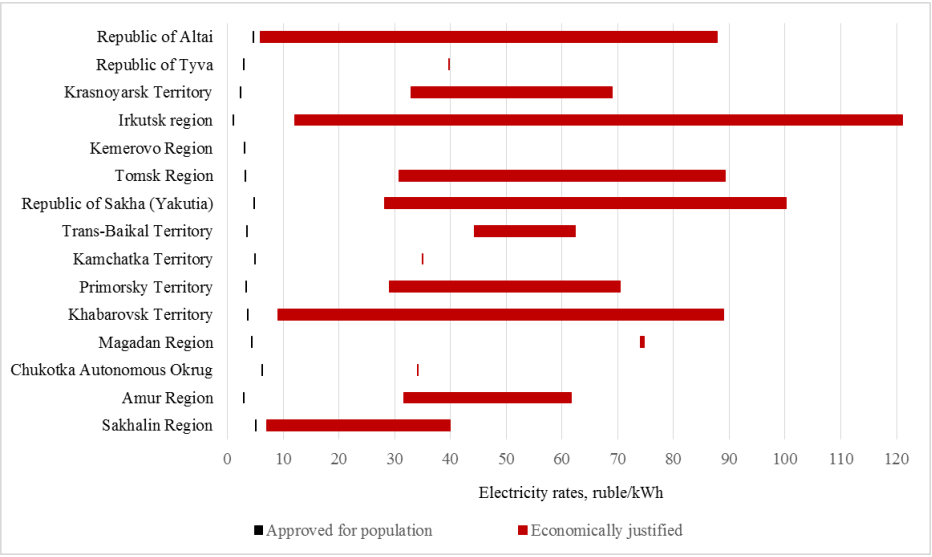

Fig. 3. Comparison of economically justified and approved electricity rates for the population (as of the first half of 2022).

Among all the territories at issue, the highest electricity rates are observed in the constituent entities of the Russian Federation that are part of the Arctic zone, i.e., the Republic of Sakha (Yakutia) and the Chukotka Autonomous Okrug. The electricity rates are also extremely high in the most remote and hard-to-reach areas of the Kamchatka Territory and the Sakhalin Region.

The fuel component is also prevailing in economically justified rate for thermal energy (Table 7). In contrast to electricity rates, the thermal energy rate is not approved in general for the entire constituent entity of the Russian Federation, but for each energy utility.

Table 7. Thermal energy rates (as of the first half of 2022)

Federal district of the RF	Rate, thousand rubles/Gcal	
	Economically justified	Approved for population
Siberian	3.4 – 50.0	2.6 – 8.2
Far-Eastern	2.0 – 63.2	0.6 – 25.0

The highest values of economically justified rates for thermal energy are observed in the Arctic areas of the Krasnoyarsk Territory, the Magadan Region, and the Kamchatka Territory (up to 50, 63, and 35 thousand rubles/Gcal respectively).

5 Conclusion

The results of the research presented in the paper facilitate solving one of the fundamental scientific problems of implementing the global and national climate agenda and the policy of low-carbon development of the Russian energy sector in terms of off-grid remote areas.

In general, the largest number of autonomous power plants that provide electricity to off-grid settlements are located in Siberia and the Far East (the Krasnoyarsk Territory, the Republic of Sakha (Yakutia), and the Khabarovsk Territory). These entities, along with Kamchatka Territory, where energy sources of a larger unit capacity are located, stand out in terms of installed capacity, electricity production, and fuel consumption. In most of the constituent entities of the Russian Federation at issue, the largest number of energy sources with an installed capacity of less than 1 MW is located in settlements with the population of up to 200 people. The primary fuel consumed by these plants is diesel fuel (94%).

About a quarter of the energy sources are located in the Arctic zone. Their capacity, electricity generation, and fuel consumption are slightly less than 40% of the total values for off-grid hard-to-reach areas of the eastern regions of the Russian Federation. More than half of the fuel used by the many utility boiler houses in these areas is coal.

Fuel prices depend on the transport infrastructure and delivery logistics. Given the poor development of transport infrastructure and fuel delivery problems, the average price of diesel fuel in the study area is 60-70 thousand rubles/t for winter diesel fuel and 70-80 thousand rubles/t for arctic diesel fuel. In the most remote settlements, it reaches 120 -145 thousand rubles/t. The ranges of coal prices on average are 2.5–7.0 thousand rubles/t for brown coal and 5.0–10 thousand rubles/t for hard coal. In the most remote areas, they reach 30 and 76 thousand rubles /t respectively.

The classification and analysis of the parameters of the energy technologies being currently in operation in the off-grid hard-to-reach areas showed rather high values of carbon intensity of energy production.

The carbon intensity of electricity generation from diesel power plants is 0.6-1.1 kg CO_2/kWh, depending on the power range of diesel generators. The range of carbon intensity of thermal energy production is 550-947 kg CO_2/Gcal, depending on the type of coal and the capacity of the boiler unit.

The analysis of the features of the existing structure and parameters of energy supply to the off-grid hard-to-reach areas of the eastern part of the Russian Federation made it possible to formulate the directions for the transition to low-carbon energy. Liquefied natural gas can become the main alternative type of fuel when a system for its transportation and use is built. The replacement of diesel fuel and coal with LNG will reduce the release of carbon dioxide into the atmosphere by more than 1.5–2 times [15]. The most acceptable low-carbon technologies for large industrial consumers are nuclear and hydrogen ones, for utility consumers – those based on renewable energy sources. At the same time, the choice of the most feasible option for energy supply can be made according to the criterion of the minimum cost of the prevented carbon dioxide emission.

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