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Costs of Coal Abatement for Residential Heating to Reduce Urban Air Pollution in Asian Russia: Evidence from Krasnoyarsk

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Abstract: Heat and electricity generation are major sources of air pollution in many large cities worldwide. In Siberian cities, the heat supply significantly contributes to air pollution, as coal remains the primary energy fuel in most of Asian Russia. Krasnoyarsk, the second-largest city in the macro-region by population, serves as a clear example of urban air pollution. In recent years, public authorities have implemented several measures to reduce pollutant emissions. These measures include modernizing thermal power stations, replacing inefficient small boiler houses, and converting residential heating to more environmentally friendly types of fuel. However, our analysis shows that these policies have not yet resulted in a significant transition away from using coal for heating. One of the primary reasons is that alternative fuels are unable to compete with coal in terms of price. The proposal suggests transitioning private households to pellet heating. Our goal is to evaluate the potential environmental and economic impacts of this measure. We estimate the necessary subsidy size for the successful implementation of both initiatives. In conclusion, converting households from coal to pellet heating can reduce the emissions of nitrogen oxides, carbon monoxide, sulfur oxides, and suspended particles by 0.2%, 8.5%, 4.4%, and 2.7%, respectively, of the total pollutant emissions in Krasnoyarsk. Furthermore, this conversion can provide economic benefits by supporting local pellet producers who heavily rely on export markets. If practically implemented, the proposed approach could solve one of the most significant development issues of one of the largest Russian cities within a few years, with only 2.5% of the annual city budget expenditure.

Keywords: urban air pollution; environmental policy; coal abatement; private households; stand-alone heating sources; wood pellets; Krasnoyarsk; Eastern Siberia

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1. Introduction

Many Russian cities are permanently affected by intense air pollution. Generational changes and a gradual increase in living standards are the main factors in the ever-increasing public demand for improved air quality. In the last decade, public policy has finally begun to respond to this critical challenge. In 2012, the launch of the national project "Ecology" marked the spending of up to USD 1.5 billion a year on various activities designed to address numerous nationwide environmental problems, including air pollution issues. Although some of the planned initiatives have been successful, high levels of pollution persist in many Russian regions.

One of the largest Siberian cities, Krasnoyarsk, is a clear example. Large industrial enterprises, a multi-hundred-thousand vehicle fleet, the hollow relief, decreasing wind speeds, and the ice-free Yenisei River in winter are the main factors determining the significant air pollution [1–3]. During periods of low wind speeds, pollutants accumulate in the surface air layer due to a combination of the air temperature, atmospheric pressure, wind

speed, and direction [4]. This leads to exceeding the maximum permissible concentrations of key pollutants: particulate matter, nitrogen oxides, formaldehyde, and benz(a)pyrene. Poor air quality becomes not only visually noticeable, but is also strongly experienced by many people as it leads to breathing difficulties. During such periods, official meteorological authorities declare a *regime of unfavorable meteorological conditions* (UMC, or *NMU*, in Russian). In addition to the discomfort, high concentrations of particulate matter and nitrogen dioxide increase the risk of respiratory diseases, while benz(a)pyrene has carcinogenic effects. In 2021, 35 UMC days were recorded in Krasnoyarsk. In 2022, the UMC periods lasted a total of 33 days, and, as of November 2023, the period had already lasted more than 51 days for the current year [5].

In terms of the volume of air pollutant emissions, the largest sources are energy and industrial facilities. The vast majority of energy for the city is generated by coal-fired combined heat and power plants (thermal power plants, TPPs), while one of the largest hydroelectric power plants in Russia, located 40 km away from the city, supplies mainly the Krasnoyarsk Aluminum Plant (part of United Company RUSAL). However, there is a minor source of energy supply that is also an important contributor to air pollution. The city, with almost four hundred years of history, retains a fairly large sector of private low-rise houses (the so-called *private sector*), mostly built of wood and heated by stand-alone stoves or boilers [6]. Thermal power plants and boiler houses produce about 26% of the pollutant emissions [6,7], while the share of stand-alone heating sources can reach 15% [8]. This estimate is the least accurate as it is based on many assumptions due to the lack of data on the number of heating devices, their technological characteristics, the fuels used, etc. The main fuel for all heat supply sources is coal. This circumstance is the most important factor in the environmental pollution, as coal combustion is accompanied by the emission of significant amounts of sulfur dioxide, nitrogen oxides, and particulate matter, which form smog and negatively impact public health. Therefore, the transition from coal to more environmentally friendly fuels is one of the strategies to mitigate the negative environmental impact of the energy sector. Analyzing the reduction of coal consumption at the local level is part of the global energy transition, which is driven by the need for low-carbon development throughout the world economy. Along with other goals to mitigate the effects of climate change, the need to reduce the production and use of coal, oil, and gas is undeniable [9]. Some studies, however, show the unevenness of the energy transition process according to the level of socio-economic development of the territories. In countries heavily dependent on coal, such as China, India, and South Africa, the abandonment of coal energy is leading to extremely sharp national declines. Thus, achieving the global goal of keeping temperature growth within 1.5 °C will require additional efforts, primarily from the countries of Europe and North America in the industrial and transport sectors [10]. Moreover, differences in the national energy policies' impacts are observed even at the regional level. For example, China's coal-to-gas (CTG) policy reduced the SO_2 and $PM_{2.5}$ levels in southern cities (by 5.9% and 1.2%, respectively) but had no significant impact on northern cities [11]. It has also been shown that replacing coal-fired combined heat and power with more environmentally friendly alternatives will lead to a disproportionate increase in residential heating costs, especially in poor areas, raising questions of the potential social risks and inequities in implementing coal abandonment strategies [12]. Such risks must be considered by local governments and decision makers when developing clean energy substitution policies that reduce coal consumption. It is also important to understand that, at the global scale, the energy transition efforts themselves may initially lead to a temporary increase in carbon emissions, since building and operating a low-carbon energy system itself will require energy, including energy derived from fossil fuels [13]. The opportunities and risks of such transition in Russia are widely discussed [14–17]. Coal is a designated fuel for Krasnoyarsk TPPs, which was determined by the city's proximity to a large coal deposit and the favorable thermotechnical properties of the implemented fuel grade [18]. It was estimated that the availability of tax benefits for the extraction and subsidies for the railroad delivery of coal make it a profitable source of energy, despite the

negative environmental consequences [19]. Accordingly, the conversion of TPPs to other energy sources is impossible.

The fuel type is not the only factor involved in the negative impact of heat production on the atmosphere. Pollutant emissions also depend on the types of heat supply sources and their technological characteristics. Thermal power plants use electrostatic precipitators to clean flue gases, which capture more than 99% of particulate matter [20]. At the same time, almost all boiler houses are not equipped with cleaning systems at all. In addition, thermal power plants have a higher combustion temperature of fuel, which also reduces the share of pollutants in emissions. The height of the gas flues of heat supply sources is of particular importance. The height of Krasnoyarsk's heat power plants' flues varies from 180 to 276 m, so, if a south-western wind direction prevails, the emissions from TPPs are blown outside the city limits [21]. Boiler house chimneys are much lower, ranging from 18 to 120 m (100 and 120 m at only one sole boiler house) and are located inside residential buildings. The height of stand-alone heating sources' chimneys is 2–3 m and they are scattered throughout the city. Consequently, it is emissions from small heat supply sources that have the most important impact on the formation of the large volume of air pollutants in the surface layer of the atmosphere of Krasnoyarsk.

The combustion of solid fuels used for residential heating and cooking is a cause of air pollution in populated areas in many countries around the world. Residential heating determines up to 20% of the particulate matter emissions in the world's cities [22]. Many countries have implemented policies to reduce emissions from stand-alone heating sources. The adoption of such policies is related to the increased interest in the environmental well-being of the population and the climate commitments of various countries. Public policy measures to reduce emissions from residential heating include [23]:

- national emission standardization and the certification of heating equipment;
- information and education activities aimed at informing the public about the state of the environment, the risk factors of using solid fuel and (or) inefficient equipment, new fuels and heating technologies, and government policies;
- direct bans on the use of certain fuels and (or) heating equipment;
- financial incentives to switch to more environmentally friendly fuels and replace the heating equipment. Usually, subsidies that fully or partially cover the costs of purchasing and installing new equipment, preferential tariffs for the use of new fuels, or tax incentives are applied. Such measures are the most widespread; equipment replacement programs exist almost in every European country and in some states of the USA, China, and Latin America.

The main goal of these policies is to reduce the emissions of particulate matter (PM2.5 and PM10), sulfur dioxide, carbon monoxide, and benz(a)pyrene. Flaga-Maryańczyk et al. emphasize that the best indicator of the environmental policies' effectiveness may be benz(a)pyrene, as its emissions are more related to residential heating [24]. Lopez-Aparicio et al. note the difficulty of estimating the actual effect of emission reductions directly from a heating replacement subsidy policy because of the presence of other environmental measures. These measures may be aimed at reducing emissions from other sources, such as transport, as well as using other instruments to change consumer behavior [25].

To estimate the economic and social efficiency of environmental policies, it is common to compare the costs of their implementation to the benefits of emission reductions and improved public health. Some studies note that giving consumers the option to choose heating equipment from several alternatives may result in the choice being not the best in terms of emission reductions. This leads to the inefficient use of policy funds [26].

When designing measures to reduce emissions from stand-alone heating sources, it should be considered that these tools are aimed at changing consumer behavior. Observations show that if it is possible to keep using old equipment or old fuel instead of replacing it, consumers will require some incentives. Violations of the rules of operation of new equipment are also observed. This is especially true for low-income populations [26]. Therefore, fuel substitution policies need to take into account the income inequality of the

population, as well as supply-side and price-supportive interventions at the end of the subsidy period [27].

Improving the environmental well-being of the population is an important challenge for Russia. At the same time, the problem of emission reductions from stand-alone heating sources is poorly covered in scientific publications and is rather a subject of political discussion. The country has a federal "Clean Air" project within the national "Ecology" project, which aims to reduce air emissions in the major industrial centers of the country. The key task of the project in 2023 was to switch private households from coal to gas. However, as Krasnoyarsk is a non-gasified region, other solutions are needed for the city. It should be noted that the possibility of regional gasification is being discussed [28,29]. In September 2023, the President of the Russian Federation publicly ensured the implementation of corresponding measures until 2028 [30]. However, the environmental problems of the city can and should be solved much faster. The environmental effects of replacing coal with coal briquettes and converting private households to electricity have previously been calculated for Krasnoyarsk, but these studies do not estimate the economic effect [31,32]. We are the first to discuss the possibilities of reducing emissions from stand-alone heating sources in Krasnoyarsk by heating with pellets. Moreover, we aim at assessing the potential environmental and economic effects of the proposed measures.

For this purpose, we firstly analyze data on the number of private households and their heating and emissions and explain why the current emission reduction policies have not led to the abandonment of coal for heating. Then, we provide justification for the use of pellet heating in Krasnoyarsk and estimate the environmental and economic effects of substituting coal with pellets to heat individual residential houses. In the Conclusions, we discuss the obtained results, including their limitations, and provide additional conditions necessary for the project to convert private households to more environmentally friendly fuels to be successful.

2. Materials and Methods

We start by collecting and analyzing data on the specifics of the heating of private houses in Krasnoyarsk. To collect data on the structure of the heat supply in Krasnoyarsk, we use the official Heat Supply Scheme. The map of the locations of private houses (Figure 1) is produced with QGIS 3.30.1—an open-source geographic information system (GIS). The open source basemaps used for the private sector's digitalization are from OpenStreetMap Standard and Google Satellite. The private household polygons of each district are manually drawn by visually evaluating and analyzing the city images from both maps. The areas of private houses differ significantly from other types of buildings and urban elements. Since no suitable instruments are found for this task, the polygons are drawn manually.

Then, we study coal phase-out projects in Krasnoyarsk. Data on previous experiments and the current policy on converting private households to environmentally friendly fuel are from official publications of the Government of Krasnoyarsk Krai. We apply content analysis techniques to the comments under corresponding news to assess the population's attitudes towards the policy activities. In addition, we conduct a series of in-person interviews with the residents of individual residential buildings to gather information about their heating arrangements. We further substantiate the feasibility of using pellets to heat private residences using data from similar studies and data from pellet producers.

The methodology for the assessment of the environmental impact of the conversion of private households from coal to pellets is based on the application of emission factors for pollutants typical for Krasnoyarsk. We use the European Environment Agency's emission factors [33]. A Tier 1 value is applied for coal, and a Tier 2 value is applied for pellets. Tier 1 takes into account only the fuel type and does not include the combustion technology. Tier 2 includes both the fuel and combustion technology. In Krasnoyarsk, the population can use various stoves and manual and automatic boilers of different capacities. Therefore,

we use Tier 1 to describe the initial situation. For the design option, we allow the use of Tier 2 because this option only involves burning pellets in a solid fuel boiler.

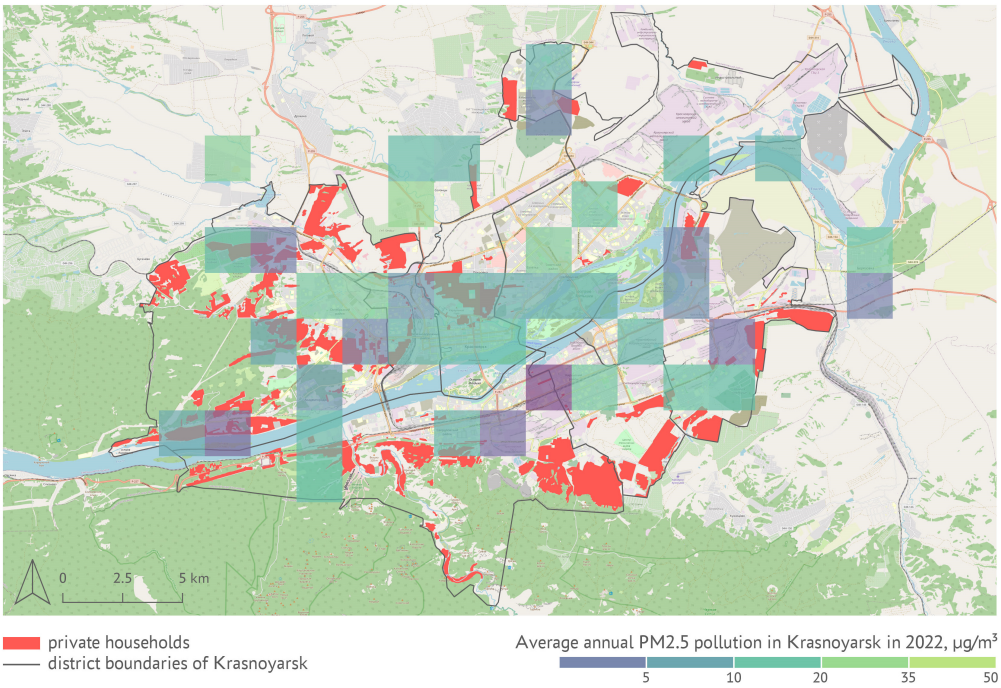


Figure 1. Locations of private households in Krasnoyarsk combined with spatially defined polygons of PM2.5 pollution observations. Source: elaborated by the authors using QGIS version 3.30.1, open access maps provided by OpenStreetMap Standard and Google Satellite. Air pollution data: Krasnoyarsk air monitoring system, http://air.krasn.ru (accessed on 10 December 2023).

3. Results

3.1. Coal Phase-Out Projects in the Private Sector in Krasnoyarsk

The private household sector of Krasnoyarsk is scattered throughout the city, across several small districts with individual low-rise, mainly wooden buildings. In Figure 1, we depict the spatial placement of the private households within the city. According to the Krasnoyarsk District Heating Scheme, there are 15,000 private houses, but detailed data on the distribution of houses by city district are available only for 10,183 houses [6]. Figure 2 illustrates cases of typical private houses in Krasnoyarsk.



Figure 2. Cases of typical private houses in Krasnoyarsk. Source: authors' photo.

We collect a database of independent heat supply sources describing 13,614 furnaces: 6566 coal and 7048 wood-burning. It can be assumed that the remaining houses (about

1400) are heated by other sources—electricity or liquefied gas. This coincides with the statement of the Siberian Generating Company indicating that coal and firewood are used to heat 88% of private houses [34].

The use of solid fuel and low-height chimneys, dispersed throughout the city, including the lowlands, causes smoke from stand-alone heating sources to accumulate in the surface air layer. Thus, the analysis of the pollutants' surface concentrations shows that stand-alone heating sources determine the exceedance of benz(a)pyrene standards across 24.2% of the city's territory, although their gross emissions are 70 kg per year against 1700–1900 kg of industrial emissions [32].

There have been several attempts to reduce coal consumption for the heating of private households in Krasnoyarsk over the period 2019–2022. In 2019, during the XXIX World Winter Universiade, the Siberian Coal Energy Company (SUEK) provided smokeless fuel (coal briquettes) to residents free of charge. Such briquettes are produced from brown coal through its deep processing; they have higher heat efficiency compared to coal and burn without smoke or soot formation [35]. As a result of laboratory measurements, it was found that burning smokeless briquettes significantly reduced the specific emissions of all key pollutants [32]. During the experiment, mobile laboratories recorded a two-fold decrease in the surface concentrations of carbon monoxide, nitrogen dioxide and nitrogen oxide, and suspended solids, and a four-fold decrease in benz(a)pyrene [36]. At present, this type of fuel is freely available, with discounted prices for the private sector. However, the authors' observations and available information suggest that there was no mass transition to this type of fuel after the end of the experiment.

Another experiment was launched by the Siberian Generating Company (SGC) in 2021. About 100 private households were switched to electric heating as part of the pilot project. The project involved reducing the electricity tariff for electric heating to a level at which the costs would be comparable to coal. As of December 2022, the project participants were compensated for two thirds of their costs: they paid 1 ruble per kWh within the established consumption norm, and 3.66 rubles per kWh if it was exceeded. The experiment showed that some project participants preferred not to pay for their electricity at the full tariff in case they exceeded the established norm, preferring to burn coal with the former heating equipment, since the dismantling of the old equipment was not a mandatory condition for participation in the experiment. In November 2021, the experiment was declared successful, and, during 2022, it was planned to convert around 3000 private households to electric heating [37], but this did not happen. In December 2022, the SGC again stated that the project was ready for widespread implementation, but the project would not offer discounts. In this case, consumers will pay for electricity at regular rates, and the cost of heating even within the normative limits will significantly exceed the cost of coal. At the same time, switching to electric heating has an obvious ecological effect, as there are no emissions when using an electric boiler. Obviously, the transition to electric heating implies an increase in the capacity of coal-fired thermal power plants, but TPP has significant advantages over small sources in terms of emissions. Modeling results show that if half of the households switch to electricity, the areas with a negative impact of pollutants in the surface air layer can be reduced close to zero [31].

The "Clean Air" project of the national "Ecology" project gave Krasnoyarsk new opportunities to solve the problem of reducing emissions from stand-alone heating sources. In 2019, the government approved the rules for the cities participating in this project [38]. The first version of the rules envisaged co-financing only for residential gasification projects, which was not suitable for Krasnoyarsk due to the lack of gasification in the region. In May 2022, the rules were supplemented with measures for the conversion of private households from coal or stove heating to gas, electric, or combined heating, including the purchase, installation, and mounting of in-house gas, electric or combined equipment, metering devices, and heating systems. Accordingly, since August 2022, the "comprehensive program for the conversion of private households from coal heating to more environmentally friendly types of heating, including electric heating" has been in effect in Krasnoyarsk. In July

2023, the rules were amended to allow federal co-financing of the purchase, installation, and mounting of solid fuel boilers with an automatic fuel supply, which have established environmental characteristics.

Thus, to date, under the program for the conversion of private households from coal heating to more environmentally friendly types of heating (hereinafter, the Program), Krasnoyarsk residents are able to switch from coal heating to one of the four options (Table 1). When choosing a heating option, the program finances the purchase and installation of expensive equipment at the expense of the budget, with further payment for heating at the expense of the homeowner. The planned amount of federal budget financing is 1725 million rubles for the period 2022–2024.

Table 1. Options for switching private households in Krasnoyarsk from coal heating to more environmentally friendly types of heating. Source: Ministry of Industry, Energy, Housing and Utilities of Krasnoyarsk Krai.

Heating Type	Budget Funding	Expected Heating Cost for a House with the Area of 100 sq. m per Month, Thousand Rubles	Additional Costs for the Homeowner
District heating	Construction and reconstruction of heat supply facilities, including heat pipelines, centralized hot water supply systems, individual facilities of such systems (up to the boundaries of the land plot of the homeowner)	4–5	Connection to the district heating system—from 500,000 to 900,000 rubles
Heating with liquefied petroleum gas	Purchase and installation of in-house gas equipment, metering devices, heating systems	8–10	None
Electric heating	Purchase, installation of in-house electrical equipment, heating systems	8–10	None
Coal heating	Purchase, installation of an automatic solid fuel boiler	2–3	None

The analysis of comments on the news about the Program [39,40], as well as personal conversations with the owners of private households, showed that the main argument against the phasing out of coal is the high price of alternative types of heating. The main argument in favor is the ease of use of the equipment. "*Electricity that saves our environment is not affordable for ordinary people. On the other hand, the maintenance of the electric boiler is much easier: my husband only needs to go and press one button*", says a pensioner, a participant in the experiment on the transition to electric heating. "*Everywhere is clean, no need to carry coal and pour out ash*", notes a resident who switched his home heating from coal to liquefied petroleum gas. In addition, many homeowners are unwilling or unable to reconstruct their homes or backyards. One homeowner notes, "*We would choose district heating, but we cannot spend 500–900 thousand rubles on it. Our plot is not suitable for liquefied petroleum gas, and the size of the boiler room is not suitable for an automatic coal boiler. We would choose electric heating, but it will be much more expensive than coal*". At the same time, this homeowner, like many others, does not link the city's environmental problems with stand-alone heating sources: "*The private sector used to be bigger, but they didn't talk about environmental problems*".

Thus, district heating and electric heating are the most promising in terms of reducing emissions, but are too expensive for the population. Without tariff compensation, these options are likely to be chosen by a small number of homeowners. As for liquefied gas, this option implies both high heating costs and the installation of equipment on the site, which is not always possible.

Obviously, coal is the cheapest fuel for the population. The use of a familiar fuel with more environmentally friendly heating equipment is often the most affordable transitional public policy option to reduce emissions from stand-alone heating sources. Studies show

that the emissions from an automatic coal-fired boiler can be lower than the emissions from stoves or manual boilers. It has been established that the optimization of the solid fuel combustion process, including its automatic feeding, reduces the emissions of suspended particles and polycyclic aromatic hydrocarbons, which include benz(a)pyrene [41]. Therefore, the installation of automatic solid fuel boilers is a compromise between environmental policy goals and a population that does not wish to pay extra heating costs.

Currently, wood pellets are one of the widely discussed types of more environmentally friendly fuel. In many countries, the installation of pellet boilers is included in emission reduction programs. In Russia, there are projects with their use at municipal boiler houses, and the creation of the domestic pellet market is supported by the state. In this regard, we consider it appropriate to examine pellet heating in more detail.

3.2. Pellet Market

In the last decade, the global pellet market has been growing rapidly: the production volume has increased from 27 million tons in 2015 to 41 million tons in 2020. Furthermore, 22 million tons of pellets were used to heat residential and commercial premises in 2020 [42]. The main consumers of pellets are European countries: the United Kingdom, Denmark, Italy, Germany, and the Netherlands. The increase in pellet consumption is associated with the policy of switching to more environmentally friendly fuels in order to reduce pollutant emissions and to fulfill public commitments under the climate agenda.

The volume of pellet production in Russia increased almost threefold over the same period, while up to 94% of pellets were exported [43], of which up to 90% were sent to European countries (Figure 3). After the ban on the import of Russian wood pellets to the European market, supplies to Asian countries were increased, but it was not possible to completely cover the lost export volume [44]. Redirecting trade flows from western markets to Southeast Asia is considered unprofitable due to the high costs of transportation and the relatively low price of the product. In this context, state support for timber companies includes compensation for the costs of transporting industrial products, and there are some reasons to believe that this subsidy will allow many producers to enter new markets [45]. However, to support pellet producers and to create a demand in the domestic market, it was proposed to use pellets as fuel for municipal boiler houses and stimulate their consumption by private households [46]. This decision may become the key in overcoming new forestry complex development restrictions for a few eastern and northwestern regions of the country [47]. Since the price of pellets has a high share of transportation costs, this type of fuel is most efficient to use near the production sites [48]. The biofuel market in Russia is highly concentrated, and the spatial distribution of production is very uneven [49].

In Russia, the objectives of the green economy transition strategy are directly linked to the goals of the modernization of production processes [50]. However, the assessment of Russia's bioenergy potential [51] shows that only 12% of this potential has been used as of 2017. Waste from forest products makes up 23% of the total bioenergy potential in Russia.

It is widely believed that one of the main advantages of pellets is their environmental friendliness and carbon neutrality: it is assumed that the carbon dioxide released during combustion is absorbed by trees during their lifetime [52]. However, increasing biomass consumption is causing combustion to occur at a faster rate than reforestation. Some recent studies show that the use of biomass is even more detrimental in reducing net greenhouse gas emissions than the use of fossil fuels [53]. In addition, the growing demand for biofuels means that not only sawmill waste but also round wood itself is now used for their production, which is in conflict with the original concept of the "cleanness" and "environmental friendliness" of pellets [44,54].

Pellets do have advantages over other types of solid fuel in terms of pollutant emissions that have a negative impact on public health. Various studies show that burning pellets instead of burning coal results in lower overall emissions of pollutants [55,56], including emissions of particulate matter and sulfur dioxide [57–59]; however, more nitrogen oxides may be formed [57,60]. Benzo(a)pyrene emissions can be either higher or lower

compared to coal, depending on the type of biomass and the type of heating equipment [61]. Emission parameters are influenced by a few factors: the characteristics of the fuel (types of wood, production technologies), the types of equipment—furnaces and boilers—and their technological characteristics and features.

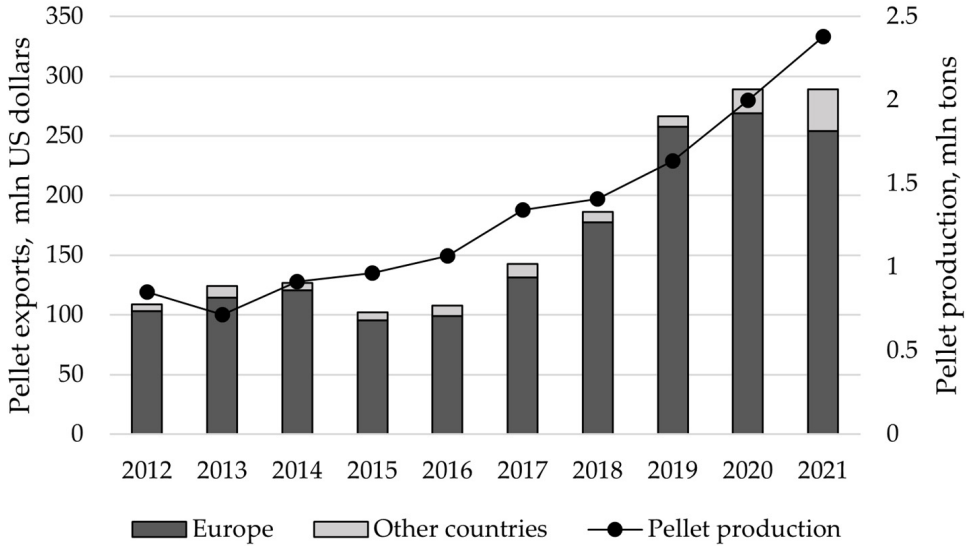


Figure 3. Pellet production and exports in Russia in 2012–2021. Source: Rosstat data, TradeMap data.

The use of wood pellets as an alternative energy source is considered very promising in European countries [62,63] and Southeast Asia [64,65]. A few studies have been devoted to a specific type of wood pellets—torrefied pellets [66,67]. Torrefaction involves the heat treatment of crushed raw materials at temperatures up to 300 °C. The pellets produced in this way have lower humidity and higher calorific value [67], although their price is not competitive due to the high capital costs of production [66]. Studies have been conducted to compare the efficiency of using various types of biofuels, e.g., wood chips, pellets, and coconut shells [68]. There is also such an alternative as the co-firing of coal with wood pellets [69–71], although its effectiveness and feasibility in Russia has yet to be assessed.

Thus, pellets produced from sawmill waste have significant advantages over coal in terms of environmental properties, as well as in the context of achieving low levels of greenhouse gas emissions. Pellet production should be stimulated by the state, especially for companies that have lost access to European markets.

3.3. Possibilities of Pellet Use in Krasnoyarsk

There are several large enterprises producing pellets concentrated in Krasnoyarsk Krai. One of them is a woodworking company, Enisey LLC (Enisey LLC), located in Berezovka, a suburb of Krasnoyarsk. The annual volume of pellet production was 80 thousand tons in 2018, and it was planned to increase the volume to 135 thousand tons by 2022 [72]. Therefore, heating private households with pellets can both improve the environmental situation and support local production by creating a domestic demand for its products.

To estimate the economic and environmental effects of converting private households to pellet heating, it is necessary to determine the number of houses where the equipment can be replaced. The number of private houses in Krasnoyarsk is estimated from 10 thousand to 13 thousand, according to several different sources. About half of them are heated with coal, while the rest use wood and other fuels. In this study, we estimate only the replacement of coal heating, so, for our calculations, the number of houses where the equipment will be replaced is assumed to be 6.5 thousand. At the same time, according to our estimates, Enisey LLC's annual pellet production volume is enough to heat about 9 thousand houses, i.e., there should be no fuel shortage.

The potential environmental effect of substituting coal with pellets is estimated based on emission factors from the Technical Guidance to Prepare National Emission Inventories of the European Environment Agency (Table 2). Emission factors are given for different fuels (Tier 1) and combustion technologies and fuels (Tier 2). We use Tier 1 for coal because there are no accurate data on the heating equipment characteristics used by the population, and we use Tier 2 for pellets because we propose to install automatic pellet boilers. Emission factors are presented for a larger list of pollutants including those typical for Krasnoyarsk (Table 2).

Table 2. Assessment of the potential environmental effect of substituting coal with pellets for heating of individual residential houses in Krasnoyarsk. Source: MEP/EEA air pollutant emission inventory guidebook 2019 [33]; Government Reports on the State and Protection of the Environment in Krasnoyarsk Krai in 2021 [7].

Pollutant	Emission Factor, g/GJ		Emission Reduction when Switching from Coal to Pellets, Tons (% of Total Pollutant Emissions in Krasnoyarsk)		
	Brown Coal	Wood Pellets	1000 Houses	3000 Houses	6500 Houses
Nitrogen oxides (NO_x)	110	80	4.8 (0.03)	14.5 (0.09)	31.5 (0.2)
Carbon monoxide (CO)	4600	300	695.1 (1.3)	2085.4 (3.9)	4518.4 (8.5)
Sulfur oxides (SO_x)	900	11	143.7 (0.7)	431.1 (2.0)	934.2 (4.4)
Total suspended particles (TSP)	444	62	61.8 (0.4)	185.3 (1.2)	401.4 (2.7)

The emission reduction when switching from coal to pellets is calculated according to the following equation:

$$Emission\ reduction = (EF_{coal} \times Heat \times Houses) - (EF_{pellets} \times Heat \times Houses) \quad (1)$$

where EF_{coal}, $EF_{pellets}$ are the emission factors, g/GJ.

Heat is the heating demand, GJ. The heating demand is determined for a conventional house of 100 square meters, based on the standard consumption of communal services for heating, established for Krasnoyarsk for one-story wooden houses built before 1999 [73]. In 2023, the demand was 4.29 gcal (17.96 GJ or 4.98 MW) per square meter per month or 161.6 GJ through the whole heating season, equal to 9 months.

Houses is number of houses that will switch from coal to pellets.

The emission factors for pellets are lower than those for coal for all pollutants considered, with the largest emission reductions for carbon monoxide and sulfur oxides. For nitrogen oxides and suspended particulate matter, there is no significant reduction in emissions at the city scale, but the reduction occurs in the surface air layer, which reduces the negative impact on public health. The presented results have significant limitations, as the emission factors are highly dependent on the fuel characteristics, heating equipment, combustion technologies, etc. Therefore, the most relevant estimates of emission factors can be obtained by the laboratory testing of the coal and pellet brands used in the cookers and boilers that will be used by the population.

The economic characteristics of the pellet heating option are estimated similarly to the options proposed by the Program (Table 3). The cost of heating is determined based on the price and the required volume of pellets, which in turn is calculated according to the following equation:

$$Required\ pellet\ volume = \frac{Heat}{Calorific\ value} \quad (2)$$

where *Heat* is the heating demand, MW. The demand for heating is defined as in the previous calculation (*Heat* in Equation (1)).

Table 3. Characteristics of the option of transferring private households in Krasnoyarsk from coal to pellets. Source: author's calculations.

Calorific Value, MW per Ton	Average Price, Thousand Rubles per Ton	Heating Demand for a House of 100 Square Meters per Month, MW	Estimated Cost of Heating a House of 100 Square Meters per Month, Thousand Rubles	Cost of Automatic Pellet Boiler, Thousand Rubles
4.6–5.2	6	4.98	5.8–6.5	180–205

Calorific value and *price* are given for pellets produced by Enisey LLC.

According to the assessment performed, pellet heating can compete on price with electric heating and liquefied petroleum gas heating, but, like other fuels, loses to coal. It is possible to create a demand for pellets by setting pellet prices comparable to coal prices for the population. For the producer, the price gap can be compensated for by subsidies from the budget. At the average cost of heating with pellets of 6.2 thousand rubles per month, and heating with coal of 2.5 thousand rubles per month, the amount of compensation for one house will be 3.7 thousand rubles per month. Table 4 shows the projected amount of subsidy throughout the whole heating season, equal to 9 months, for different numbers of private households.

Table 4. Projection of budget expenditure for the option of transferring private households in Krasnoyarsk from coal to pellets. Source: author's calculations.

Projection of Budget Expenditure, Million Rubles	1000 Houses	3000 Houses	6500 Houses
Subsidies to the pellet producer	33.3	99.9	216.5
Additional budget expenditure for purchase of new heating equipment (automatic pellet boilers)	205	615	1332.5

In the event that 6500 houses are switched from coal to pellets, the number of subsidies to compensate for the shortfall in income to the producer will amount to 216.5 million rubles per year (heating season). The maximum estimate assumes that all 6500 houses are technically capable of installing a pellet boiler. The technical feasibility study on the retrofitting of pellet fuel boilers requires data collection on individual households, which could be the subject of future studies. The projected additional budget expenditure includes costs for the purchase of new heating equipment (automatic pellet boilers). The boiler costs are given for two common models of automatic pellet boilers of the local trademark ZOTA with the capacity of 15 kW (Table 3). The upper limit of the boiler price is selected for calculation. In the case of 6.5 thousand houses, the additional budget expenditure will amount to 1332.5 million rubles for the whole period of the program. The operating life of the pellet boiler according to the manual is 10 years, and routine maintenance is mainly carried out independently, so the operating costs can be neglected. However, additional costs may be associated with educating the population on the correct operation of the equipment. All these amounts are comparable to the planned funding of the Program, which amounts to 1725 million rubles for 2022–2024.

4. Conclusions

Stand-alone heating sources make a significant contribution to the pollution of the surface air layer and negatively impact public health. In Krasnoyarsk, these effects are exacerbated by the use of coal and inefficient heating equipment, mainly stoves. Over 2019–2021, the city conducted several experiments to convert households to other fuels (coal briquettes and electricity), but they failed to achieve widespread adoption. Since

2022, Krasnoyarsk has received funding from the national project "Ecology" for the implementation of the city's program to transfer the heat supply for private households to more environmentally friendly fuels. Residents are asked to choose from four options: connection to district heating; the installation of equipment for heating with electricity or liquefied hydrocarbon gas; and heating with coal, provided that an automatic coal boiler with established environmental characteristics is installed.

We propose to consider one more alternative—the mass transition of private households to pellet boilers. According to our calculations, the ecological effect of transferring a number of houses from coal to pellet heating is a reduction in the emissions of nitrogen oxides, carbon monoxide, sulfur oxides, and suspended particles by 0.2%, 8.5%, 4.4%, and 2.7% of the total emissions of pollutants in Krasnoyarsk. The main factor determining the estimated emission reductions is the emission factors. As noted above, this is a significant limitation of the study, as emission factors are highly dependent on the fuel characteristics, heating equipment, combustion technologies, etc. Consequently, our results can be correctly compared only with those studies where the European Environment Agency emission factors are applied. At the same time, the emission reduction estimates that we obtained are adequate, which is confirmed by their percentage ratio to the total emissions in Krasnoyarsk.

Unlike other studies, in addition to assessing the environmental effects of substituting coal with pellets for the heating of individual residential houses, we estimated the costs of implementing this measure. To stimulate the demand for pellets, we propose the budget financing of pellet boiler installation, as well as the reduction of their prices to those comparable with coal. We also propose to compensate for the income loss to the pellet producers with subsidies from the budget. In the event that 6500 houses are switched from coal to pellets, the amount of subsidy required to compensate for the shortfall in income to the producer will amount to 216.5 million rubles per year (heating season). Additional budget expenditures for the purchase of new heating equipment (automatic pellet boilers) for 6.5 thousand houses will amount to 1332.5 million rubles for the whole period of the program. The costs of implementing these measures do not exceed the allocated funds from the "Clean Air" federal project.

Several other factors are to be considered when deciding to convert a private household to more environmentally friendly heating. If there is an approved policy for the development of an area with apartment buildings, there would be no benefit in investing in expensive and complex equipment that requires the rebuilding of the house and the site. The installation of an automatic pellet or coal boiler is the most suitable decision for such houses. Secondly, in Krasnoyarsk, some houses are dilapidated and are at risk of demolition. For this category of houses, it is possible to resume the provision of coal briquettes, which proved their effectiveness during the XXIX World Winter Universiade experiment. Since September 2023, three more cities in the Krasnoyarsk Krai have become participants in the "Clean Air" program: Achinsk, Lesosibirsk, and Minusinsk. These cities also have a large share of air pollution from stand-alone heating sources. Due to the lack of gasification, it can be assumed that Krasnoyarsk's experience will be useful for these cities. Pellet heating can be a good solution at least for Lesosibirsk, where large pellet production facilities are also located.

For the project to convert private households to more environmentally friendly fuels to be successful, several conditions are necessary. Firstly, high-quality preliminary work is needed to collect data on the number of residential buildings using stove heating, the types of fuel used, the characteristics of the installed heating equipment, and the possibility of using new equipment. Secondly, an information campaign about the possibilities of using different types of fuel and heating equipment is needed, potentially shifting the focus from solving the city's environmental problems to the ease of use of the new equipment and the positive effects on public health. Finally, along with the transition of private households to more environmentally friendly types of fuel, work in other areas of improving

the environmental situation in the city—such as reducing emissions from industry and transport—should not be slowed down.

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