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The U-shaped relationship between low carbon goods trade and emission reductions: insights from Russian regions

ABSTRACT

Relevance. The global imperative for adopting a low-carbon economy resonates worldwide, yet comprehensive assessments specific to the Russian economy remain scant. This is especially important considering the significant differences in the level of transition to sustainable development among Russian regions.

Research Objective. This study aims to introduce a robust methodology for evaluating and analyzing the international trade of low-carbon goods (LCGs) across various Russian regions and assessing its effects on fuel combustion emissions.

Data and Methods. Data on LCGs trade were obtained from the Federal Customs Service of Russia. In conjunction, datasets from Rosstat and the Central Bank of Russia were incorporated for comprehensive econometric modeling. The analytical framework employed Tobit and quantile regressions.

Results. The study uncovers significant disparities among Russian regions regarding the intensity of low-carbon goods exports and imports. This variation highlights the diverse competencies in LCGs production, as well as differing ecological agendas and consumption patterns across regions. Additionally, the research demonstrates that, although the widespread adoption of advanced production technologies is positively correlated with increased fuel combustion emissions, a U-shaped relationship exists where higher LCGs exports are associated with reductions in fuel combustion emissions across Russian regions to a certain degree.

Conclusions. This research highlights important implications for both federal and regional industrial and environmental policies. It advocates for the development of targeted incentives that encourage the adoption of low-carbon goods (LCGs) and advanced technologies. By doing so, policymakers can effectively promote sustainable development tailored to the unique needs and conditions of various regions, thereby fostering ecological resilience and economic growth across diverse regional landscapes.

KEYWORDS

low carbon goods (LCGs), export of Russian regions, import of Russian regions, fuel combustion emissions, advanced manufacturing technologies, Russian regions, regional disparities, regional development, International trade

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U-образная взаимосвязь между торговлей товарами с низко углеродными технологями и сокращением выбросов: выводы по регионам России

АННОТАЦИЯ

Актуальность. Глобальная необходимость перехода к низкоуглеродной экономике охватывает весь мир, однако комплексные оценки, специфичные для российской экономики, остаются редкими. Это особенно важно с учетом значительных различий в уровне перехода к устойчивому развитию среди российских регионов.

Цель исследования. Данное исследование направлено на разработку методики для оценки и анализа международной торговли товарами с низкоуглеродными технологиями (ТНУТ) в различных регионах России и оценку ее влияния на выбросы при сжигании топлива.

Данные и методы. Данные о торговле ТНУТ были получены на основе данных Федеральной таможенной службы России. В дополнение были использованы наборы данных Росстата и Центрального банка России для проведения комплексного эконометрического моделирования. В аналитической модели использован регрессионый анализ с применением Тобит и квантильных оценок.

Результаты. Исследование выявило значительные различия между регионами России по интенсивности экспорта и импорта товаров с низко углеродными технологиями. Это различие подчеркивает разнообразные компетенции в производстве ТНУТ, а также различие в экологических повестках и потребительских предпочтениях регионов. Кроме того, результаты показывают, что, хотя широкое внедрение низко углеродных технологий положительно коррелирует с увеличением выбросов при сжигании топлива, существует U-образная взаимосвязь, при которой увеличение экспорта ТНУТ связано с сокращением выбросов топлива в российских регионах только до определенной степени.

Выводы. Исследование обсуждает следствия для федеральной и региональной промышленной и экологической политики. Обсуждается необходимость разработки целевых стимулов, которые способствуют внедрению товаров с низко углеродными технологиями. Политика может эффективно содействовать устойчивому развитию, адаптированному к уникальным потребностям и условиям различных регионов, что будет способствовать экологической устойчивости и экономическому росту в разных региональных ландшафтах.

КЛЮЧЕВЫЕ СЛОВА
товары с низко углеродными технологиями, экспорт регионов России, импорт регионов России, выбросы при сжигании топлива, передовые производственные технологии, российские регионы, региональные диспропорции, региональное развитие, международная торговля

БЛАГОДАРНОСТИ
Исследование выполнено в рамках проекта «Зеркальные лаборатории» НИУ «Высшая школа экономики» по теме «Трансформации цепочек создания стоимости угольной отрасли и связанных с ней отраслей в условиях глобального энергоперехода и санкционного давления на российскую экономику» (Соглашение № 6.13.1-02/210723–1 от 21.07.2023 г.).

ДЛЯ ЦИТИРОВАНИЯ
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采用低碳技术的货物贸易与减排之间的 U 型关系：俄罗斯地区的研究结果

摘要
现实性：全球都需要向低碳经济转型，但专门针对俄罗斯经济的全面评估仍然很少见。鉴于俄罗斯各地区在可持续发展转型水平方面存在巨大差异，这一点尤为重要。
研究目**标：**本研究旨在开发一种方法，用于评估和分析在国际贸易中，俄罗斯不同地区的低碳技术产品特点，并评估其对燃料燃烧排放的影响。
数据与方法：低碳技术产品贸易数据来自俄罗斯联邦海关总署。此外，俄罗斯国家统计局和俄罗斯中央银行的数据也被用于进行复杂的计量经济学建模。分析模型采用了带有Tobit和量化估计的回归分析。
研究**结果：**研究显示，俄罗斯各地区在低碳技术产品的进出口强度方面存在显著差异。这种差异显示出各地区在低碳技术生产能力方面、环境议程和消费者偏好方面的不同。此外，研究结果表明，虽然低碳技术的广泛应用与燃料燃烧排放的增加呈正相关，但在俄罗斯各地区，低碳技术产品出口的增加与燃料排放的减少在一定程度上呈“U”型关系。
结论：该研究讨论了联邦和地区工业及环境政策的影响。它讨论了制定有针对性的激励措施来促进低碳产品的必要性。政策可以有效地促进符合不同地区独特需求和条件的可持续发展，从而在不同地区促进环境可持续性和经济增长。

关键词
低碳产品、俄罗斯的地区出口、俄罗斯的地区进口、燃料燃烧产生的排放、先进制造技术、俄罗斯地区、地区差距、地区发展、国际贸易

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Introduction

Over the past decade, there has been a significant increase in interest in analyzing the production and use of goods within the low-carbon economy. This surge is linked to the growing frequency and severity of environmental disasters and the challenges associated with meeting the United Nations Sustainable Development Goals. Despite the increasing interest and urgency, the development of green technologies is constrained by uncertainties related to climate change, technological advancements, and environmental policies (Haas et al., 2023; Knutti et al., 2010; Stern, 2016; Way et al., 2022; Portansky, 2014).

Interestingly, over the last twenty years, the share of green and renewable products in total trade volume has not increased (Mealy, Teytelboym, 2022). One reason is that many green and renewable energy products, while offering significant advantages over traditional technologies, also come with certain drawbacks.

Low-carbon technologies offer significant advantages, primarily due to their lower emissions intensity compared to carbon-intensive alternatives. For instance, solar and wind power plants emit minimal CO2 during operation, contrasting sharply with coal-fired plants. Despite considerations like production and disposal, renewable energy equipment maintains a lower CO2 footprint per unit of energy produced. These technologies are versatile across sectors (Berger et al., 2020; Gerres et al., 2019), encompassing applications from electric vehicles in transportation to solar panels and wind turbines in energy, and low-emission processes in manufacturing. This diversity necessitates tailored technological advancements suited to specific industrial and regional contexts. Another advantage is their knowledge spillover effect, fostering broader dissemination of clean technology knowledge (Dechezleprêtre et al., 2017). Yet, challenges persist. Implementing these technologies demands technical and economic sophistication, such as developing efficient energy storage and transmission systems (Mealy, Teytelboym, 2022). Initial high costs also hinder adoption, despite potential long-term economic benefits (Jaffe, Stavins, 1995; Ivanova et al., 2022).

Resistance from vested interests in carbon-intensive sectors complicates adoption (Fedyunina, Simachev, 2024). Moreover, infrastructure gaps and resource availability, like sunlight and wind, influence technology deployment. Successful adoption hinges on supportive government

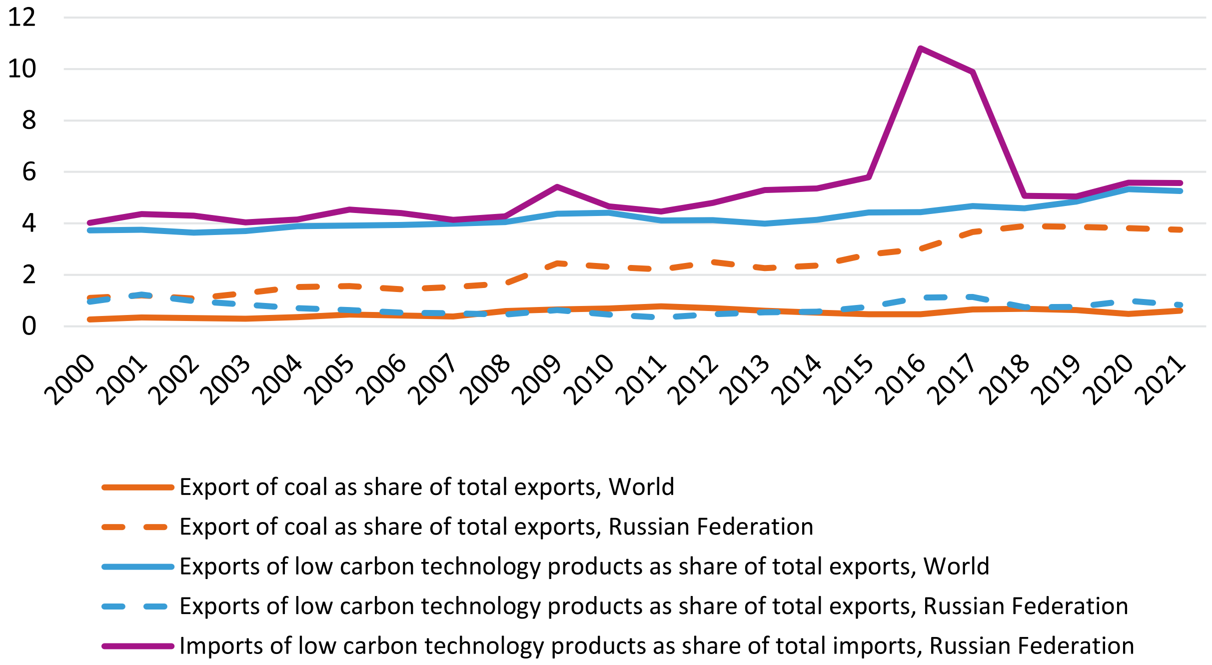

Figure 1. *Share of Coal and LCGs in Global Exports, 2000–2021*

Source: Compiled by the authors based on the International Monetary Fund. 2022.Climate Change Indicators Dashboard. Retrieved from https://climatedata.imf.org/pages/access-data (05.05.2024).

policies (Kazantseva, 2020; Popadko, Naidenova, 2020), which may include tax breaks and tariff incentives to encourage investment in renewable energy.

In conclusion, while low-carbon technologies offer substantial benefits, their widespread adoption requires overcoming technical, economic, and policy barriers in a complex socio-economic landscape (Acemoglu et al., 2016; Aghion et al., 2016). In summary, while low-carbon technologies offer numerous advantages and are essential for a sustainable future, their adoption is fraught with complexities and challenges that require coordinated efforts in policy, infrastructure, and technological innovation. The ambiguity and high level of debate surrounding the adoption of low-carbon technologies is particularly evident in the assessment of the share of low-carbon goods (LCGs) in global trade[1]. The share of LCGs in global exports increased from 3.7% in 2000 to 5.3% in 2021, with an average annual growth rate of less than 2% over this period. During the same period, the share of international coal trade also grew, effectively doubling to 0.6% of global trade by 2021 (Figure 1). Indeed, despite the currently emerging paradigm of a carbon-free energy development concept, the coal industry has all the necessary prospects for development (Nikitenko et al., 2023).

The situation regarding the spread of LCGs in the global economy is similarly complex for Russia. Over the period from 2000 to 2021, Russia has not managed to significantly increase its LCG exports, with their share in Russian exports remaining just below 1%. However, the country has been able to increase its LCG imports, with their share in gross imports rising from 4% in 2000 to 5.6% by 2021, even surpassing 10% in 2016–2017 (see Figure 1). This trend reflects recent expert analyses, which indicate that the low-carbon economy agenda has only recently begun to develop in Russia. While integrating into global technological chains in this field shows great promise, the scale of implementing low-carbon technologies within the country, although highly relevant, remains modest (Bashmakov, 2019; Bashmakov, 2020; Popova, Kolmar, 2023).

Russian regions vary significantly in the structure and efficiency of their regional energy systems, as well as in their methods for reducing pollutants (Khrustalev, Ratner, 2015). Reducing the

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[1] In this study, we define low carbon goods as products that produce less pollution than their traditional energy counterparts and will play a vital role in the transition to a low carbon economy similar to (Pienknagura, 2024).

negative environmental impact of the economy is a challenge that involves not only investment and technology but also methodological approaches. When developing economic projects for different territories, decision-makers must consider the diverse social, environmental, and economic effects (Ratner, 2016). Additionally, there is still considerable uncertainty regarding the data available for assessing the production and use of LCGs in Russian regions.

In light of the above, we believe it is crucial to continue research focused on the heterogeneity of sustainable development across Russian regions. To achieve this, we propose to examine these issues from a fresh perspective. Our goal is to expand the understanding of indicators related to the sustainable development of Russian regions and assess how they are linked to the reduction of fuel combustion emissions. Our main hypothesis is that the relationship between sustainable development and emission reduction may be nonlinear in Russian regions due to significant differences in accumulated competencies in sustainable development and a high level of regional disparities.

We introduce a novel methodology and, to the best of our knowledge, evaluate the trade of Russian regions in low-carbon goods (LCGs) for the first time. This approach can serve as a new indicator for measuring sustainable development in these regions. The findings obtained enhance and broaden the existing understanding of the disparities in production competencies and demand for sustainable development goods among Russian regions. Furthermore, we employ Tobit and quantile regression techniques to assess the role of LCGs trade in reducing CO2 emissions and identify a non-linear relationship between LCGs trade and emissions. This analysis allows us to derive implications for industrial policy at both the regional and federal levels.

This study expands on existing research in two main areas. First, we propose a methodology and present the results of assessing international trade in LCGs by Russian regions from 2016 to 2021. These assessments allow us to identify the goods that hold the largest share in Russia's gross exports and imports of LCGs. We discuss the intensity of LCG exports and imports across Russian regions and highlight significant differences between various federal districts and regions. Second, we assess the role of LCG exports and imports in reducing carbon dioxide emissions from fuel combustion, demonstrating that regional competencies in LCG production positively are positively related to the reduction of these emissions.

The paper is structured as follows. Section 2 presents our methodology for assessing international trade in LCGs for Russian regions, discusses the results obtained, and introduces the data and methods used for econometric modeling. Section 3 presents the results of the econometric assessment of the role of international trade in LCGs in Russian regions in reducing carbon dioxide emissions from fuel combustion. Finally, Section 4 discusses the findings, limitations, and directions for future research.

Theoretical basis

Our analysis draws on several key theoretical frameworks in environmental economics and regional development. Central to our approach is the Environmental Kuznets Curve (EKC) hypothesis, which posits an inverted U-shaped relationship between economic growth and environmental degradation (Grossman, Krueger, 1995). According to this theory, as regions undergo economic expansion, environmental conditions initially deteriorate due to increased industrial activity and energy consumption but improve over time as economies mature and adopt cleaner technologies. The EKC has attracted significant attention from researchers and has been empirically validated in numerous studies across different regions and countries (Bibi & Jamil, 2021; Dogan, Inglesi-Lotz, 2020; Mahmood et al., 2023). This hypothesis has also been confirmed in studies of the Russian economy and its regions (Mariev et al., 2020; Ketenci, 2018; Shkiperova, 2013), providing robust evidence of the U-shaped relationship between economic growth and emissions in Russia.

Additionally, we consider the role of foreign direct investment (FDI), drawing on the pollution haven hypothesis (Cole, 2004; Gill et al., 2018) and pollution halo hypothesis (Abid, Sekrafi, 2021; Zarsky, 1999), which explore how FDI can either increase emissions in regions with lax environmental regulations or contribute to emissions reductions through technology transfer and innovation. To capture the technological dimension, we include the number of advanced manufacturing technologies utilized, aligning with the Porter Hypothesis (Porter, van der Linde, 1995), which suggests that environmental regulations can drive innovation and resource efficiency. Furthermore, urbanization is factored into our model, as densely populated regions often exhibit higher energy consumption and emissions, though they may also benefit from cleaner infrastructure and governance systems as they develop (York, Rosa, & Dietz, 2003). Finally, by incorporating trade in low carbon goods (LCGs), we align with the trade and environment nexus, which examines how trade can influence emissions through both the scale and technique effects (Copeland, Taylor, 2004). These theoretical foundations provide a comprehensive basis for understanding the environmental impacts of LCGs trade across Russian regions.

Methods and data

Method of estimation of trade in LCGs in Russian regions

Defining which products fall under the category of low-carbon goods (LCGs) is a complex task (Pigato et al., 2020). This complexity was notably highlighted by the failure of the WTO Environmental Goods Agreement negotiations in late 2016, where negotiators could not agree on competing lists of low-carbon goods (De Melo and Solleder, 2019). Despite the lack of consensus on an official list of LCGs, recent work by Pigato et al. (2020) proposes utilizing three distinct and widely recognized lists compiled by various stakeholders: the World Bank, the Asia-Pacific Economic Cooperation (APEC) multilateral forum, and academic researchers (Glachant et al., 2013).

In this study, we adopt the approach of Pigato et al. (2020) to identify low-carbon goods. Using the commodity classification of the EAEU HS, we are able to identify 105 LCGs. These LCGs encompass a range of non-raw material, non-energy goods at various stages of production, predominantly at the advanced stages. Specifically, 96 out of the 105 goods fall into the category of high-end products, 8 are classified as intermediate products, and 1 is categorized as a basic product.

By focusing on these classifications, our research aims to provide a clear framework for identifying and analyzing low-carbon goods within the broader context of global trade and economic policy.

Trade in LCGs in Russian regions

For this study, using data from the Russian Federal Customs Service (FCS) for each federal subject of Russia over the period from 2016 to 2021 (based on the availability of FCS data), we assessed the volumes of LCG exports and imports for each region. Additionally, we calculated relative indicators that reflect the proportion of LCG trade to overall trade and the Gross Regional Product (GRP) of the regions.

According to our estimation methodology, the commodity structure of Russian LCGs exports is diversified, with the top three positions holding relatively small shares. These are Heat exchange units, whether or not electrically heated (2.1% of Russia's gross exports from 2016-2021), Measuring/checking instruments, apparatus, and machines (1.6%), and Boards, panels, consoles, desks, cabinets, and other bases for electric control or distribution of electricity (1.5%). All these categories are crucial for low carbon economy.

Heat exchange units, whether or not electrically heated, are essential for energy-efficient heating and cooling systems, such as heat pumps and waste heat recovery systems. By reducing energy consumption and emissions, these exports significantly contribute to Russia's global efforts in promoting sustainable energy practices and reflect the presence of domestically competitive products in this category on the global market. Measuring/checking instruments, apparatus, and machines play a critical role in monitoring and optimizing the performance of various low carbon technologies. They are indispensable for renewable energy installations, smart grids, and energy-efficient processes, providing accurate data crucial for enhancing operational efficiency and mitigating environmental impacts. Lastly, Boards, panels, consoles, desks, cabinets, and other bases for electric control or distribution of electricity are vital for managing and optimizing electricity distribution within renewable energy systems like solar and wind power. They also support smart grids and energy storage systems, thereby improving the efficiency and reliability of low carbon energy solutions.

The list of the top 10 LCGs by share in Russia's gross exports according to our methodology is provided in Appendix 1. Overall, this table highlights Russia's export strengths in essential components and technologies that play a foundational role in global low carbon initiatives.

Top 3 positions in Russia's LCGs import structure from 2016 to 2021 include Machinery for liquefying air or other gases (15.3% share of

Table 1

Contribution of LCGs as a Percentage of Gross Exports, Imports, and GRP in Russian regions, Average for 2016–2021

Federal District	LCG Exports (% of Gross Exports)	LCG Exports (% of GRP)	LCG Imports (% of Gross Imports)	LCG Imports (% of GRP)
Ural Federal District	3.238	0.194	0.137	0.023
Southern Federal District	2.162	0.059	0.379	0.041
Siberian Federal District	2.103	0.254	0.050	0.007
Northwestern Federal District	2.074	0.314	0.095	0.005
Volga Federal District	0.914	0.094	0.586	0.030
Central Federal District	0.615	0.013	1.105	0.054
North Caucasian Federal District	0.510	0.126	0.552	0.022
Far Eastern Federal District	0.153	0.046	1.555	0.147
Russian regions (average)	1.467	0.153	0.511	0.039
Russian regions (minimum)	0.000	0.000	0.000	0.000
Russian regions (maximum)	20.204	3.385	13.357	1.912
Russian regions (median)	0.553	0.063	0.052	0.004

Source: Authors' calculations

total imports), Electrical control and distribution apparatus (9.0% share), and other machines and mechanical appliances (7.9% share). These categories play a crucial role in advancing Russia's transition to low carbon technologies. Machinery for liquefying air or other gases supports critical air separation processes essential for renewable energy production and carbon capture technologies. Its significant import share underscores Russia's dependence on this advanced equipment to enhance sustainable energy capabilities. Electrical control and distribution apparatus are essential for efficiently managing electricity in renewable energy systems, such as solar and wind technologies. Their substantial import share highlights their role in improving reliability and efficiency within Russia's evolving low carbon infrastructure. Lastly, other machines and mechanical appliances are vital for manufacturing components used in renewable energy technologies, including electric motors for wind turbines and batteries for electric vehicles. This category's import share emphasizes its pivotal contribution to Russia's efforts in developing and manufacturing low carbon solutions. For a detailed list of the top 10 largest positions in Russia's LCGs import, please refer to Appendix 2.

The obtained estimates of LCGs exports and imports in Russian regions align with previous observations (Khrustalev, Ratner, 2015) regarding significant differences between Russian territories. Specifically, we find that the share of LCGs exports in gross exports is highest in industrially developed regions. At the federal district level, the Ural Federal District leads in this indicator, with LCG exports constituting 3.2% of gross exports. The Siberian Federal District and the Southern Federal District follow closely, with high intensities of 2.1–2.2%. The development of their own production capacities, as confirmed by export intensity, has led to a relatively low contribution of LCG imports to gross imports in these federal districts (Table 1).

Although the obtained estimates do not directly measure the volumes of production and consumption of low carbon goods (LCGs) across Russian regions, they provide valuable insights. On one hand, export data can be used to assess the presence of competitive production capacities for LCGs, which, through external effects, can promote greater consumption of LCGs within the same region. On the other hand, import data can be utilized to proxy the demand for LCGs. Despite some limitations of this approach, such as potentially underestimating production and consumption volumes, foreign trade data often serve as the only convenient source for assessing the production and use of advanced manufacturing technologies at the national and regional levels (Simachev et al., 2021). For further analysis, we will use these export and import estimates of LCGs to explain the volumes of carbon dioxide emissions from fuel combustion.

Data and methods of econometric estimation

To evaluate the environmental impact of low carbon goods (LCGs) in Russian regions, we employ the standard metric of atmospheric pollutant emissions from fuel combustion (for electricity and heat production) for the reporting year (Mariev et al., 2020). Using per capita measurements for all indicators is advisable to mitigate potential endogeneity issues. Larger regions are more likely to have industrial sectors that export and import LCGs, while also generating higher emissions from fuel combustion.

Our model incorporates control variables based on findings from previous studies that explain per capita emissions. Specifically, we include inflows of foreign direct investment, the number of advanced manufacturing technologies utilized, electricity consumption, and the urban population share. Additionally, we incorporate Gross Regional Product (GRP) per capita and its square, aligning with the Kuznets curve hypothesis, which posits a relationship between economic growth and environmental degradation. According to this hypothesis, environmental conditions initially deteriorate with economic growth but subsequently improve as the economy matures. This improvement is attributed to the increased capacity of a growing economy to invest in clean technologies and environmental protection. Conversely, in the early stages of economic development, countries may prioritize economic growth over environmental protection, leading to environmental degradation. This hypothesis has been validated for Russian regions in several studies (Mariev et al., 2020; Shkiperova, 2013).

Based on the Kuznets curve hypothesis and recent empirical studies explaining emissions associated with energy production, we employ the following variables, as presented in Table 2.

Table 2

Variables Used: Definitions, Sources and References

Variable name	Definition	Data source	References
Dependent variable			
lncarbempop	Emissions of pollutants into the atmosphere from fuel combustion (for electricity and heat generation) (carbon oxide) thousand tons per thousand population, logarithm	EMISS	Mariev et al., 2020;
Explanatory and control variables			
lnlctimpop	Import of LCGs per capita, USD, logarithm	Authors' calculations	
lnlctexppop	Export of LCGs per capita, USD, logarithm	Authors' calculations	
lngrppc	GRP per capita, RUB, logarithm	Rosstat	Ali et al., 2019; Muhammad et al., 2020; Xu, Lin, 2016; Mariev et al., 2020;
lngrppc2	Square of GRP per capita, RUB, logarithm	Authors' calculations	Grossman, Krueger, 1991; Xie, Liu, 2019; Mariev et al., 2020; Schkiperova et al., 2013;
ifdipop	Inflow of foreign direct investment per thousand population, million USD, logarithm	Central Bank of Russia	Muhammad et al., 2020; Mariev et al., 2020;
lnamtpop	Number of advanced manufacturing technologies used per thousand population, logarithm	Rosstat	Xie, Liu, 2019; Mariev et al., 2020;
lnenergyconspop	Electricity consumption per thousand population, million kWh	Rosstat	Ali et al., 2019; Muhammad et al., 2020; Mariev et al., 2020;
cityshare	Urban population share, %	Rosstat	Ali et al., 2019; Muhammad et al., 2020; Xie, Liu, 2019; Xu, Lin, 2016; Mariev et al., 2020;

Source: Compiled by the Authors

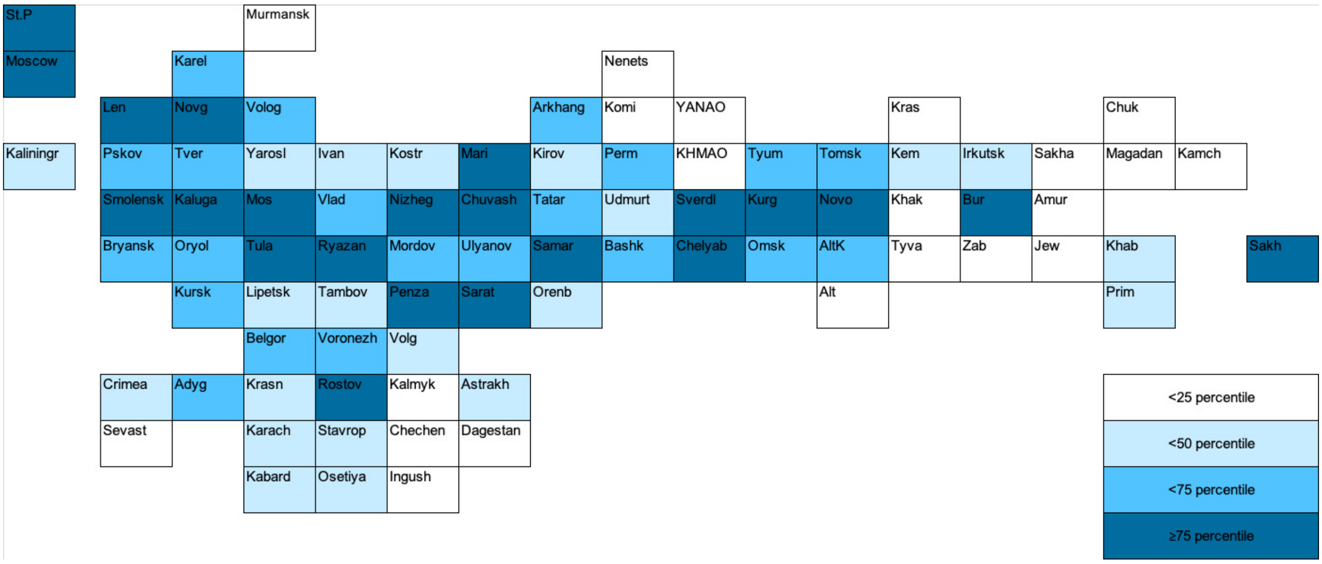

Figure 2. *Share of LCG exports in GRP across Russian regions (%), average for 2016–2021*

Source: Compiled by the authors based on own calculations

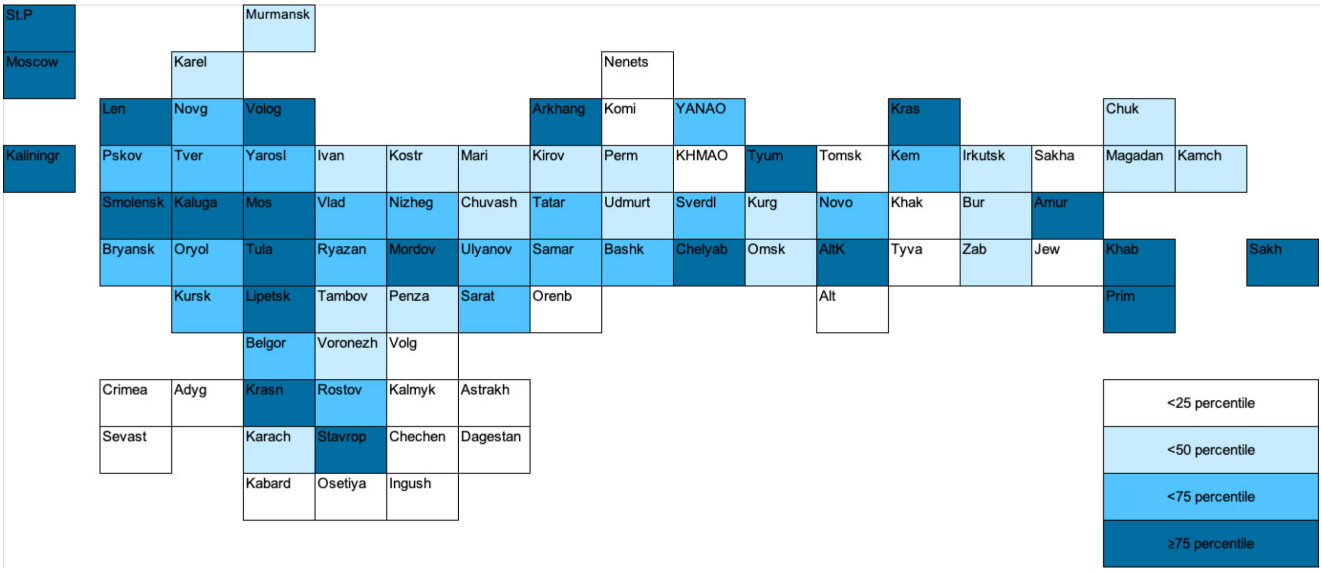

Figure 3. *Share of LCG imports in GRP across Russian regions (%), average for 2016–2021*

Source: Compiled by the authors based on own calculations

The novelty of our study lies in our departure from previous research by incorporating per capita volumes of LCG exports and imports as a key factor explaining emissions from fuel combustion. Additionally, we introduce the number of advanced manufacturing technologies used in the region as an additional variable reflecting the technological level of production. Previous studies utilized absolute and relative volumes of exports and imports (e.g., Muhammad et al., 2020; Mariev et al., 2020) as control variables, while others included various variables capturing technological levels (e.g., Xie, Liu, 2019; Mariev et al., 2020). However, none have specifically focused on factors related to advanced and low-carbon technologies. Given the significant correlation between absolute volumes of exports and imports with LCG trade, we opted to exclude them to avoid multicollinearity issues.

Figures 2 and 3 illustrate the distribution of the share of LCG exports and imports in the GRP of Russian regions, averaged over the period 2016–2021. As the figures show, the share of exports is generally higher in industrially developed and diversified regions. The distribution of imports follows a similar pattern but is also higher in border

Table 3

Descriptive Statistics of Variables

Variable	Number of observations	Mean	Std. dev.	Min	Max
lncarbempop	169	1.842	1.284	–2.256	5.150
lnlctimpop	168	9.677	1.786	0.559	12.992
lnlctexppop	162	7.936	2.278	–1.432	12.365
ifdipop	163	0.949	2.846	0.000	20.108
lnamtpop	169	0.307	0.862	–2.874	2.253
lnenergyconspop	169	1.885	0.702	0.465	4.172
cityshare	169	70.750	12.983	29.3	100
lngrppc	169	13.095	0.628	11.865	15.558

Source: Authors' calculations

regions, which is likely due to the specific features of goods entry and declaration. Imports provide less information about the region where imported goods are consumed, as goods can be further distributed to other regions after their entry.

Descriptive statistics of the variables used in the model is presented below in table 3. Although data on the export and import of LCGs spans the period from 2016 to 2021, our study is limited by the availability of fuel combustion emissions data, which is only accessible for the years 2019-2020. This restriction narrows our sample to just these two years, thereby influencing the methodologies we can employ, as we will discuss further. However, we benefit from the fact that the remaining variables are available over a longer period, and we utilize all explanatory and control variables with their first lag to further mitigate the endogeneity issue caused by simultaneity in the model.

In this study, we employ the Tobit method to analyze data with a non-uniform distribution of the dependent variable ranging from –3 to 6. This method is suitable for modeling situations where the dependent variable is censored (bounded above and below). Such constraints are common in socio-economic and psychological phenomena and addressing them is crucial for reliable analysis. The Tobit method correctly handles these bounds, accounting for measurement limitations or assumed maximum (minimum) levels. It also adheres to assumptions of residual normality and linearity between dependent and independent variables, ensuring model adequacy and minimizing distortions for enhanced statistical efficiency.

Alternatively, quantile regression could be used for estimation. This method is advantageous for several reasons. Firstly, it allows analysis at different quantile levels of the dependent variable, which is useful for non-uniformly distributed data as it captures changes in relationships across different levels (as shown in Figure 4). Secondly, quantile regression does not require residual normality or linearity assumptions, offering greater flexibility and robustness for non-standard distributions. Additionally, it accommodates outliers and extreme values, which is important in studies with significant data variability.

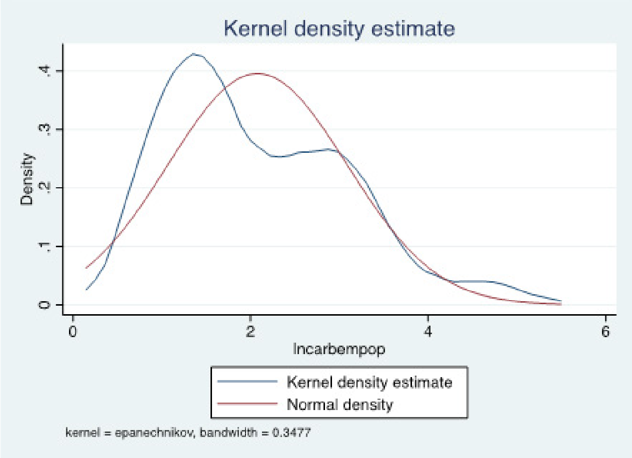

Figure 4. *Distribution of lncarbempop variable and normal distribution*

Source: Compiled by the authors based on own calculations

Results

Empirical results from Tobit regression are presented in Table 4, and results from quantile regression are detailed in Table 5. Key findings are summarized below.

Table 4

Trade in LCGs as a Determinant of Pollutant Emissions from Fuel Combustion: Tobit Regression Results

Variables	(1)	(2)
lctexppop (t-1)	−0.219***	
	(0.0412)	
lnlctimpop (t-1)		−0.0961
		(0.0594)
lngrppc (t-1)	2.709	1.232
	(4.3590)	(3.4770)
lngrppc2 (t-1)	−0.0751	−0.0216
	(0.1620)	(0.1270)
ifdipop (t-1)	−0.0351	−0.0303
	(0.0497)	(0.0441)
lnamtpop (t-1)	0.557***	0.342***
	(0.1180)	(0.1090)
lnenergyconspop (t-1)	0.425**	0.690***
	(0.1680)	(0.1630)
cityshare (t-1)	−0.00742	−0.00881
	(0.0076)	(0.0080)
Constant	−19.37	−10.39
	(29.0800)	(23.4100)
Observations	154	165
Pseudo R-sq	0.2014	0.1844
Prob>Chi2	0.000	0.000

Notation. Hereinafter *** indicates 1% significance level, ** indicates 5% significance level, * indicates 10% significance level. Standard errors are indicated in parentheses. Dummy variable for 2020 is included, but not reported.

Source: Authors' calculations

Firstly, irrespective of the estimation method used, our results exhibit substantial consistency. We find that per capita exports of LCGs in Russian regions are associated with reductions in fuel combustion emissions. This suggests that the presence of local producers of low carbon goods facilitates their adoption within the region, contributing to the broader agenda of sustainable development. Consequently, we observe that higher levels of LCGs exports correlate with decreased emissions from fuel combustion.

Regarding imports of LCGs, Tobit regression results indicate statistical insignificance, while significance is observed only at the 90th quantile in the quantile regression (column 10). This may indicate that domestic solutions dominate in most Russian regions, with imports playing a less prominent role.

Variables such as *lngrppc* (Gross Regional Product per capita) and *lngrppc2* (Gross Regional Product per capita squared) are statistically insignificant, thus failing to confirm the Environmental Kuznets Curve hypothesis at this stage. Interestingly, our exploration without key explanatory variables related to LCGs trade and the intensity of advanced production technologies initially suggested a confirmation of the Kuznets Curve hypothesis. This implies that regional adoption of advanced technologies influences the curve, warranting further investigation in future studies.

Among other control variables, we find that *lnamtpop* (per capita use of advanced production technologies) is positively associated with fuel combustion emissions. This aligns with findings from both Tobit and quantile regressions across most quantiles (columns 1–4 and 6–8). This result suggests that the complexity and energy-intensive nature of advanced production processes contribute to higher electricity consumption in regions. Moreover, it is important to recognize that the development of advanced technologies in the energy-intensive sectors themselves, including coal mining and coal processing, is promising for Russian regions (Korolev et al., 2023).

Additionally, the influx of Foreign Direct Investment (FDI) exhibits a weakly negative association with emissions – statistically insignificant in Tobit regression and significant only in columns 1, 6, and 10 of the quantile regression. This finding may imply that FDI enterprises adhere to higher international environmental standards or preferentially invest in eco-friendly facilities with lower fuel combustion emissions.

Overall, the estimated regressions demonstrate satisfactory explanatory power. The Tobit model explains 18.4% to 20.1% of the variance in the dependent variable across two different specifications, while the quantile model ranges from 22.4% to 38% depending on the quantile considered.

Figure 5 displays the elasticity (coefficient) of the relationship between per capita exports and imports of LCGs and the reduction in fuel combustion emissions in Russian regions. As shown, the elasticity is negative. The elasticity for LCGs exports is negative and exhibits a U-shaped pattern, peaking approximately between the 50th and 80th quantiles. The elasticity for LCGs imports is also negative and declines monotonically, becoming statistically significant only after the 90th quantile.

Table 5

Trade in LCGs as a Determinant of Pollutant Emissions from Fuel Combustion: Quantile Regression Results

Variables	Quantile					Quantile				
	Q10	Q25	Q50	Q75	Q90	Q10	Q25	Q50	Q75	Q90
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
lctexppop (t-1)	−0.128**	−0.189***	−0.217***	−0.239***	−0.182***					
	(0.0499)	(0.0586)	(0.0613)	(0.0670)	(0.0536)					
lnlctimpop (t-1)						0.0207	−0.0819	−0.0369	−0.122	−0.185**
						(0.0771)	(0.0694)	(0.0916)	(0.0931)	(0.0777)
lngrppc (t-1)	−1.491	2.377	1.667	−1.723	−17.16***	−2.446	−1.169	1.236	−4.759	−5.497
	(5.2840)	(6.2060)	(6.4880)	(7.0950)	(5.6770)	(4.5120)	(4.0590)	(5.3590)	(5.4490)	(4.5430)
lngrppc2 (t-1)	0.0611	−0.0701	−0.0463	0.0882	0.661***	0.106	0.0654	−0.0291	0.203	0.246
	(0.1960)	(0.2300)	(0.2400)	(0.2630)	(0.2100)	(0.1650)	(0.1480)	(0.1950)	(0.1990)	(0.1660)
ifdipop (t-1)	−0.174***	0.0249	−0.0386	−0.0727	−0.0461	−0.289***	−0.0158	0.0622	−0.0806	−0.141**
	(0.0602)	(0.0707)	(0.0739)	(0.0809)	(0.0647)	(0.0573)	(0.0515)	(0.0680)	(0.0692)	(0.0577)
lnamtpop (t-1)	0.667***	0.415**	0.460***	0.335*	0.0637	0.481***	0.422***	0.320*	0.0922	0.128
	(0.1430)	(0.1670)	(0.1750)	(0.1910)	(0.1530)	(0.1420)	(0.1270)	(0.1680)	(0.1710)	(0.1430)
lnenergyconspop (t-1)	0.484**	0.153	0.544**	0.948***	0.763***	0.345	0.359*	0.735***	1.323***	0.853***
	(0.2040)	(0.2400)	(0.2510)	(0.2740)	(0.2190)	(0.2110)	(0.1900)	(0.2510)	(0.2550)	(0.2130)
cityshare (t-1)	0.0181*	0.00585	0.00321	−0.0118	−0.0169*	0.0162	0.000615	−0.00548	−0.0173	−0.0238**
	(0.0092)	(0.0108)	(0.0113)	(0.0124)	(0.0099)	(0.0103)	(0.0093)	(0.0123)	(0.0125)	(0.0104)
Constant	8.442	−17.11	−11.71	10.74	115.5***	12.5	5.261	−10.27	30.05	34.82
	(35.2500)	(41.4000)	(43.2800)	(47.3400)	(37.8700)	(30.3700)	(27.3200)	(36.0800)	(36.6800)	(30.5900)
Observations	154	154	154	154	154	165	165	165	165	165
Pseudo R-sq	0.3311	0.2236	0.268	0.2899	0.3433	0.38	0.2489	0.240	0.2643	0.3539

Notation. Hereinafter *** indicates 1% significance level, ** indicates 5% significance level, * indicates 10% significance level. Standard errors are indicated in parentheses. Dummy variable for 2020 is included, but not reported.

Source: Authors' calculations

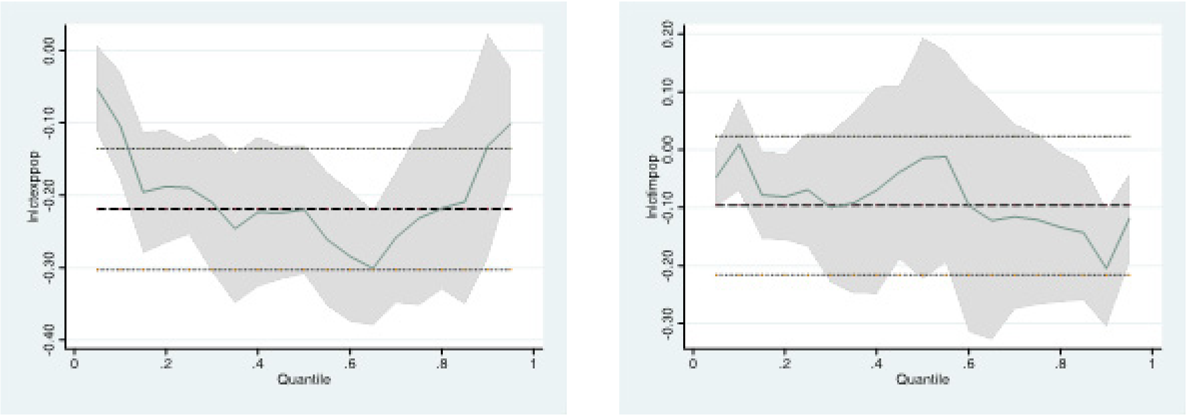

Figure 5. *Impact of LCGs Exports (Left) and Imports (Right) on Fuel Combustion Emissions Pollution in Russian Regions: Quantile Regression Results*

Source: Compiled by the authors based on own calculations

Conclusion

The spread of sustainable development goals is increasingly reflected in the growing contribution of low-carbon goods (LCGs) to global trade. However, this growth remains gradual, as the global economy continues to rely heavily on traditional energy sources, particularly coal. As this study has shown, LCG trade exhibits significant variation across Russian regions. Some regions are actively engaged in both exporting and importing these goods, while others show minimal involvement. This is an important finding, reinforcing the existing evidence of profound inequalities among Russian regions in their ability to adopt advanced technologies and develop innovation capacities. Such disparities are apparent both in the availability of innovative solutions on the supply side and the demand for them.

Our analysis reveals a non-linear relationship between LCG export intensity and emissions reduction, following a U-shaped pattern. When the level of LCG exports is relatively low, its impact on emissions reduction is insufficient, likely due to weak external effects. However, when export intensity is high, the correlation with emissions reduction diminishes, possibly due to regional economic barriers or a lack of sufficient incentives for widespread adoption of technologies that could significantly reduce emissions. These findings indicate that simplistic policy approaches aimed at equalizing technological distribution across regions might overlook the complexities of regional economic dynamics.

Rather than focusing solely on uniform technological dissemination, a more effective approach to industrial policy would be to raise the performance of lagging regions by transferring best practices from the leading ones. At the same time, it is crucial to continue fostering the development of advanced regions by supporting both the demand for efficient technological solutions and the identification and prioritization of promising technologies on the supply side. Encouraging regions that are already ahead in LCG adoption to push further, while ensuring that regions falling behind have access to these advancements, can help reduce the technological gap.

Our study also highlights that LCG imports can significantly reduce emissions in regions where these emissions are particularly high. This is another critical insight for industrial policy, as it underscores the cumulative effect of importing LCG technologies. Once a certain threshold is crossed, these imports can begin to have a measurable impact on reducing fuel combustion emissions. Therefore, from the perspective of sustainable development, reducing barriers to the importation of advanced low-carbon technologies and equipment—currently not produced domestically—becomes imperative.

Tax incentives for companies that invest in high-cost, cutting-edge foreign LCG technologies would serve as an effective tool to stimulate demand. This is especially important as global competition intensifies over access to the best foreign solutions, while countries simultaneously seek to protect their own leading technologies from being exported. Establishing clear mechanisms for international cooperation in the low-carbon technology sector is crucial to ensure that Russian industries can access these advanced solutions. Collaborative frameworks could be explored to facilitate technology transfer, helping domestic firms integrate foreign expertise and overcome regional technological stagnation.

At the same time, while protecting domestic manufacturers from foreign competition can be useful in the early stages of technological development, such protection should not become a long-term strategy. It is essential to encourage competition in order to promote knowledge exchange and ensure that Russian low-carbon technologies remain globally competitive. Domestic producers will benefit from being exposed to international standards and innovation, which can help them enhance their own competitiveness.

Furthermore, targeted support for research and development (R&D) in regions with high potential for LCG innovation could stimulate the emergence of new solutions. Public-private partnerships, alongside state-backed grants and incentives for technological advancement, will be key to closing the technological gap between Russia's regions. In addition, investments in infrastructure that supports LCG adoption, such as specialized transportation systems for renewable energy technologies, could enhance regional participation in global LCG trade.

In conclusion, addressing both the supply and demand challenges of LCG trade will require a multifaceted approach. Supporting lagging regions, fostering innovation in leading ones, and encouraging international collaboration will not only reduce regional inequalities but also position Russia to play a more prominent role in the evolving global low-carbon economy.

Appendix 1

Top 10 positions of Russian LCGs export by share in gross exports from 2016–2021

HS Code Description	Relation to Low Carbon Goods and Technology	The share in the gross export of LCGs of Russia in 2016-2021
Heat exchange units, whether or not electrically heated	Essential for energy-efficient heating and cooling systems, including heat pumps and waste heat recovery systems, which reduce energy consumption and emissions.	2.1%
Measuring/checking instruments, apparatus, and machines	Critical for monitoring and optimizing the performance of low carbon technologies, such as renewable energy installations, smart grids, and energy-efficient processes, ensuring accurate data for improving efficiency and reducing emissions.	1.6%
Boards, panels, consoles, desks, cabinets, and other bases equipped with two or more apparatus for electric control or distribution of electricity	Key for managing and optimizing electricity distribution in renewable energy systems (solar, wind), smart grids, and energy storage systems, enhancing the efficiency and reliability of low carbon energy solutions.	1.5%
Parts of nuclear reactors	Vital components for nuclear reactors, which provide a significant source of low carbon energy by generating electricity without direct carbon emissions.	1.1%
Other machines and mechanical appliances, including electric wire coil-winders, and machines for mixing, kneading, crushing, grinding, screening, etc.	Support the manufacturing and processing of components used in renewable energy technologies, electric motors, batteries, and other low carbon solutions, contributing to the production and development of sustainable technologies.	0.9%
Parts and accessories of the articles of 90.13	Important for maintaining and enhancing the performance of optical instruments and appliances used in low carbon technologies, such as precision measurement devices in renewable energy and energy efficiency applications.	0.7%
Automatic regulating/controlling instruments and apparatus, not elsewhere specified in 90.32	Crucial for the automated regulation and control of systems in renewable energy installations, smart grids, and energy-efficient buildings, ensuring optimal performance and energy savings.	0.7%
Aluminum casks, drums, cans, boxes, and similar containers, excluding those for compressed/liquefied gas, with capacity not exceeding 300 liters	Used for the safe and efficient storage and transportation of materials, including chemicals and components for renewable energy technologies, reducing environmental impact through recyclability and lightweight construction.	0.6%

HS Code Description	Relation to Low Carbon Goods and Technology	The share in the gross export of LCGs of Russia in 2016-2021
Slag wool, rock wool, and similar mineral wools, in bulk/sheets/rolls	Used as insulation materials in buildings and industrial processes, improving energy efficiency by reducing heat loss and energy consumption, thus lowering carbon emissions.	0.6%
AC generators (alternators), of an output greater than 750 kVA	Key components in large-scale renewable energy systems, such as wind and hydroelectric power plants, converting mechanical energy into electrical energy efficiently, supporting the generation of low carbon electricity.	0.5%

Source: Authors' calculations

Appendix 2

Top 10 positions of Russian LCGs import by share in gross imports from 2016–2021

HS Code Description	Relation to Low Carbon Goods and Technology	The share in the gross import of LCGs of Russia in 2016-2021
Machinery for liquefying air or other gases, whether or not electrically heated	Supports air separation processes critical for renewable energy production, such as manufacturing components for wind turbines, and for carbon capture and storage (CCS) technologies.	15.3%
Boards, panels, consoles, desks, cabinets, and other bases equipped with two or more apparatus for electric control or distribution of electricity	Essential for the efficient control and distribution of electricity in renewable energy systems (solar, wind), smart grids, and energy storage systems, enhancing the reliability and efficiency of low carbon technologies.	9.0%
Other machines and mechanical appliances, including electric wire coil-winders, and machines for mixing, kneading, crushing, grinding, screening, etc.	Crucial for manufacturing and processing components used in renewable energy technologies, such as electric motors for wind turbines, electric vehicles, and batteries, contributing to the development and production of low carbon solutions.	7.9%
Filtering or purifying machinery and apparatus for gases, other than intake air filters for internal combustion engines	Vital for reducing greenhouse gas emissions in industrial processes, supporting clean air initiatives, and enabling carbon capture and storage (CCS) technologies, which are integral to low carbon strategies.	3.6%
Parts of the filtering or purifying machinery and apparatus of HS code 8421 (excluding centrifuges, including centrifugal dryers)	Support the maintenance and efficiency of gas filtering and purifying systems, which are crucial for emissions reduction and air quality improvement in low carbon industrial applications.	2.6%
Gears and gearing (excluding toothed wheels, chain sprockets, and other transmission elements presented separately); ball or roller screws; gearboxes, etc.	Key components in renewable energy technologies, such as wind turbines and electric vehicles, ensuring efficient power transmission and mechanical performance, thereby supporting the shift to low carbon energy and transportation systems.	2.6%
Distilling/rectifying plant, whether or not electrically heated	Used in the production of biofuels and other renewable energy sources, contributing to the diversification of low carbon energy options and reducing reliance on fossil fuels.	2.5%
Parts of other gas turbines of HS codes 8411.81 and 8411.82	Utilized in gas turbines that can run on renewable biofuels or be integrated with renewable energy systems, thereby supporting low carbon power generation solutions.	2.3%
Electric accumulators, including separators therefor, whether or not rectangular (including square), lead-acid, of a kind used for starting piston engines	Important for energy storage in renewable energy systems, including solar and wind power installations, and for electric vehicles, facilitating the use and integration of low carbon technologies by providing reliable energy storage solutions.	2.3%
Measuring or checking instruments, apparatus, and machines	Essential for monitoring and optimizing the performance of low carbon technologies, including renewable energy installations and smart grids, ensuring efficient operation and accurate measurement of emissions and energy consumption.	2.2%

Source: Authors' calculations

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