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Opportunities for the Development and Management of Low-Carbon Energy Production in Russian District Heating Facilities Using Hydro-Steam Turbine Installations

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ABSTRACT

The growing global emphasis on climate change mitigation has intensified efforts to transition from carbon-intensive energy sources to sustainable, low-carbon alternatives. In this context, district heating facilities, particularly in regions like Russia, represent a key opportunity for reducing greenhouse gas emissions through innovative energy solutions. The paper reports on the results of studies exploring various avenues for a transition to a carbon-neutral economy, particularly in the Russian Federation. The research aims to develop a hydro-steam turbine installation for geothermal power plants and heating boilers to substantiate and create new energy production infrastructure. For this purpose, the authors identify the volume of the market for hydro-steam turbines for boiler houses required to predict the reduction of CO_2 emissions as a result of the application of the installations in Russia. Proceeding from the performed calculations, the paper offers an estimate of the decrease in CO_2 emissions due to the implementation of this innovation in Russia. The use of hydro-steam turbine installations in cogeneration schemes at heating plants will increase the reliability of power supply to district heating sources and reduce specific fuel consumption in the production of electricity. The total theoretical potential of greenhouse gas emission reduction due to the implementation of hydro-steam turbines in Russian boiler houses exceeds 500,000 tons CO_2 annually.

1. INTRODUCTION

The socioeconomic policies of countries that subscribe to sustainable development principles [1, 2] increasingly focus on reducing the influence of factors that affect global climate indicators [3, 4]. The set of physical parameters indicated by the World Meteorological Organization (WMO) [5] links changes in atmospheric composition to energy changes in the climate system and the response of land, ocean, and ice, and the published dynamics of global climate indicators provide an overview of changes in the climate system [6, 7]. These ideas together with the results of scientific research in recent decades suggest that the atmospheric concentration of three greenhouse gases – carbon dioxide, methane, and nitrous oxide – plays a significant role in the changes of the Earth's surface annual average temperature [5, 8, 9].

At present, numerous technologies are being developed and refined to create opportunities for the transition to a carbon-neutral economy [10-12]. Each country has its features in the development of technological opportunities for such a transition [13]. These features are linked to the country's climate, availability of fossil fuels, economic structure, energy development, etc. [14, 15]. Nevertheless, although, for example, green energy technologies are being developed to address complex social, political, and economic challenges, including the creation of technological opportunities for the transition to a carbon-neutral economy, their scaling within a single country, a group of countries, or across the entire planet must have an economic foundation [16-18]. The most obvious initial step in energy saving is the development of such technologically important areas as the conversion of thermal power plants to combined cycle plants, which will allow to cut the consumption of fuel and associated gases by 1.5 times or more [18-21]. It is possible to develop certain innovative directions that significantly improve the overall efficiency of electricity generation [22, 23]. This refers to the introduction of installations using secondary and low-potential heat: hydro-steam turbines (HSTs), cycles using organic heat carriers, expansion turbines, and cogeneration plants [24, 25]. Another promising trend in energy and power engineering is the use of metamaterials [26, 27] and surface modification technology for structural materials [28, 29], which significantly increase the efficiency and service life of fuel consuming devices.

Therefore, the transition to a carbon-neutral economy must be comprehensive and implemented through a combination of various technological and managerial solutions [30]. The transition may occur through intermediate stages, characterized by the large-scale use of efficient methods for electricity generation and conservation, leading to a reduction in greenhouse gas emissions [31].

Despite global advancements in low-carbon energy production, the Russian district heating system has been slow to adopt sustainable technologies, particularly in the context of integrating renewable energy sources with traditional heating infrastructures. The lack of efficient cogeneration systems in Russia's extensive boiler house network results in continued high emissions and fuel consumption. Taking into account Russia's climatic, economic, and other factors, one of the development directions in the transition to a carbon-neutral economy could be the enhancement of energy-saving processes through the development of infrastructure and changing the fuel mix in favor of low-carbon fuels, predominantly gas [32-34].

To address these challenges, the study investigates the following key research questions:

What is the potential for reducing CO_2 emissions in Russia's district heating facilities through the implementation of hydro-steam turbine installations?

How can the integration of hydro-steam turbines into heating systems enhance energy efficiency and fuel savings?

What are the technical and market barriers to scaling the adoption of hydro-steam turbines in Russia's existing heating infrastructure?

Based on this, in accordance with the priorities of Russia's Strategy for Social and Economic Development with Low Greenhouse Gas Emissions until 2050 [11], a hydro-steam turbine unit has been developed for geothermal power plants and heating boilers, adapted to modern Russian conditions.

The paper is organized as follows: Section 2 presents a review of the relevant literature, providing the background on global climate policies and technological advancements in low-carbon energy production. Section 3 describes the research methods used to assess the potential for hydro-steam turbine implementation in Russia's district heating systems. In Section 4, the research findings are discussed, including calculations related to CO_2 emission reductions and energy efficiency improvements. Section 5 concludes the paper by summarizing the key outcomes and offering recommendations for future research and policy implications.

2. BACKGROUND

Russia has many technologically backward industries, while the heating of buildings entails high energy costs due to the harsh climate and low energy efficiency of a large part of the housing stock [19]. In addition, the realization of the concept of the electric world in Russia, under which all basic energy needs are satisfied by carbon-free electricity, is practically unfeasible until 2060 for technological and economic reasons (Table 1) [19, 34].

At present, Russia retains huge potential for energy savings. The country's energy intensity based on GDP calculated by the purchasing power parity of ruble to dollar dropped by 2.7 times from 2000-2021. Despite this decrease, Russia was 1.7 times above the world average in 2021, overpowering Germany by 2.7 times, the USA – by 1.8 times, and China – by 1.2 times [35, 36].

According to Russia's 2021 National Inventory Report [37], the primary component of greenhouse gases in the country is CO_2, accounting for 79.2% of total emissions and 69.7% of net emissions. The second place is held by methane, making up 14.9% of total emissions and 21.5% of net emissions. The emissions of NO_2 and other greenhouse gases are less significant [37]. The contributions of the sources of CO_2 have been investigated as part of several research projects and summarized by Filippov [19] and the 2021 National Inventory Report [29].

Table 1. Greenhouse gas emissions from energy production and consumption in Russia, 2019, compiled based on data [19, 34]

Source of Emissions	Emissions in Energy Production and Consumption, Mt CO_2 (e)	Structure of Emissions in Energy Production and Consumption (%)	Share in Total Greenhouse Gas Emissions (Including Emissions from Non-Energy Processes) (%)**
1. Fuel combustion	1451.7	87.0	68.5
Fuel extraction and processing	64.3	3.9	3.0
Production of electricity and heat	752.9	45.1	35.5
Including: power plants	577.4	34.6	27.2
boiler houses	175.5	10.5	8.3
Construction and industry	161.7	9.7	7.7
Agriculture	15.8	1.0	0.7
Transport	246.8	14.8	11.6
Other sectors	24.9	1.5	1.2
Population	185.3	11.1	8.7
2. Fuel leakage and evaporation*	216.0	13.0	10.2
Total	1667.7	100.0	78.7

*Fuel leakage and evaporation during production, transportation, and consumption.

**The table does not include greenhouse gas emissions from non-energy processes, such as some industrial, chemical, agricultural, biochemical, and other processes, which account for 21.2% of total emissions.

As evidenced by Table 1, the leading source of greenhouse gas emissions in Russia is the production of electricity and thermal energy, which generates 35.5% of the overall emissions (including greenhouse gas emissions from non-energy processes). Specifically, power plants account for 27.2% and boiler houses for 8.3% of emissions. If we consider only the share of greenhouse gas emissions from energy production and consumption, the production of electricity and heat accounts for 45.1%, that is, almost half of the emissions.

Given the scale of the district heating infrastructure of Russia, the largest northern country, the use of HSTs operating in the cogeneration cycle in heating boilers can significantly reduce CO_2 emissions by substituting high carbon footprint electricity. Therefore, the aim of this study is to develop an HST unit for geothermal power plants and heating boilers to substantiate and create a new infrastructure for electricity generation.

2.1 Calculation of the potential capacity of HSTs for the Russian boiler house market

The unit capacity of an HST is determined by the electrical capacity of a standard electric generator driven by an HST. According to GOST 12139-84 (Russian Federation), the capacity of generators in the 10-150 kW range should correspond to one of the following values: 10, 15, 18.5, 22, 30, 37, 45, 55, 63, 75, 90, 110, 132, or 150 kW (the upper limit of the specified range was determined in view of the possibility of HSTs being installed on the limited area of the existing boiler houses). Based on the given estimates of minimum, maximum, and average HST capacities, the following unit capacities of the plants were accepted:

– for boiler houses with a capacity of 3 to 20 Gcal/h: 10, 22, 45, or 75 kW (the capacity of 22 kW is introduced to minimize the number of HSTs installed on a single object);

– For boiler houses with a capacity of 20 to 100 Gcal/h: 75 or 150 kW;

– For boiler houses with a capacity of more than 100 Gcal/h: 75 or 150 kW.

These calculations account for the following conditions:

– The scaling of the new technology will be limited to 10% of the total number of boiler houses, which will be the main outcome of the 1st stage of innovation implementation, after which conclusions can be drawn and the main results can be determined, including a real summary assessment of greenhouse gas emission reductions;

– The market is segmented by the installed capacity of boiler houses: from 3 to 20 Gcal/h, from 20 to 100 Gcal/h, and above 100 Gcal/h.

The performed studies of HST cycles established the specific electric power (net) of the turbine that can be generated per 1 kW of the boiler house's heat capacity, which amounts to 0.0035 kW (e)/kW (t).

The electric power of an HST is calculated using the formula:

$$NEHST = 1163\ nsp\ Qb \tag{1}$$

where, nsp = 0.0035 kW(e)/kW(t) is the specific electric power (net) of the turbine;

Qb is the heating capacity of the boiler house, Gcal/h.

Calculations according to Eq. (1) suggest the following HST capacity levels:

– 12-81 kW – For boiler houses with a capacity of 3 to 20 Gcal/h, average installed capacity of the HST – 46.5 kW;

– 81-230 kW – For boiler houses with a capacity of 20 to 100 Gcal/h, average installed capacity of the HST – 155.5 kW;

– For boiler houses with a capacity of over 100 Gcal/h, the average installed capacity of the HST – 230 kW.

3. METHODS

3.1 Assessment of potential opportunities and estimation of CO_2 emission reductions

To assess the reduction in CO_2 emissions resulting from the implementation of the innovation in Russia, a calculation was made, and a preliminary evaluation of the scale of the Russian market for hydro-steam turbines in heating boilers was conducted.

According to statistical data [38-40] in 2021, Russia had 391 cogeneration thermal power plants with a capacity of over 500 kW, and approximately 77.1 thousand heating boilers, including: 59.3 thousand with a capacity of up to 3 Gcal/h, 13.4 thousand with a capacity of 3 to 20 Gcal/h, and 4.3 thousand specialized gas heating boilers with a capacity of up to 0.001 Gcal/h, used by budget-funded organizations.

In centralized heating systems, besides thermal power plants, there were around 2.5 thousand boilers with a capacity of 20 to 100 Gcal/h and 626 boilers with a capacity of more than 100 Gcal/h. Since 2019, the Federal State Statistics Service (Rosstat) has separately accounted for cogeneration units, including those with a capacity of up to 25 thousand kW (227 units) and more than 25 thousand kW (164 units), as well as electric boilers and other installations (977 units).

The report [40] also provided data on the dynamics of the number of boilers with a capacity of 20–100 Gcal/h: since 2015, their number decreased by 212 units; at the same time, the number of boilers with a capacity of over 100 Gcal/h increased by 187 units, and the number of cogeneration units grew by 158 units.

It should be noted that the vast majority of boilers operate on gas, especially those with a capacity of over 20 Gcal/h, though coal also accounts for a significant share. The share of renewable energy sources and biofuels remains small. For example, the segments of liquid and transport biofuels, biogas-based electricity generation, and waste processing are statistically insignificant, and most of the solid biofuel produced (up to 90% of pellets) is exported abroad [41].

In conclusion, according to the data from the report [40], the total installed capacity of all heat energy sources in Russia in 2021 amounted to 856.4 thousand Gcal/h. The majority of this installed thermal capacity is accounted for by urban heating boilers, with 11.5 thousand Gcal/h, or about 50%, while thermal power plants contribute 1.2 thousand Gcal/h, or 11%.

3.2 Research subject and HST installation scheme

To achieve the set goal, based on the data on potential capabilities and the assessment of CO_2 emission reductions, we focused on justifying the efficiency of implementing hydro-steam turbines (HST) and geothermal power plants, as well as heating boilers. The basic installation scheme of the HST in a geothermal power plant was published in the study [38]. In geothermal fields, waste heat from GeoPP separators was used for electricity generation.

The reactive HST using hot water energy (Figure 1) designed as a Segner wheel is distinguished by a simple design and manufacturing process [12, 35].

Hot water, heated to 100-150°C, is fed to the center of the HST shaft, passing through radial channels to the Laval nozzles, where it boils and accelerates as it exits the expanded nozzle into a low-pressure environment. The flow of the mixture, with a mass flow rate of G and velocity W, creates a reactive force R=GW, which drives the generator's rotor, enabling the generation of electrical energy.

Figure 2 presents the proposed scheme of an HST installation for a heating boiler house as per the respective invention patent [39].

While geothermal plants use water from the steam separator as the working medium, in heating boilers, it is the hot water of the boiler circuit. At the turbine outlet, the steam-water mixture is separated in the separator into water and steam, which transfers its heat to the network water in the heat exchanger of the first heating stage.

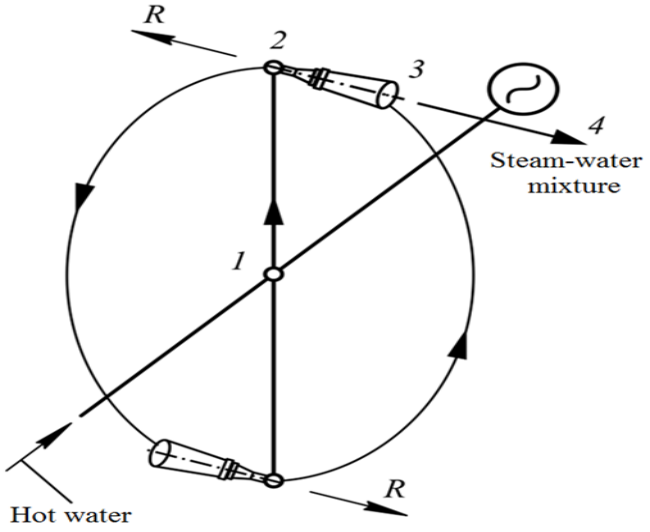

Figure 1. Principal scheme of HST operation

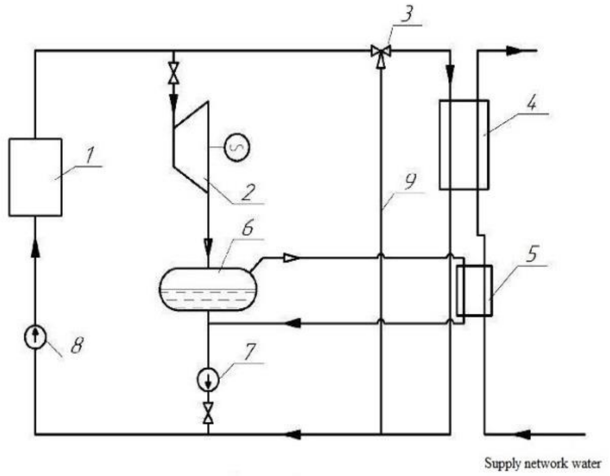

Figure 2. Principle scheme of an HST installation at a heating boiler house

Note: 1 – water boiler; 2 – HST; 3 – three-way valve; 4 – second stage heating heat exchanger; 5 – first stage heating heat exchanger; 6 – separator; 7 – condensate pump; 8 – boiler circuit pump; 9 – bypass pipeline.

3.2.1 Calculation of the potential capacity of HSTs for the Russian boiler house market

The unit capacity of an HST is determined by the electrical capacity of a standard electric generator driven by an HST. According to GOST 12139-84 (Russian Federation), the capacity of generators in the 10-150 kW range should correspond to one of the following values: 10, 15, 18.5, 22, 30, 37, 45, 55, 63, 75, 90, 110, 132, or 150 kW (the upper limit of the specified range was determined in view of the possibility of HSTs being installed on the limited area of the existing boiler houses). Based on the given estimates of minimum, maximum, and average HST capacities, the following unit capacities of the plants were accepted:

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– For boiler houses with a capacity of 20 to 100 Gcal/h: 75 or 150 kW;

– For boiler houses with a capacity of more than 100 Gcal/h: 75 or 150 kW.

These calculations account for the following conditions:

– The scaling of the new technology will be limited to 10% of the total number of boiler houses, which will be the main outcome of the 1st stage of innovation implementation, after which conclusions can be drawn and the main results can be determined, including a real summary assessment of greenhouse gas emission reductions;

– The market is segmented by the installed capacity of boiler houses: from 3 to 20 Gcal/h, from 20 to 100 Gcal/h, and above 100 Gcal/h.

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The electric power of an HST is calculated using Eq. (1).

Calculations according to Eq. (1) suggest the following HST capacity levels based on the goal of evenly distributing units of various capacities across Russia’s heating boilers (taking into account the distribution of boilers by thermal capacity):

– 12-81 kW – For boiler houses with a capacity of 3 to 20 Gcal/h, average installed capacity of the HST – 46.5 kW;

– 81-230 kW – For boiler houses with a capacity of 20 to 100 Gcal/h, average installed capacity of the HST – 155.5 kW;

– For boiler houses with a capacity of over 100 Gcal/h, the average installed capacity of the HST – 230 kW.

4. RESULTS

4.1 Total installed capacity of HSTs

The total potential installed capacity of an HST for the Russian market according to the presented calculations is reported in Table 2.

Table 2. Total installed capacity of HSTs for the Russian market

Boiler House Capacity (Gcal/h)	Number of Boiler Houses (pcs.)	Average Installed HST Capacity (kW)	Potential Installed HST Capacity (kW)
3-20	13,400	46.5	623,100
20-100	2,500	155.5	388,750
100 and above	626	230	143,980
	TOTAL:		1,155,830

4.2 Assessment of the total number of HSTs for the Russian market

For a preliminary assessment of the potential number of HSTs to be installed at facilities in Russia, we assume that units of different capacities are distributed evenly across boiler houses, considering the breakdown of the latter by thermal capacity. The results of our calculations are presented in Table 3.

Table 3. Distribution of units by boiler houses depending on the capacity of the latter

Boiler House Capacity (Gcal/h)	Number of Boiler Houses (pcs.)	HST Unit Capacity (kW)	Number of HSTs (pcs.)
3-20	13,400	10	3,350
		22	3,350
		45	3,350
		75	3,350
20-100	2,500	75	1,250
		150	1,250
> 100	626	75	313
		150	313

Table 4. Assessment of the required number of HSTs to service boiler houses

HST Unit Capacity (kW)	Number of HSTs (pcs.)	Share in Production Volume (%)
10	3,350	20.27
22	3,350	20.27
45	3,350	20.27
75	4,913	29.73
150	1,563	9.46
TOTAL:	16,506	100.00

Table 5. Target indicators of total HST production volume by 2030

HST Unit Capacity (kW)	Number of HSTs (pcs.)	Share in Production Volume (%)	Share in Total Sales (%)
10	335	20.27	3.89
22	335	20.27	8.56
45	335	20.27	17.51
75	491	29.73	42.80
150	156	9.46	27.23
TOTAL:	1,652	100.00	100.00

Proceeding from these calculations, Table 4 presents the preliminary assessment of the potential volume of production of HSTs.

The target benchmark for the HST project is to achieve a market share of 10% by the beginning of 2030, which will amount to more than 1,600 installed units. This can be considered as the first stage in reducing greenhouse gas emissions. To reiterate, 2030 is proclaimed in the Strategy of socioeconomic development of the Russian Federation with low greenhouse gas emissions (Low-Carbon Development Strategy) as the year when greenhouse gas emissions are expected to start to decrease [11]. The targets for total HST production volume by the start of the 2030s are provided in Table 5.

5. DISCUSSION

Based on the results of the study, we can draw several theoretical and practical conclusions. The theoretical conclusions, which we deem important to discuss, suggest that in order to achieve a reduction in CO_2 emissions, a comprehensive implementation of technological solutions is required. These actions need to be based on political, organizational and technological solutions to minimize the amount of greenhouse gases of anthropogenic origin [42]. Notwithstanding, the experience of countries, unions, and the global community demonstrates that a forced transition to carbon neutral economy may give rise to various socioeconomic problems, ranging from rising energy prices to problems in the energy supply of regions and even countries. This is especially evident in countries rich in fossil fuels, for which such a transition is not justified economically and cannot be realized by market methods, but can only be accomplished by state management, regulation, and harmonization methods. The Russian Federation is one of these countries [13, 43]. Filippov [19] provides the following list of possible modern technological directions for the decarbonization of the economy:

– Intensification of energy saving, including in energy production, conversion, transportation, and consumption;

– Changing the fuel mix in favor of low-carbon fuels by replacing coal with natural gas;

– Substitution of fossil fuels with carbon neutral biomass;

– CO_2 capture in power and industrial plants with subsequent transportation and disposal;

– Increased use of nuclear energy;

– Transition to carbon-free renewable energy resources.

The practical conclusions of our study were focused on answering the question of whether the use of hydro-steam turbines in Russian heating boilers can be considered effective. Based on the directions highlighted in the study, the approach to reducing CO_2 emissions that we chose as a focus of our research appears to have proven effective after the start of the application of HSTs in Russia. As a result of the use of HSTs in heating boiler plants, the electricity obtained from the external network will be substituted. In the unified power system of Central Russia, the average specific consumption of fuel equivalent amounts to 0.3 kg fuel equivalent/kW·h. A gas-fired power plant with the specified efficiency emits 0.473 kg CO_2/kW·h. The specific consumption of fuel equivalent additionally consumed by the boiler when an HST in cogeneration mode is included in its scheme is about 0.15 kg of fuel equivalent/kW·h. Thus, the substitution of grid electricity by HSTs results in a reduction of emissions reaching 0.237 kg CO_2/kW·h, or 58% of current levels. The equipment of 10% of the existing boiler houses with HSTs will enable the production of up to 240 ths. MWt·h of low-carbon energy annually, reducing CO_2 emissions by 55,700 t. The theoretical potential for emission reduction due to the introduction of HSTs in boiler plants in the Russian Federation is more than 500,000 t of CO_2 a year. The capital cost of HSTs is much lower than that of gas piston and turbine plants [38], as well as steam turbine plants [44] with water and organic working media.

The production and installation of HSTs in 10% of boiler houses will be the main outcome of the 1st stage of innovation implementation within the framework of the Low-Carbon Development Strategy [11]. The 1st stage will also yield a realistic assessment of greenhouse gas emission reductions at HST facilities, an assessment of further improvement of the technology, and a strategic assessment of further scale-up.

To minimize economic risks at the 1st stage, million-plus cities can be taken as potential regional markets for the primary promotion of HST; according to Rosstat, Russia has 15 million-strong cities [44].

6. CONCLUSIONS

Due to the fact that the main source of greenhouse gas emissions in Russia is the production of electricity and heat, creating 35.5% of total greenhouse gas emissions, an HST installation for geothermal power plants and heating boilers was developed. The method of electricity generation in HSTs consists in the use of hot water as a working medium of the cycle.

The total potential capacity of HSTs for the Russian market determined by the capacity of boiler houses was calculated totaling more than 1,150 MWt. The estimated potential number of HSTs that can be installed in facilities in the Russian Federation is more than 16,000 units. The target benchmark for the project of organizing HST production is to achieve a market share of 10% by the beginning of 2030, which is more than 1,600 HST units installed.

The equipment of 10% of the existing boiler houses with HSTs will enable the production of up to 240 ths. MWt·h of low-carbon energy a year, reducing CO_2 emissions by 55,700 t. The theoretical potential for emission reduction due to the introduction of HSTs in boiler plants in the Russia is more than 500,000 t of CO_2 a year. The production of HSTs and their installation at 10% of the country's boiler houses will be the outcome of the 1st stage of innovation introduction under the low-carbon development strategy. Another result of the 1st stage will be a realistic assessment of greenhouse gas emission reductions in facilities where the innovation will be implemented, an assessment of further improvement of the technology, and a strategic assessment of further scale-up.

Among the limitations of the obtained results, we should refer to the country's specifics, which should be considered when introducing HSTs. In the Russian Federation, like in other countries rich in fossil fuels, a forced transition to a carbon-neutral economy cannot be implemented using market methods. It can be achieved by means of state governance, regulation, and harmonization. Considering the climatic, economic, and other factors specific to Russia, one of the directions for the transition to a carbon-neutral economy is the development of processes to intensify energy saving through the development of infrastructure and change in the proportion of the currently used fuel types in favor of low-carbon fuels.

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