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Social, Economic, and Environmental Effects of Electricity and Heat Generation in Yenisei Siberia: Is there an Alternative to Coal?

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Abstract: The energy sector is one of the most important pollutants in the atmosphere and causes significant emissions of greenhouse gases. In Russia, coal is the main contributor to the fossil fuel consumption of thermal power plants and boilers, thus affecting atmospheric air pollution by releasing particulate matter and nitrogen oxides, which are strongly associated with a negative impact on human health. This problem is especially acute for the resource regions of Yenisei, Siberia, a 2.5+ mln sq km macro-region in the very heart of Russia. In this paper, we analyze the impact of the structure of electricity and heat generation on emissions of pollutants and climate-active gases in Yenisei, Siberia, and give an overview of their social, ecological, and economic effects. More than 75% of electricity in Yenisei, Siberia, is produced by hydroelectric power plants that do not pollute the atmosphere. The rest of the electricity is generated in the cogeneration mode by thermal power plants, which are cores of the heat supply designs of cities. The share of individual coal-powered heat sources is still high. A detailed analysis of existing equipment and technologies at existing thermal power plants is needed to select options for their modernization to reduce emissions while keeping coal in use. Our calculations for the biggest cities of Krasnoyarsk Krai show that investments in the transition to heating with pellets will require RUB 184.7 million for Nazarovo and RUB 313.9 million for Kansk. At the same time, switching to electric heating is more than twice as expensive: RUB 498.6 million for Nazarovo and RUB 847.5 million for Kansk. The additional costs will range from RUB 21 to RUB 45.4 thousand per household per year for the pellet variant and from RUB 56.8 to RUB 122.5 thousand per year for electric heating, which could triple the annual heating costs. Thus, these options are unlikely to be implemented without direct state support. We argue that creating an attractive living environment in Yenisei, Siberia, must begin with intensive public investment in mitigating the environmental externalities caused by coal emissions.

Keywords: air pollution; coal energy; environmental externalities; social and economic benefits; heat and electricity; combined heat and power plants; climate change; Yenisei, Siberia

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1. Introduction

Both conventional and renewable electricity and heat power generation impact the quality of the environment. It is wrong to think that renewable energy sources are less harmful in this sense. Though they are "green" during the process of energy generation, at other stages of the life cycle (extraction of raw materials, production of components, transportation, and recycling) they might emit far more pollutants [1–4]. The inefficient use of renewable sources negates their benefits by increasing the consumption of fossil fuels at the stages preceding generation [5]. Nevertheless, the main negative effects of energy production are related to air pollution from the combustion of fossil fuels in combined heat

and power plants. Importantly, it also contributes to the greenhouse effect, as fossil fuel combustion is supposed to emit large amounts of greenhouse gases.

The fuel type is a key factor determining the volume and structure of pollutant emissions from thermal power plants. While natural gas is a fairly environmentally friendly energy source, coal is the direct opposite. Coal combustion is accompanied by significant emissions of particulate matter, sulfur dioxide, and nitrogen oxides into the atmosphere. High concentrations of these substances in the atmosphere are associated with adverse effects on human health [6–8]. A ban on the sale of coal in cities leads to a significant reduction in the concentration of smoke in the air, resulting in a sharp decline in mortality from respiratory and cardiovascular disease [9,10].

Electricity and heat generation produce up to 40% of global CO_2 emissions. Coal leads to carbon dioxide emissions per unit of energy produced [11,12]. Coal-fired plants account for more than 70% of CO_2 emissions in the world [13], up to 84% in the United States [14], and more than 90% in China [15]. The production of heat is also a source of significant impact on the environment and the climate. Today, the share of district heating in the world is about 8%, the rest of the heat consumers use individual sources. Combined electricity and heat production at cogeneration plants is the most common form of heating for local communities. In 2021, about 90% of local heating used fossil fuels, mostly coal; consequently, this sector accounted for 3.5% of global carbon dioxide emissions. Therefore, the reduction of emissions from coal is one of the main tasks of most climate change mitigation strategies.

In this regard, the transition from the use of coal to natural gas is one of the most viable directions for mitigating the negative ecological impact of the energy sector [16]. The environmental effects of this transition are obvious: the reduction of emissions of nitrogen oxides, sulfur dioxide, and suspended particles is estimated at 60–90% [17]. The climate change mitigation effect is not so unambiguous. The natural gas supply chain often leaks methane, which global warming potential is at least twenty-five times higher than for carbon dioxide. For this and other reasons, not all studies are positive about the climate effects of switching generation from coal to gas [18].

Among other factors that negatively influence electricity and heat generation on air quality are the number and location of generation sources within settlements, the type and characteristics of applied equipment and emission cleaning technologies, etc. [19]. For example, it was found that the incomplete combustion of traditional biomass used by the rural population causes significant harm to the health of women and children who spend a lot of time at home [20].

It is crucial to understand that the direct social and economic effects of generation emissions are mainly related to their environmental consequences, while the climate factor is more long-term. This problem is especially important for countries where the share of traditional energy sources is still high.

In recent years, the global energy industry has been developing under conditions of increasingly stringent environmental and climatic requirements for the reduction of associated emissions. At the same time, a significant effect can be achieved only by reducing the volume of generation, which is rarely possible for several social and economic reasons. One solution is the development of renewable energy, which not only helps to reduce atmospheric emissions but also provides conditions to sustain economic growth [21,22]. The impact of renewable energy on employment is assessed in different ways [23]. Some studies note that the potential for job creation in renewable energy is higher than in conventional energy [24]. The opposite effects should also be considered, such as the loss of employment in traditional energy, rising electricity prices, and reduced demand and investment in other sectors [25,26].

Many countries are implementing policies to increase the share of renewable energy sources and reduce the use of fossil fuels. Thus, over the past 20 years, the share of renewable energy in total energy generation in the world has increased from 18.8% in 2000 to 28% in 2021. Hydropower remains the main source of renewable energy, with an almost

unchanged share in the total generation structure (15.3% in 2021) with an increase provided by the spread of wind and solar energy. Wind and solar power are most developed in Denmark (51.9% of the national generation), Luxembourg (43.4%), and Lithuania (36.9%) [27]. However, the leaders in the share of renewable energy in 2021 were Norway (99.5%), Costa Rica (99.1%), and Tajikistan (92.5%), with almost complete dependence on hydropower. The use of renewable energy sources is also developing in the heating sector, where Sweden, Denmark, and Austria are the leaders in implementing biofuels and household waste to produce heat [27].

Despite the growing use of renewable sources, the share of energy from burning fossil fuels is still higher than 60% on a global scale. The main types of fuel used are coal and gas. China, India, and the U.S. lead in the amount of energy generated from coal, while Mongolia, South Africa, and India are the top users of coal in total energy production. Reducing the use of coal is crucial to meeting climate change mitigation goals, but in 2021, coal-fired power generation was again 9% higher than last year (a record high since 1985) [28]. According to Bloomberg, the trend holds in 2022 [29]. The increase in coal use will be a cause of record CO_2 emissions from the energy sector (12 billion tons). One reason is the recovery of the world economy after the COVID-19 crisis, followed by the rise in demand for electricity, which could only be met by fossil fuels.

These trends confirm that coal phase-out is proving to be difficult in practice. Diluiso et al. [30] review multiple studies on coal phase-out at the national, regional, and local levels. Such studies usually include a description of the existing generation structure, the state, and prospects of the coal industry, drivers and barriers to coal phase-out, scenarios, and the effects of coal transition. One of the key drivers for coal phase-out today is the climate agenda and country commitments under the Paris Agreement. High production costs in the coal industry, availability of renewable energy, and local environmental problems are also mentioned as drivers of the coal transition. The consumption of local coal by power plants and the dependence of the economy on its production are among the most common barriers to the coal transition. Among the economic effects of the coal transition, most studies point to the risks of job losses in both the energy and coal mining sectors. Increased unemployment causes negative social effects, such as lower living standards, increased poverty, increased social tensions, and migratory outflows from coal regions. Positive social effects include a decrease in the incidence of respiratory and cardiovascular diseases. In addition, Farsaei et al. show that abandoning coal-fired generation in some countries can lead to increased energy imports from neighboring countries with higher fossil fuel use. As a result, the region's total emissions increase [31].

Opportunities and risks for the Russian economy associated with changes in the structure of energy generation are controversial [32–35]. In Russia, thermal power plants generated about 60% of all electricity in 2021. The share of nuclear power is 20% and is one of the highest among the G20 countries. Hydropower plants also produce a significant share of energy (19%). The contribution of other renewable energy sources is only about 1%. Russia possesses a large territory, which differs by geographical, climatic, and socio-economic conditions. Therefore, there are regional differences in the structure of energy generation and fuel usage. Nuclear power is developed in only 11 out of 85 Russian regions, and hydropower generation is much more widespread (31 regions). Even though renewable energy constitutes a small share of the country's energy balance, in some regions, it covers a significant portion of local energy consumption. Wind power plants provide 80% of the needs of the Republic of Adygea and Kalmykia. Solar stations are the main source of power in the Altai Republic (77.3%), and geothermal stations provide 24.3% of Kamchatka Krai's energy demands. Thermal power plants mostly use natural gas (77.6%) and coal (22.4%), but the structure of the used fuel also differs by territory: in the European territories, the use of gas prevails, while in Siberia and the Russian Far East, coal remains the main fuel. This is due to the uneven distribution of coal in the country and the location of gas infrastructure. Siberia and the Far East have up to 80% of coal reserves and are not connected to the unified gas supply system, which makes coal the most accessible type of fuel. On the other hand,

the predominance of coal largely determines the difficult environmental situation in these territories. The macro-region estimates of the costs and benefits of electricity for three types of generation (coal, gas, and solar) are calculated in [36]. It is shown that for solar power plants, it is difficult to compete with conventional sources due to the lack of economies of scale. While the existing system of electricity tariff formation, the availability of tax incentives for mining, and subsidies for rail delivery of coal make coal a profitable energy source even considering its negative environmental effects.

Climatic conditions in Russia require both the residential and industrial sectors to be heated. A total of 572 thermal power plants produced heat in Russia in 2020, apart from 77.3 thousand boiler houses [37]. Combined heat and power plants provide heat mostly to large cities; boiler plants and individual heat sources heat small cities and rural settlements. Small boilers are usually located inside urban development and use solid fuel, so they have the greatest negative impact on the air quality of settlements. Despite the large number of studies devoted to the coal transition, most of them consider only electricity generation, while heat supply is rarely discussed. District heating problems are mainly discussed in a few cities in Germany and China. Heat supply has significant potential to reduce emissions, but it is impossible to fully replace renewable energy sources with heat produced by thermal power plants, and the capital costs for the transition to low-carbon heating are high [38]. In addition, it is noted that in an effort to meet climate goals, the technology and infrastructure of existing heating systems are often ignored [39].

In this paper, we focus on an informal union of the three geographically close regions along the Yenisei River in Siberia: Krasnoyarsk Krai, the Republic of Tyva, and the Republic of Khakassia [40]. Though the two largest hydroelectric power plants in Russia are located here, the population is supplied with electricity and heat by thermal power plants and boiler houses. In Yenisei, Siberia, the average share of coal thermal energy generation is 70%, while in the Republics of Tyva and Khakassia it almost reaches 100%. Coal emissions and a harsh continental climate, combined with declining wind speeds, create conditions for the regular accumulation of harmful substances in the most densely populated areas [41]. Purpose of the study us analyze the impact of the structure of electricity and heat generation on emissions of pollutants and climate-active gases in Yenisei, Siberia, and discuss possibilities for reducing the use of coal and the associated social and economic effects. Our contribution is that we looked in more detail at heat generation by both large facilities and the decentralized segment, including small boilers and individual heating sources. Using the examples of several cities, we have estimated the costs required to stimulate the substitution of coal in the segment of individual heating.

2. Materials and Methods

Many sources were used to collect data. In the regional context, data on electricity and heat production by facility type, electricity consumption by type of economic activity, emissions of main pollutants from fuel combustion, data on population morbidity, and main economic indicators of the energy industry operation were investigated. These data are provided by the Federal State Statistics Service of the Russian Federation (Rosstat).

The balances of power generation and consumption by region and data on individual power consumers from the Schemes and Program for Prospective Development of the Electric Power Industry of each region were used.

At the municipal level, the impact of generation facilities on pollutant emissions and population morbidity was studied. These data were collected from the Government Reports on the State and Protection of the Environment and "On the State of Sanitary and Epidemiological Welfare of the Population" of each region. Additionally, the results of summary calculations of atmospheric air pollution in the cities of Krasnoyarsk Krai were used.

Characteristics of thermal power plants are derived from the Heat Supply Schemes of the cities in which the generation facilities are located. In addition, data from the official

website of Siberian Generating Company, one of the largest energy companies in Siberia, were used.

3. Results

3.1. Electricity Generation

Electric power facilities in Yenisei, Siberia, are part of the Krasnoyarsk (includes Krasnoyarsk Krai and the Tyva Republic) and Khakassia energy systems and are part of the United Energy System (UES) of Siberia. Krasnoyarsk Krai also has an isolated power system in the Norilsk Industrial District. The electric power facilities in the Turukhansk district of Krasnoyarsk Krai are part of the Krasnoyarsk Energy System but have electrical connections only with the Ural UES and have no connection with the Siberian UES [42]. In Khakassia, centralized power supply does not cover the southern part of the Tashtypsky district, where consumers use local gasoline power plants [43].

The power system of the Tyva Republic is energy deficient. The region meets its needs, transferring electric power from Krasnoyarsk, Krai, and Khakassia. At the same time, Tyva exports some electricity to Mongolia. Remote *kojuun*s (municipalities) of the Tyva Republic are powered by diesel units [44]. Krasnoyarsk Krai and Khakassia also sell power to adjacent power systems: from Krasnoyarsk Krai to Kemerovo Oblast, Altai Krai, Tomsk Oblast, and the Tyva Republic and from Khakassia to Krasnoyarsk Krai, Tyva, and Kemerovo Oblast. The consolidated balance of electricity in the Yenisei, Siberia, regions is shown in Table 1.

Table 1. The electricity balance of the energy systems of Yenisei, Siberia, in 2020 was one million kWh. Source: Schemes and Programs of Perspective Development of the Electric Power Industry of the Yenisei, Siberia, regions.

	Tyva Republic	**Khakassia Republic**	**Krasnoyarsk Krai**
Consumption	802.5	16,588	54,306.4
Power plant production	37.2	30,086	65,406.4
Receiving electricity *from* adjacent regions	889.7	NA	6352.8
Transmission of electric power *to* adjacent regions	–124.4	–13,498	–17,452.8

The two largest Russian hydropower plants, Sayano-Shushenskaya and Krasnoyarskaya, erected on the Yenisei River, generate more than 50% of the macro-region's electricity. Hydropower plants are also important for the needs of the remote Norilsk Industrial District, as they generated 55% of its electricity in 2021. The structure of electricity generation in the regions of Yenisei, Siberia, by type of power plants is shown in Figure 1.

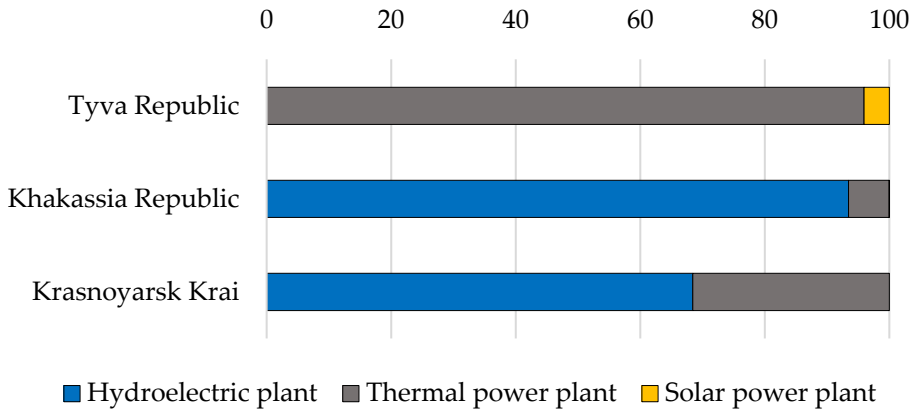


Figure 1. Electricity generation in Yenisei, Siberia, by type of power plant in 2021, %. Source: Rosstat data.

Figure 2 shows the location of generation facilities on the territory of Yenisei, Siberia.

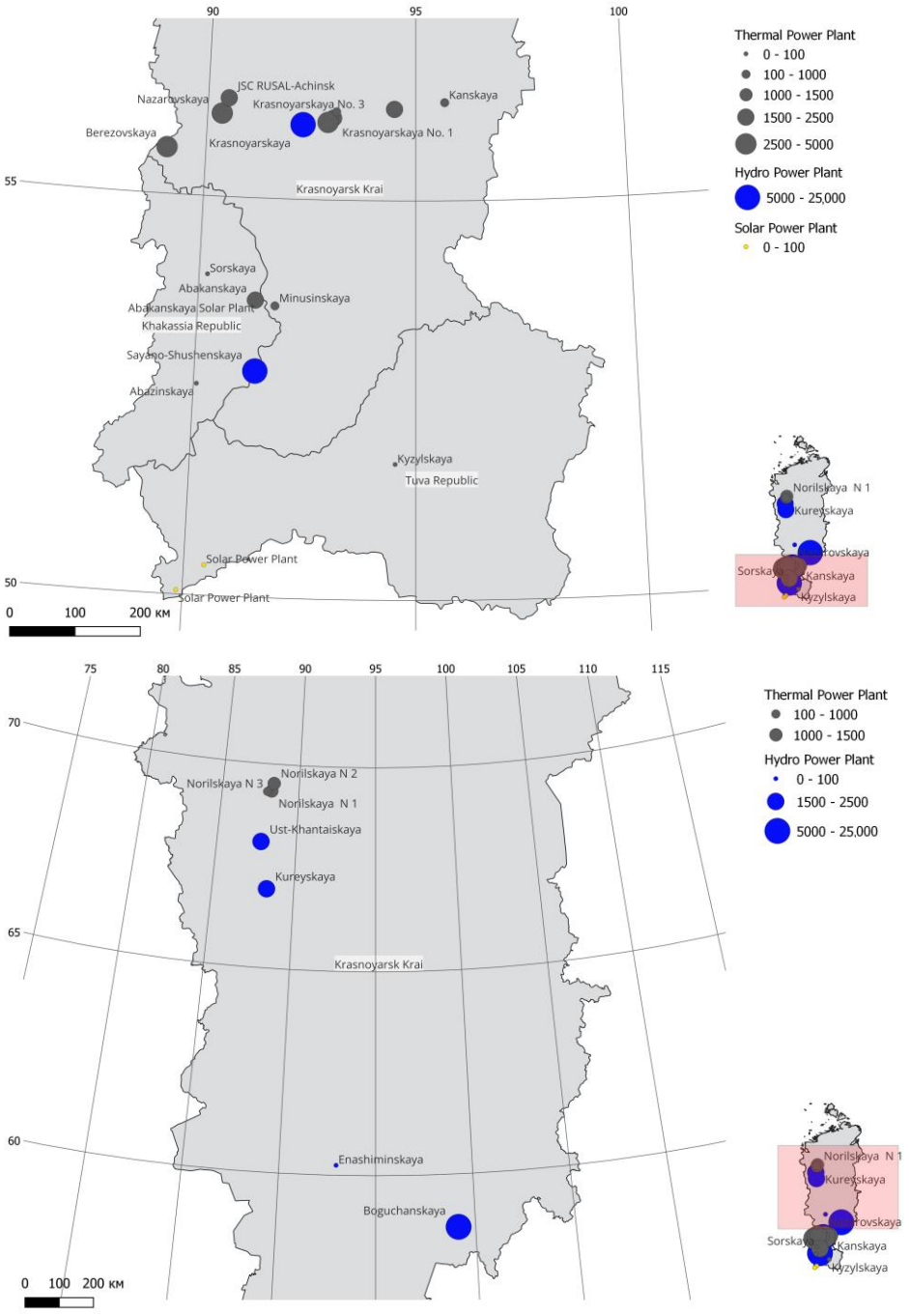


Figure 2. Electricity generation in Yenisei, Siberia, in 2020, mln kWh. Source: Schemes and Programs of Perspective Development of the Electric Power Industry of the Yenisei, Siberia, regions. Made using QGIS version 3.28. Administrative boundaries are retrieved from the Russian Geological Research Institute. URL: https://vsegei.ru (accessed on 14 November 2022).

The main consumers of electricity generated by hydropower plants are large industrial enterprises, mostly of non-ferrous metallurgy: Sayanogorsky, Khakassky, Krasnoyarsky, Boguchansky, Aluminum plants, and the Norilsk Mining and Metallurgical Company. Thermal power plants provide electricity and heat to the population and industrial enterprises in large cities. In addition, thermal power plants play an important role in ensuring the reliable operation of the entire power system. Electricity generation at hydroelectric power plants depends on the water level in the rivers. For example, in 2022, due to the low water

level in the Yenisei, the Abakanskaya Thermal Power Plant had to cover part of the fallout of the Sayano-Shushenskaya Hydropower Plant [45]. Solar power plants on the territory of Tyva were commissioned in 2021 to provide energy to isolated and remote areas of the Republic and allowed to reduce the consumption of diesel fuel [46]. Abakanskaya Solar Power Plant provided electricity to one of the districts of Abakan during the test operation in 2016 [47]. The overall structure of electricity consumption is shown in Figure 3.

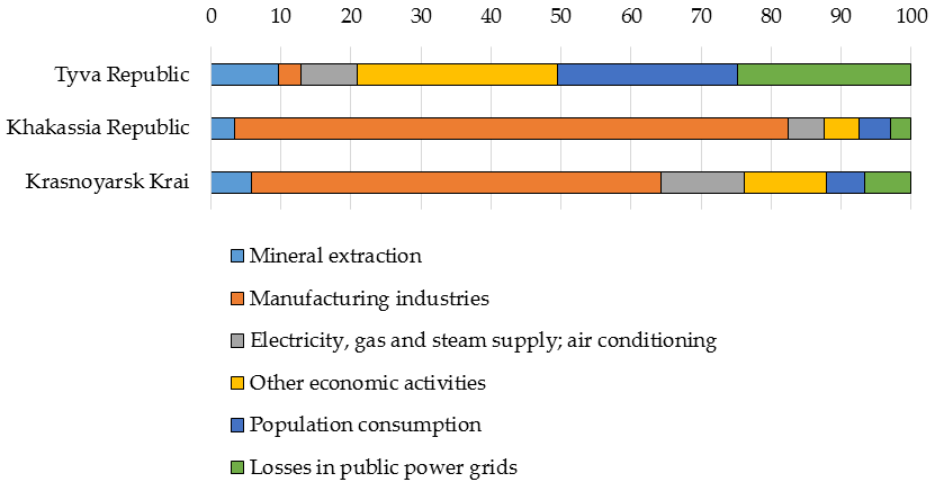


Figure 3. Electricity consumption in Yenisei, Siberia, by economic activity in 2020, %. Source: Rosstat data.

Krasnoyarsk Krai and Khakassia accommodate energy-intensive industries, so the share of households in total electricity consumption is insignificant. In the Republic of Tyva, on the contrary, most of the electricity produced covers the needs of the population. In addition, Tyva has high losses in power grids due to high wear and tear on equipment.

If we classify hydropower plants as renewable energy sources, the structure of energy generation in Yenisei, Siberia, is favorable, as renewable sources generate 76.6% of electricity. However, the environmental well-being of the population is strongly affected by the intensive emissions of thermal power plants, which are located directly in the settlements. Most thermal power plants operate in cogeneration mode, i.e., they produce electricity and heat.

3.2. Heat Generation

Heat supply in Russia is carried out both (1) centrally and (2) by means of autonomous sources. The first segment is subject to official statistical accounting, the second is not poorly reflected in statistical data. According to official figures, 2197 heat supply sources with a total capacity of 2255.8 Gcal/h were in operation in Yenisei, Siberia, by the end of 2021. In the Republics of Tyva and Khakassia most of the heat is generated by boiler houses. In Krasnoyarsk, Krai combined heat and power plants are employed. The distribution by regions and types of sources is shown in Figure 4.

Official data do not provide complete and consistent information about heat sources. There is also no data on boilers that meet the needs of industrial enterprises [48]. It was not possible to find information on some individual stations, e.g., the Kyzylskaya Thermal Power Plant in the Tyva Republic. It has a small capacity and is probably accounted for as part of boiler houses.

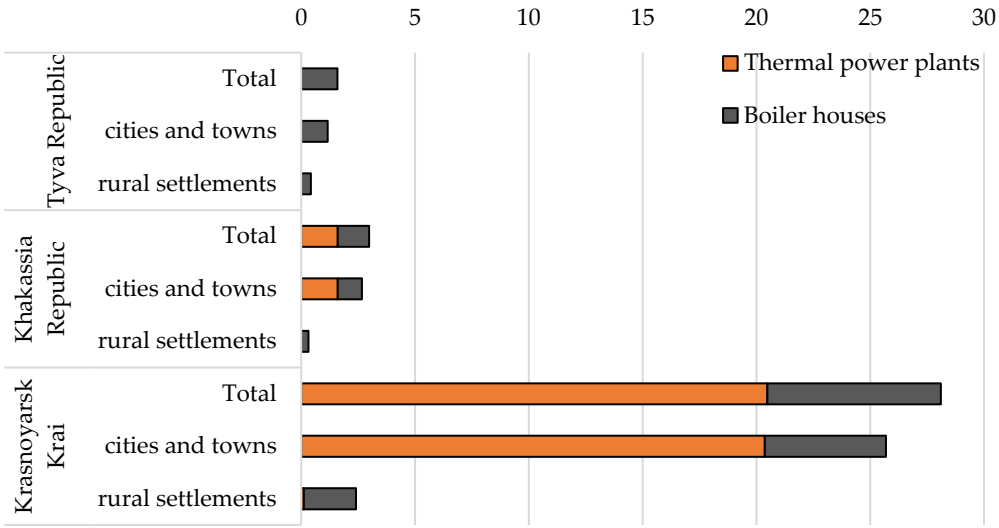


Figure 4. Heat production by the regions of Yenisei, Siberia, in 2021 by heat supply sources, million Gcal. Source: Rosstat data.

Power plants and boilers in Yenisei, Siberia, use mostly coal. In the Republics of Tyva and Khakassia, its share is almost 100%, while oil fuel accounts for only 0.1%. In Krasnoyarsk Krai, the share of coal is 67.3%, gas accounts for 30.7%, and oil for 2%. Natural gas is the main fuel for heat and power plants in the Norilsk industrial district. The gas supply system is local and has no access to the unified gas supply system in Russia. Gas is produced at the Pelyatkinskoye, Severo-Soleninskoye, Yuzhno-Soleninskoye, and Messoyakhskoye fields and is transported through a trunk gas pipeline to Dudinka and Norilsk. Table 2 describes the major sources of heat generation in Yenisei, Siberia, and the main types of fuel used.

Table 2. Heat generation facilities in Yenisei, Siberia. Source: Heat Supply Schemes for Cities in Yenisei, Siberia. Note: GRES—State District Power Plant (Thermal Power Plant).

Region	Heat Generation Facilities (Thermal Power Plant)	Main Fuel Type
Tyva Republic	Kyzylskaya	Kaa-Khem hard coal
Khakassia Republic	Abakanskaya Abazinskaya Sorskaya	Irsha-Borodinsky, Chernogorsky brown coal grades
Krasnoyarsk Krai	Berezovskaya Nazarovskya Krasnoyarskaya GRES-2 Krasnoyarskaya No. 1 Krasnoyarskaya No. 2 Krasnoyarskaya No. 3 Kanskaya Zheleznogorskaya Minusinskaya JSC RUSAL-Achinsk LLC Teplo-Sbyt-Servis	Berezovsky, Nazarovsky, Borodinsky, Irsha-Borodinsky brown coal grades
Norilsk industrial district	Norilskaya No. 1 Norilskaya No. 2 Norilskaya No. 3	Natural gas

There are large coal mines in the macro-region, so coal is the most available and cheapest fuel for power plants. Krasnoyarsk Krai produced 35.5 million tons of coal in

2020, which is almost 9% of the total production in Russia. Brown coal from Kansk-Achinsk basin, including Berezovskoye, Nazarovskoye, Irsha-Borodinskoye, and Pereyaslovskoye fields, is used for power generation at local plants. Four fields of the Minusinsk coal basin are located in the Republic of Khakassia. In 2020, 26 million tons of coal were extracted from them [49]. Ulug-Khem coal basin is located in the Republic of Tyva, as well as a large Elegest field with little coking coal. Kaa-Khem hard coal is used for supplying heat. In addition to the availability of the raw material base for coal, Siberia has the most developed transport infrastructure [50].

Except for the Zheleznogorsk Thermal Power Plant, all thermal power plants operate in cogeneration mode and provide heat and electricity to industrial enterprises and the population of large cities. Small towns and rural settlements receive heat from boiler houses and individual autonomous sources. Boiler houses mainly use coal, some boilers run on electricity and fuel oil. Residential houses in the private sector also most often use coal, less often wood or other fuels. In Yenisei, Siberia, there are many small boiler houses that are often not equipped with instrumentation, which prevents the organization of a proper accounting of fuel consumption and the volume of generated heat energy.

3.3. The Impact of Energy Production on the Quality of Atmospheric Air

3.3.1. Electricity Generation

The production of electricity and heat has a significant impact on the environment, mainly on atmospheric air. The share of pollutant emissions from electric power, gas, and steam generation in total atmospheric 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, and 46% of nitrogen oxide.

It Is obvious that coal-fired thermal power plants are the main contributors to air pollution. For this reason, for Yenisei, Siberia, the air pollution indicators from the activities of power plants are higher than for Russia as a whole. Electric power, gas, and steam generation yield 24.9% of total air emissions in Khakassia and 27.6% in Krasnoyarsk Krai. There are no corresponding data on Tyva, but emissions from fuel combustion accounted for about 93% of all emissions from stationary sources. Table 3 also shows the shares of emissions of the most common pollutants from fuel combustion for power and heat generation.

Table 3. Share of pollutant emissions from fuel combustion for electricity and heat generation in total emissions for the region in 2017, %. Source: Rosstat data. Note: the indicator is not calculated after 2017.

Region	Particulate Matter	Sulfur Dioxide	Nitrogen Oxide	Carbon Dioxide
Tyva Republic	94.8	99.6	96.0	98.7
Khakassia Republic	46.6	54.3	74.8	16.7
Krasnoyarsk Krai	60.2	4.9	65.7	23.6

In Tyva, which has virtually no industry, almost all air pollutant emissions come from fuel combustion. In Krasnoyarsk Krai and Khakassia, this indicator is lower due to the emissions of other industries, primarily non-ferrous metallurgy enterprises. At the same time, for some municipalities with generation facilities, their contribution to total atmospheric emissions may be more than 90% (Table 4).

Table 4. Impact of large power generation facilities on atmospheric air quality in municipalities. Source: Government Reports on the State and Protection of the Environment, Siberian Generating Company.

Municipality	Generation Facility (Thermal Power Plant)	Emissions of Pollutants from the Generation Facility in 2020, Thousand tons	Share of Generation Facility Emissions in the Total Emissions of the Municipality, %
Kyzyl	Kyzylskaya	1.1	25.8
Abakan	Abakanskaya	11.2	92.6
Abaza	Abazinskaya	1.6	69.6
Sharypovo district	Berezovskaya	13.1	90.9
Nazarovo	Nazarovskya	29.4	92.7
Krasnoyarsk	Krasnoyarsk No. 1, No. 2, No. 3	36.7	33.5
Kansk	Kanskaya	2.1	16
Zelenogorsk	Krasnoyarskaya GRES-2	3.9	19.6
Minusinsk district	Minusinskaya	2.9	80.6

The impact of the energy industry on the atmosphere always draws attention, while the harm caused to other parts of the environment is often underestimated. Meanwhile, the energy industry is a major consumer and polluter of water resources. Energy generation consumed 42,9% of fresh water in Russia in 2019. It is also responsible for 49.7% of wastewater discharge and 7.4% of polluted wastewater [51]. Although the contribution of generation facilities to water pollution by chemicals is relatively small, thermal pollution is important, as well as the consequences of major accidents. The accident at Norilskaya Thermal Power Plant No. 3, which occurred in May 2020, is widely known. As a result of a leak from a diesel fuel tank, 20 thousand tons of oil products contaminated the Daldykan and Ambarnaya rivers [52]. Another case is the leakage of more than 40 tons of machine oil into the Yenisei River after the catastrophic accident at the Sayano-Shushenskaya Hydro Power Plant in 2009.

Huge amounts of ash and slag waste are the companions of power generation at thermal power plants. Ash dumps negatively impact groundwater and soil. Samples collected near the ash dump of Krasnoyarsk Thermal Power Plant No. 1 give evidence of pollution of groundwater with barium and oil products [53].

3.3.2. Heat Generation

In Yenisei, Siberia, a significant part of the heat supply of settlements is provided by boilers of different capacities and individual autonomous sources. It is difficult to estimate their contribution to atmospheric air pollution due to several factors. Firstly, there is a lack of sufficient municipal statistical data on air quality. Secondly, there is no qualitative measurement of emissions at generation facilities. At the same time, it is small heating sources, whose pipes are located at low heights in densely populated areas of cities, that are responsible for the most serious damage to human health.

In 2020, the Ministry of Energy of Russia began to demand that the Heat Supply Schemes include a section with an assessment of the real contribution of the energy sector to environmental pollution. Now, of the three regional capitals of Yenisei, Siberia, only Krasnoyarsk obeyed that requirement. Table 5 shows that thermal power plants emit most of the pollutants. However, for some substances, such as soot and carbon monoxide, the volume of emissions from boilers exceeds emissions from Thermal Power Plants. At that, boilers produce only about 15% of heat energy in the city. Therefore, per-unit emissions from boilers are four times higher than per-unit emissions from Thermal Power Plants [54].

Table 5. Total air pollutant emissions from energy sources in Krasnoyarsk. Source: Heat Supply Schemes of Krasnoyarsk.

Substance	Total for Registered Energy Sources Tons per Year	Thermal Power Plants		Recorded Boiler Houses	
		Tons per Year	%	Tons per Year	%
Nitrogen dioxide	9985.8	8219.7	82.3	1766.1	17.7
Nitrogen oxide	4664.5	4378.3	93.9	286.2	6.1
Carbon (soot)	1105.5	238.2	21.5	867.2	78.4
Sulfur dioxide	25,515.2	20,039.4	78.5	5475.8	21.5
Carbon oxide	7356.1	1554.6	21.1	5801.5	78.9
Benzapyrene	0.0	0.0	50.0	0.0	50.0
Inorganic dust: 70–20% silicon dioxide	19,183.5	14,280.7	74.4	4902.7	25.6
Total	67,810.5	48,710.9	71.8	19,099.6	28.2

Thus, even coal-fired thermal plants have significant environmental and economic advantages over small boilers, as they provide greater reliability of heat supply, have lower fuel consumption and pollutant emissions, and are subject to more stringent emission controls. Large thermal power plants are equipped with ash collectors, while boilers do not have them. At the same time, boiler plants are usually located near residential buildings and social infrastructure [55]. Existing thermal power plants can be modernized to reduce pollutant emissions. The use of the best technologies for coal combustion will reduce the anthropogenic load on the environment [56].

Some cities in Yenisei, Siberia, implement plans to replace inefficient boilers and connect their consumers to thermal power plants. The Siberian Generating Company is responsible for such activities in Krasnoyarsk, Kansk, Nazarovo (Krasnoyarsk Krai), Abakan, Chernogorsk (Republic of Khakassia), and Kyzyl (Republic of Tyva). According to the company data, pollutant emissions were reduced by 10 thousand tons per year for 5 years with the help of the program. Shutting down boiler plants sufficiently reduces the local effects of air pollution [57].

It is difficult to analyze the contribution of the private sector to environmental pollution, so only some estimates for the biggest cities in Krasnoyarsk Krai are available (Figure 5). There are neither similar data for the other cities in the region nor the republics of Tyva and Khakassia.

Autonomous heating sources make a significant contribution to air pollution in cities where there are no large industrial polluters. On the contrary, in cities where enterprises of other industries are located, the share of autonomous heating sources in emissions is relatively small. For example, in Nazarovo, the thermal power industry is virtually the only source of pollution, giving 93% of emissions. In all surveyed cities, autonomous heating sources influence exceedances of maximum permissible concentrations by nitrogen dioxide, carbon monoxide, dust, and suspended substances [58]. These exceedances were recorded within the boundaries of residential areas, so the emissions from autonomous heating sources have a negative impact on the health of people living in these areas.

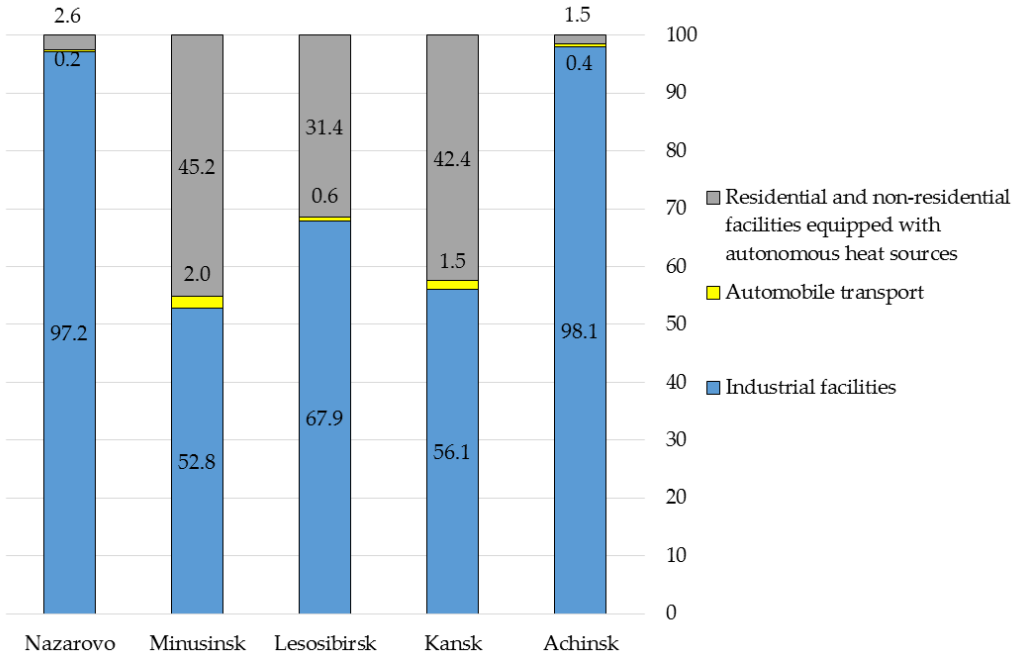


Figure 5. Structures of atmospheric air pollution in cities of Krasnoyarsk Krai by type of pollutants in 2020. Source: compiled according to the conclusions of the summary calculations of atmospheric air pollution in the cities of Krasnoyarsk Krai.

3.4. Social and Economic Effects of Energy Generation

3.4.1. Public Health

Electricity and heat production are two of the main pollutants of the surface layer of the atmosphere. Energy enterprises emit particulate matter, nitrogen oxides, and sulfur dioxide into the atmosphere, which are responsible for a negative impact on human health, especially manifested in respiratory diseases (Table 6).

Table 6. Respiratory diseases morbidity of the population (registered diseases in patients diagnosed for the first time in their lives, per 1000 people). Source: Statistical Collection Health Care in Russia. Note: Cases exceeding the national average level are highlighted in color.

Region	Population	2015	2016	2017	2018	2019	2020
Russian Federation	All population	337.9	351.6	353.5	359.8	356.2	370.6
	Children (0–14 years old)	1157.6	1173.8	1168.3	1171	1160	1020
Tyva Republic	All population	296.3	260.4	260.2	258.5	266.8	259.4
	Children (0–14 years old)	670.8	535.5	545.8	543.6	570	511
Khakassia Republic	All population	311.7	348	370.6	368.2	378.1	364.9
	Children (0–14 years old)	898.2	1077.6	1155.3	1145.5	1165	961
Krasnoyarsk Krai	All population	276.1	289.3	297	294.5	296.3	336
	Children (0–14 years old)	983	992.3	997	996.1	964	877

Regionally, morbidity indicators provide little information, since there are strong differences within regions in terms of the level and accessibility of medical care, incomes, and lifestyles of the population. Emissions of pollutants are also unevenly distributed across the territory.

Of course, these data do not suggest that the high incidence of diseases is caused solely by the negative impact of electricity and heat generation. However, it makes no sense to deny the connection either. In addition to the objective impact on health, the possible negative impact is widely discussed and is one of the factors in decisions concerning where to stay for long-term periods [59]. Given the outflow of the population from the regions of

Siberia, improving living conditions, including environmental conditions, is an important measure to consolidate the population of the territory.

3.4.2. Economic Effects

The main trends in changing the structure of energy generation are the transition to gas instead of coal and the development of renewable energy sources. Both the social and economic consequences of this shift might be more tangible for the population.

Except for the Republic of Khakassia, electricity and heat generation give a small contribution to the gross value added and the number of employees in Yenisei, Siberia. However, the industry is closely connected with coal mining, as coal from the Kansk-Achinsk basin is used as fuel for thermal power plants. Accordingly, part of the macro-region population is also employed in coal mining. The wages of employees of organizations that produce and distribute electricity, gas, and steam in all regions are higher than the average for the economy. It is interesting that salaries in the energy industry in Tyva are significantly lower than the regional average, while in Khakassia, they are significantly higher than the average (Table 7). The explanation may lie in the fact that in the predominant hydropower industry in Khakassia, wages are characterized by a premium compared to the wages of boiler workers, which are common in Tyva.

Table 7. Contribution of electricity, gas and steam supply, and air conditioning in the gross value added and employment of the regions of Yenisei, Siberia, 2020. Source: Rosstat data.

Region	Share of the Activity, %		Wages in Sector to the Average Wage in the Economy	
	In Gross Value Added	in Employment (Including Coal Mining)	All Economy	Industry Average
Tyva Republic	2.2	2 (2.6)	1.01	0.75
Khakassia Republic	11.8	3 (5.2)	1.27	2.17
Krasnoyarsk Krai	3.3	3.2 (3.6)	1.08	1.27

Even though employment in the energy sector accounts for a small share of the regions, for some cities, the generation facilities are city-forming enterprises. In the 1970s and 1980s, the city of Nazarovo developed around the coal mine and the Nazarovskaya Thermal Power Plant. Energy-intensive industries appeared in the city and the number of jobs increased. During the economic downturn of the 1990s, some of the enterprises were shut down. During the same years, power plants in the European part of Russia that used Nazarovsky coal were gasified. Today, the plant consumes up to 95% of the coal of the Nazarovsky coal mine. Nazarovsky coal mine and Nazarovskaya Thermal Power Plant are city-forming enterprises [60]. The situation is similar in Sharypovo, the development of which is associated with the Berezovsky coal mine and Berezovskaya Thermal Power Plant. In 2017, the electric power industry produced more than 50% of the total output in the city [61]. For the population of such cities, changes in the structure of energy generation, namely the abandonment of the use of coal, can significantly affect living standards and increase migration outflows.

On the other hand, according to some estimates, the number of jobs per 1 mW of the used capacity of a solar power plant is 7.41 people per mW versus 1.01 person per mW for coal-fired generation. At the same time, in coal-fired power generation, jobs are created directly to support energy production, while in solar power, labor is needed for the construction, production, and installation of equipment. However, the high potential of renewable energy in the creation of new jobs in Siberia is leveled by a lack of industrial production of equipment for power plants on its territory [4].

The price of different types of fuel varies greatly (Figure 6). As coal is cheaper than gas, sometimes residents of gasified settlements continue to use other types of fuel [62].

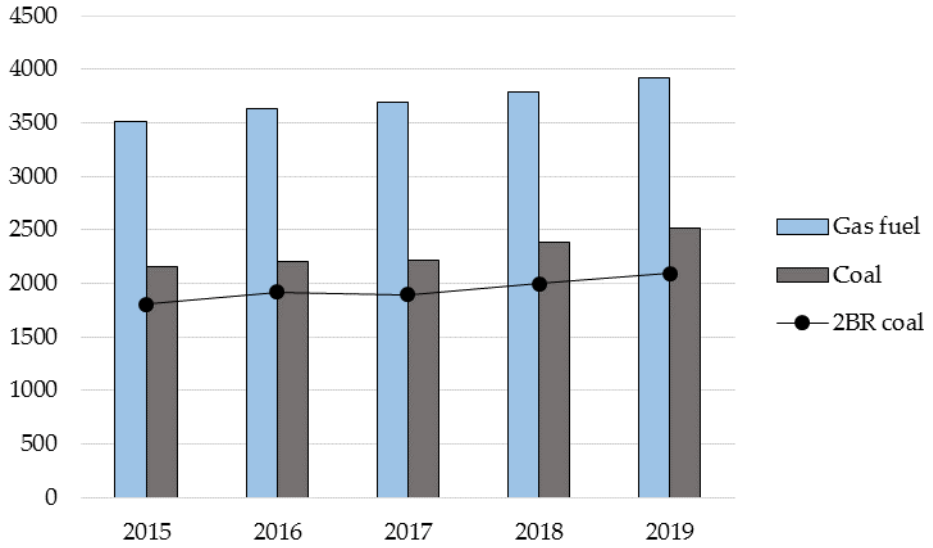


Figure 6. Prices for the main fuels for thermal power in Russian rubles per ton of fuel equivalent. Source: Informational and Analytical Report Heat Power and District Heating in Russia.

The possibility of the gasification of Yenisei, Siberia, is widely discussed. It is noted that the gasification of large energy facilities would require large expenditures to re-equip power plants and would increase the cost of generated energy. This will make gas more expensive than coal for the population. Therefore, the real need for gasification is estimated lower than the nominal one. At the same time, it is too expensive to gasify the domestic sector separately [62].

A change in the structure of fuel used is also possible in the private sector. An alternative to coal in Yenisei, Siberia, can be firewood, pellets, and electric heating. Table 8 shows the comparative characteristics of several types of fuel for autonomous heating sources. Of course, there are different brands of coal, types of wood, and pellets. For the calculation, the most popular options are chosen. Prices may also differ depending on the manufacturers and localities. The calculation uses the average prices of consumer goods in accordance with official statistics.

Table 8. Characteristics of fuel for individual heating. Source: Rosstat data.

Region	Fuel Type	Unit of Measure	Calorific Value, Kcal per Unit	Price, RUB per Unit	Unit Price, RUB per Kcal
Tyva Republic	2BR Coal	kg	4100	2.868	0.0007
Khakassia Republic				3.017	0.0007
Krasnoyarsk Krai				2.518	0.0006
Tyva Republic	Mixed firewood	kg	2600	2.260	0.0009
Khakassia Republic				1.709	0.0007
Krasnoyarsk Krai				3.489	0.0014
Tyva Republic	Pellets	kg	4100	6.400	0.0016
Khakassia Republic					0.0016
Krasnoyarsk Krai					0.0016
Tyva Republic	Electricity	kW per hour	864	3.650	0.0042
Khakassia Republic				2.360	0.0027
Krasnoyarsk Krai				2.830	0.0033

For all regions, coal is the cheapest fuel. Electric heating is much more expensive than alternatives. Using the example of several cities in the Krasnoyarsk region, we evaluated the additional costs that would arise in the case of switching from coal to pellets or electricity.

Cities were selected based on the availability of data on the number of individual heating sources that use coal. The calculation is made according to the following formula:

$$Total\ Cost = \Delta Price \times Hr \times k \times Sq \times Season \times Stoves, \quad (1)$$

where $\Delta Price$ is the difference in unit price compared to coal (Table 9).

Table 9. Calculation of the total cost of converting individual heating to more environmentally friendly fuels. Source: author's calculations.

City	Difference in Cost Compared to Coal, RUB per Kcal		Heating Rate, Gcal per One Square Meter of Total Living Space per Month	Additional Household Spending on Heating, RUB per Year	Stoves in the Private Sector are Counted, pcs	Total Cost of Switching to a more Environmentally Friendly Fuel, RUB One Million
Achinsk	Pellets Electricity	0.001 0.0027	0.0504	45,360 122,472	6361	288.5 779.0
Kansk	Pellets Electricity	0.001 0.0027	0.0494	44,460 120,042	7060	313.9 847.5
Minusinsk	Pellets Electricity	0.001 0.0027	0.0234	21,060 56,862	11,747	247.4 668.0
Nazarovo	Pellets Electricity	0.001 0.0027	0.0458	41,220 111,294	4480	184.7 498.6

Hr is the consumption rate of heating per 1 sq. m per month, established by order of the Ministry of Industry, Energy, Housing, and Communal Services of Krasnoyarsk krai. Standards differ depending on the year of the construction of the house, the material of the house, and the number of floors. The calculation takes into account single-story houses made of wood built before 1999 as the most popular category, where stove heating is used.

Moreover, *k* is a gcal to kcal conversion factor equal to 1,000,000.

Sq is the average area of the house, in the calculation taken as 100 square meters.

Season is the duration of the heating season (equal to 9 months).

Stoves is the number of stoves using coal.

Calculation results are presented in Table 9.

Monthly additional costs of households will be about 10% of average wages in urban areas in the case of pellets and up to 30% for electricity, not including the cost of modifying heating equipment. It is also worth noting the standard of living in Siberian regions: the level of poverty in the Tyva Republic is 31.7% and is one of the highest in Russia. In Khakassia and Krasnoyarsk Krai, the poverty level is much lower (18.5% and 17% respectively) but exceeds the average Russian level (12.1%) and varies significantly by territory. In this regard, the population of small towns would rather prefer the preservation of environmental problems than switch to heating from cleaner, but expensive sources on their own. Therefore, the rejection of coal is impossible without support from the government.

Pellets seem more promising for several reasons. First, the production of pellets in Russia is growing rapidly and needs sales markets. Secondly, most cities receive electricity from nearby thermal power plants, so switching to electric heating requires an increase in energy production, again at the expense of burning coal. Attaining electricity from hydroelectric power plants requires additional costs for power grids. Third, electric heating will result in higher costs for home heating system modifications compared to pellets.

State support for the use of pellets is possible in different ways: subsidies and tax incentives for producers to reduce the price of products or compensation of households for the purchase of pellet boilers and monthly heating costs. In Table 9, we estimated the amounts of annual subsidies in the case of compensation for additional costs of households associated with the transition from coal to pellets. The calculated subsidies will amount to

15–20% of own revenues of the budgets of cities, so funding must come from other levels of the budget system or as part of the national project "Ecology".

4. Conclusions

Energy generation in Yenisei, Siberia, includes hydroelectric power plants, which meet the needs of energy-intensive industries, and thermal power plants, which operate in cogeneration mode and provide energy to the population and industry of large cities. Renewable energy is underdeveloped because there are only a few solar plants. A large number of boilers of various capacities operate in the heating system. There is also a large segment of individual heating sources for the needs of the rural population and the private sector in cities.

A feature of the macro-region is the almost ubiquitous use of coal in both power plants and the private sector. This determines the significant contribution of the energy sector to emissions of pollutants, including greenhouse gases. Decentralized heating poses the greatest danger to the population because generation facilities are located inside residential buildings and affect the quality of the surface layer of the air. This is one of the factors of increased incidence of respiratory diseases among the population of Yenisei Siberian cities.

We have investigated the possibility of changing the structure of energy generation aimed at reducing coal, and the associated socio-economic effects of these changes. The directions of coal abandonment discussed in similar studies are not fully suitable for Yenisei, Siberia. Most of the studies discuss electricity generation, while in Yenisei, Siberia, most of the electricity is already generated by hydroelectric power plants that do not pollute the atmosphere. At the same time, more than 90% of their capacity covers the needs of energy-intensive industries, especially those placed close to a source of cheap and reliable energy. The exception is the Tyva Republic, which is energy deficient, receives power from the Krasnoyarsk krai and the Khakassia Republic, and uses diesel power plants in remote areas. For such areas, it is economically efficient to develop renewable energy in the form of solar power plants or small hydroelectric power plants. Replacing coal-fired generation with renewable energy is inexpedient because thermal power plants are included in the heat supply systems of cities.

Changes are possible in the structure of the fuel used. To date, the gasification of the regions of Yenisei, Siberia, is being discussed, but there is no adopted project. In addition, the abrupt abandonment of coal can be accompanied by negative economic consequences. Yenisei, Siberia, uses local coal; therefore, abandoning coal would lead to a loss of employment in the mining sector and an increase in energy tariffs. This will reduce the standard of living of the population, especially in cities that are closely linked to coal. Therefore, today, for Yenisei, Siberia, it seems more realistic to develop the energy sector, based on the preservation of coal generation. However, in order to minimize environmental risks, it is necessary to introduce the best technologies for coal combustion, install gas cleaning equipment, and continuously monitor emissions. These actions will lead to positive environmental and social effects of reduced emissions and improved quality of life.

Our calculations for the biggest cities of Krasnoyarsk Krai show that investments in the transition to heating with pellets will require RUB 184.7 million for Nazarovo and RUB 313.9 million for Kansk. At the same time, switching to electric heating is more than twice as expensive: RUB 498.6 million for Nazarovo and RUB 847.5 million for Kansk. The additional costs will range from RUB 21 to RUB 45.4 thousand per household per year for the pellet variant and from RUB 56.8 to RUB 122.5 thousand per year for electric heating, which could triple the annual heating costs. Thus, these options are unlikely to be implemented without direct state support.

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