

REGIONAL DYNAMICS OF GREENHOUSE GAS EMISSIONS IN RUSSIA, 2017–2023: STRUCTURE AND DRIVERS

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ABSTRACT. This article analyzes greenhouse gas emission trends in Russian Federation regions from 2017 to 2023, calculated using the author's methodology. The methodological approach combined a sectoral decomposition of regional changes (identifying the leading driver and assessing the concentration of changes in one or two sectors), measuring structural shifts in the sectoral structure of emissions (the Gatev index), and testing the dynamic factors using a logarithmic change model. The national emission trajectory over the study period was undulating. Emissions declined in 2017–2020 and recovered in 2020–2023, with fuel combustion representing the dominant driver at both stages. However, structural adjustments in most regions were limited, and notable structural shifts were driven by changes in non-fuel sectors, i.e., fugitive emissions from mining, industrial processes, and agriculture. This highlighted the importance of sectoral specialization and local intra-sector factors in interpreting regional dynamics. The regression model for the full period 2017–2023 revealed a statistically significant relationship between emission dynamics and changes in economic activity and energy intensity, while for shorter subintervals, the robust relationships are weaker, reflecting the impact of shocks and high sectoral heterogeneity. The analysis also reveals differentiated decoupling patterns between economic growth and greenhouse gas emissions across Russian regions, with 29 regions (approximately 35%) demonstrating absolute decoupling effects. The results demonstrated that the analysis of subnational trajectories requires a combination of aggregated estimates and sectoral interpretation, taking into account differences in emission generation mechanisms when developing low-carbon development policies.

KEYWORDS: low-carbon development, energy intensity, regional analysis, sectoral decomposition, structural shifts, decoupling

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INTRODUCTION

Global greenhouse gas (GHG) emissions continue to grow, and in 2024 amounted to 53.2 GtCO₂-eq, i.e., increased by 1.3% compared to 2023 and by 65% since 1990¹. The primary driver of this growth is emissions associated with fossil fuel combustion and industrial processes. The broad consensus on the anthropogenic drivers of greenhouse gas emissions growth, reflected in the signing of the Paris Agreement and the development of the United Nations Sustainable Development Goals (Goal 13 – Climate Action), underscores the commitment of the global community and individual countries to limit rising temperatures through emission reductions. Despite increased investment in low-carbon development projects and mechanisms, current national contributions and measures remain insufficient² to meet the Paris Agreement's goal of holding warming to well below 2°C and pursuing efforts to limit it to 1.5°C above pre-industrial levels during the 21st century. The trend of annual growth, similar to economic dynamics, was interrupted by the 2008–2009 crisis and the COVID-19

pandemic. The pandemic triggered the largest decline in emissions for the period under review since 1990 (–7% compared to 2019)³ (Carbon Brief 2020) while the reduction in daily global emissions reached up to 17% (Le Quéré et al. 2020). The aforementioned reductions were temporary, and by 2021 emissions had rapidly rebounded, reaching a new record high⁴. According to the International Energy Agency, the post-pandemic “recovery” was further stimulated by increased coal combustion. The volatile dynamics of global emissions suggest that without targeted systemic measures, temporary emission declines are quickly offset by even sharper subsequent increases.

In such circumstances, understanding GHG emission dynamics at the regional (subnational) level is crucial, as national trends represent an aggregate of regional processes. Different regions may exhibit opposing trends; without breaking down the dynamics by territory and sector, it is impossible to understand which mechanisms are dominant. It is also important to recognize that climate action is implemented locally, with actors in cities and regions possessing a genuine mandate to influence

¹https://edgar.jrc.ec.europa.eu/report_2025?

²<https://www.ipcc.ch/report/ar6/syr/resources/spm-headline-statements/?wpmobileexternal=true>

³<https://www.carbonbrief.org/global-carbon-project-coronavirus-causes-record-fall-in-fossil-fuel-emissions-in-2020>

⁴<https://www.iea.org/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021>

emission trends. This article aims to assess GHG emission dynamics in Russian regions for the period 2017–2023, identifying the leading drivers and spatial variations in these changes. Particular attention is given to the phenomenon of decoupling between economic growth and greenhouse gas emissions, which represents a central concept in contemporary climate economics and sustainability research.

State of Research on the Problem

International studies on GHG emission differences focus on the influence of energy, economic, technological, and demographic factors. Early classical international studies emphasized the role of energy consumption, which, according to later research, resulted in an underestimation of the contributions of population and technological factors (Shi 2001). Over time, the range of considered factors expanded, and the first studies began to examine the combined influence of population, wealth, economic scale, and technological characteristics⁵ (Meyerson 1998; Schmalensee et al. 1998). In the early 2000s, the focus shifted to empirically testing the heterogeneity of the introduced dependencies. A study by Shi (2003) showed that, according to cross-country data, CO₂ emissions, on average, grow faster than population (i.e., 1% increase in population was associated with a disproportionately large increase in CO₂ emissions, surpassing 1%) with this effect being more pronounced in developing economies (Shi 2003). Dinda and Coondoo, examining the causal relationship between GDP per capita and emissions, found that the direction of this relationship varies across country groups: in some, economic growth is accompanied by rising emissions, while in others, the opposite pattern is observed (Dinda and Coondoo 2006). An important step in accounting for the impact of factors was the use of the IPAT model, and, later, the stochastic version of the STRIPAT model. Dietz and Rosa developed a stochastic (regression) version of the IPAT identity (Impact = Population × Affluence × Technology) and, using cross-country data, demonstrated how population, wealth, and technology are related to GHG emissions (Dietz and Rosa 1997). The impact of population is not strictly proportional, while

the impact of wealth is nonlinear, i.e., growth in GDP per capita contributes to the growth of emissions up to approximately \$10,000 per person, after which the effect decreases/weakens.

STRIPAT is one of a family of methods used by international researchers to analyze differences in GHG emissions. When decomposing observed changes into their contributing factors, applied studies commonly employ the Kaya identity alongside IDA/LMDI methods (Ang 2005). The IPAT approach belongs to the econometric methods, which aim to estimate the elasticity and heterogeneity of effects — that is, how emissions respond to changes in population, wealth, and technology. Input-output approaches are used when structural and intersectoral relationships must be taken into account. Causal methods are used to understand how a particular decision, policy, or crisis has affected emissions, and scenario models are used to construct trajectories and pathways to achieve climate goals (Table 1).

These methodological approaches have significantly shaped the understanding of the dynamics of emissions. Decomposition methods (Kaya identity, IDA/LMDI) have made it possible to distinguish between effects of scale (economic growth), structural effects (changes in the structure of industry) and effects of intensity (energy intensity and carbon intensity), thereby clarifying the relative contribution of economic growth to efficiency gains. Econometric approaches such as IPAT/STRIPAT have made it possible to estimate the elasticity of emissions depending on population size, level of well-being, and technology, revealing cross-country heterogeneity and nonlinear relationships. Input-output models have contributed to understanding cross-industry and materialized emissions flows, while causal methods and scenario modeling have provided insight into the effects of specific policies, crises, and long-term transitions to a low-carbon economy. Taken together, these approaches demonstrate that the dynamics of emissions are multifactorial and context-dependent, rather than determined by the mechanical impact of economic growth.

Sector-specific applications have also combined decomposition analysis with decoupling assessment, for example for energy-related CO₂ emissions (Klimenko

Table 1. Main families of methods for analyzing the dynamics of greenhouse gas emissions

Family of analysis methods	When is it applied?	Key works
Decomposition of contributions: Kaya method, LMDI	These methods help answer the question of <i>what drives emission changes</i> , i.e. quantifying the contributions of volume, structure, and intensity of growth across various factors and time periods	LMDI as the most common index decomposition standard in energy and CO ₂ studies: (Ang 2005). Shapley decomposition of CO ₂ emissions without residue: (Albrecht et al. 2002)
Econometric models of drivers (elasticities): STRIPAT	When it is necessary to assess how strongly factors are related to emissions: elasticity by population/income/technology, testing for heterogeneity of effects between groups of countries/regions	Canonical works on STRIPAT and CO ₂ : (Dietz & Rosa 1997).
Structural approaches and relationships: SDA/MRIO (input-output)	When inter-industry and inter-regional linkages need to be accounted for — and when the key question is where in the value chain emissions are generated — a consumption-based approach to emission accounting becomes appropriate	Comparison of SDA and IDA and their application to CO ₂ analysis: (Hoekstra & van den Bergh 2003). MRIO and the “carbon footprint of countries” (consumption-based): (Hertwich & Peters 2009).
Causal assessments and scenario modeling	When it is necessary to assess the impact of policy implementation, the impact of a crisis on emissions (cause-and-effect relationships), or to construct future emission trajectories and compare them with climate goals	Causal assessment of the effect of the EU ETS on emissions (Dechezleprêtre et al. 2023). Scenario approaches and modelling of GHG emissions trajectories: IPCC AR6 WGIII Annex III.

⁵<https://enb.iisd.org/journal/engelmann.html>

et al. 2026; Zhang et al. 2018). In a large-scale review of the literature on emission drivers and GHG dynamics conducted in 2023, McCurdy and Rhodes concluded that all variables examined can be grouped into seven broad categories: demographic, economic, energy-related, technological, transport, political, and other (as a residual category). Emission growth is most commonly associated with population size, energy consumption, and GDP per capita (Table 2), while the factors most frequently linked to emission reductions include the square of GDP per capita and the expansion of alternative and renewable energy production (McCurdy and Rhodes 2023). Empirical evidence from countries with declining emissions confirms the importance of energy-related and structural factors: Le Quéré et al. (2019) associate declining CO₂ emissions in 18 developed economies with decreasing fossil-fuel use, increasing renewable energy deployment, and lower energy demand, while Lamb et al. (2022) demonstrate substantial differences in emission reduction trajectories across individual economic sectors. At the same time, the relationship between economic growth and environmental costs is not universal: research on geo-ecological transitions reveals divergent environmental trends and the spatial redistribution of environmental burden, underscoring the importance of accounting not only for scale factors but also for changes in economic intensity and structure (Lopatnikov 2020). The importance of territorial differentiation has also been emphasized in Russian studies of green economic development, which demonstrate the need to account for substantial differences in economic structure, resource use, and environmental pressure across Russian regions (Bobylev et al. 2015). More recently, this approach has been extended directly to low-carbon development, with regional strategies proposed as a means of aligning national climate targets with regional economic structures and the decarbonization programs of major businesses (Bobylev et al. 2024).

The non-linear and spatially heterogeneous relationship between economic growth and greenhouse gas emissions has also been explored through the concept of decoupling. Decoupling refers to the extent to which economic growth can occur without a proportional increase in emissions and is commonly distinguished into relative and absolute forms. Evidence of long-run decoupling between economic output and emissions has been identified for major emitting economies, although its magnitude and stability vary substantially across countries (Cohen et al. 2018).

The accumulated empirical evidence on decoupling has been summarized in several systematic reviews. Wiedenhofer et al. (2020) demonstrate considerable variation in the indicators, geographical scales, periods, and methodological approaches used in decoupling research. Haberl et al. (2020) show that absolute decoupling is observed in a number of cases, particularly for CO₂ emissions, although the achieved rates are generally insufficient to ensure the rapid reductions required by ambitious climate targets. Vadén et al. (2020) similarly emphasize that decoupling outcomes depend substantially on the indicator, geographical scale, and period considered.

The decoupling approach has also been applied at the subnational level. For example, Song et al. (2020) used an extended Tapio model to assess CO₂-GDP decoupling across Chinese provinces. Similar regional applications have assessed the environmental and economic efficiency of energy resource use through the decoupling framework in Beijing and the coal-producing Shanxi Province (Nikonorov et al. 2023). In Russia, decoupling analysis has been applied to individual regions and groups of regions. At a broader spatial scale, Bobylev et al. (2019) identified decoupling between economic growth and several forms of environmental pressure in Russia and most of its federal districts, although the results differed substantially across regions and environmental indicators. Previous studies examined the Kemerovo Region (Akulov 2013), the regions of the Southern Federal District (Anikina and Anikin 2019), the Vologda Region (Yashalova 2014), and Russian cross-border regions (Zabelina 2019). The analysis has also been extended to individual sectors of regional economies, as demonstrated for the Komi Republic by Fomina (2022). More recent research has applied the decoupling approach to the coal-mining industry of the Kemerovo Region (Kumaneeva et al. 2026).

Emission dynamics in the Russian Federation according to the National Emissions Cadastre (1990–2023)

Dynamics of total anthropogenic GHG emissions in the Russian Federation, excluding the land use, land-use change, and forestry sectors, in 1990–2023 are characterized by a pronounced decline in the 1990s, a subsequent recovery in the 2000s, and a phase of moderate fluctuations after 2010. In 2023, total emissions excluding this sector amounted to 2,082.9 million t CO₂-eq, which is 33.8% lower than the 1990 level (3,147.5 million t CO₂-eq). At each stage, the GHG drivers were changed:

Table 2. The most frequently used indicators in assessing the factors and dynamics of greenhouse gas emissions

Group of indicators	Indicators
The scale of the economy and the level of development	• GDP/GRP per capita • GDP/GRP volume • GDP/GRP per capita growth • Per capita income • Per capita consumption of goods and services
Demographics and urbanization	• Population size • Population density • Share of urban population
Energy	• Energy consumption • Energy consumption per capita • Energy intensity of the economy • Share of renewable energy sources • Consumption of alternative energy
Others	• High-tech exports • Trade openness • Level of motorization

The first stage (1990–1998) was characterized by a significant reduction in GHG emissions, primarily due to the general economic downturn in Russia following the collapse of the USSR. However, the decline was slower than the decrease in production, as the ongoing structural shifts in the economy and changes in the fuel balance did not contribute to their reduction. Energy production and consumption fell at a rate 20% slower than overall production volumes, resulting in a smaller reduction in emissions than would have been expected from a systemic crisis.

The second stage (1999–2007) was associated with emissions stabilization during a period of economic growth based on a consistent shift in growth drivers (import substitution, rising oil prices, and growing consumption). The resumption of industrial production and increased energy consumption were offset by the implementation of energy-efficient technologies and the closure of obsolete enterprises. The rate of increase in emissions was significantly lower than the decline in previous years. According to the inventory, from 2000 to 2008, total emissions (excluding land use, land-use change and forestry sector) increased by 141.3 million t CO₂-eq. According to inventory-based estimates, economic growth over this period was not fully reflected in proportional emission increases, suggesting relative decoupling at the macro level, with energy retaining its dominant role in the emission structure (Fig. 1).

The third stage (2008–2009) was associated with a short-lived, crisis-driven decline in GHG emissions triggered by the global financial crisis, followed by a swift recovery. In the logic of periodization, it is appropriate to distinguish this stage as shock with cyclical factors predominating over structural ones.

The fourth stage (2010–present). Minor fluctuations in GHG emissions after 2010 have been associated with the lack of a clearly defined growth driver in the economy: the dynamics are unstable, with periods of decline alternating with phases of moderate growth. Thus, in 2013–2016, total emissions (excluding land use, land-use change and forestry sector) decreased by 94.9 million t CO₂-eq.

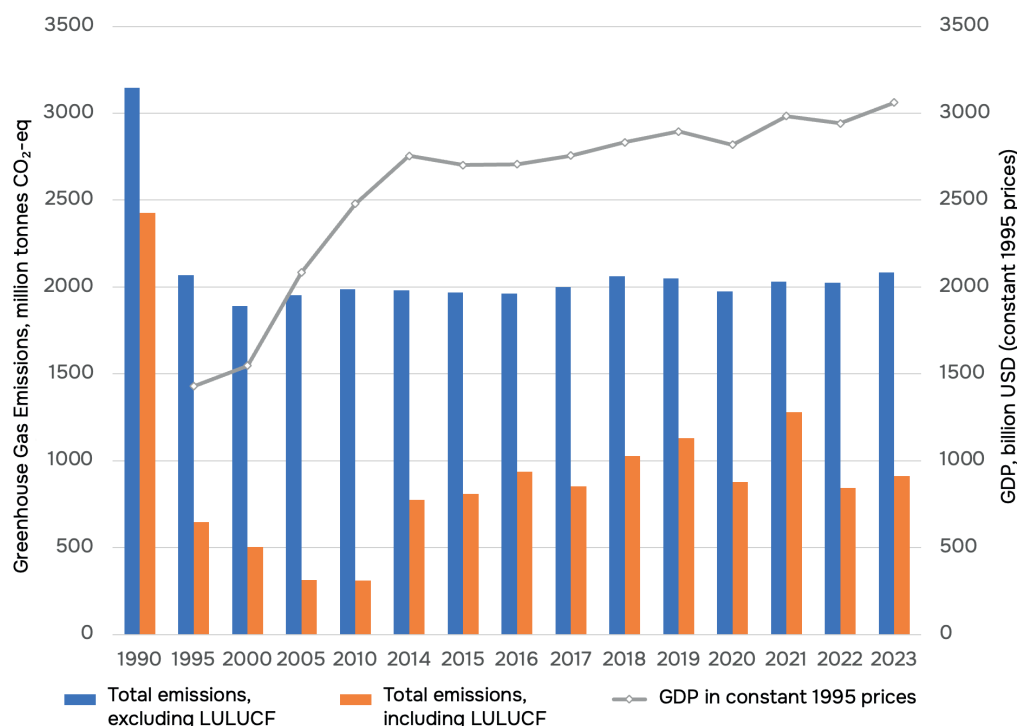
In 2017–2018, growth was noted (the inventory records an increase of 5.1% compared to 2016). In 2019, total emissions decreased by 0.5% with GDP growth, and in 2020, under the influence of the COVID-19 pandemic, emissions decreased by 3.6%. In 2021, emissions increased by 2.7%, in 2022 they remained virtually unchanged (-0.2%), and in 2023 they increased again by 2.9% along with the increase in GDP.

Thus, emission dynamics in the Russian Federation are largely determined by the scale of economic activity and associated changes in fossil fuel consumption, primarily by processes in the energy sector, which accounts for the bulk of emissions excluding land use, land-use change, and forestry. Long-term changes are further shaped by shifts in economic structure, energy efficiency, and fuel mix, while climatic factors — such as temperature trends and interannual variability — indirectly affected energy demand and, consequently, fuel combustion volumes. The degree of dependence of GHG emissions decreases with high rates of economic growth and increases with slower economic growth. Today, the dynamics have become more complex, multifactorial, and geographically differentiated.

The selected period of 2017–2023 belongs to the fourth stage of emissions dynamics and represents a relatively stable macroeconomic regime compared to the transformational shock of the 1990s or the period of rapid recovery in the 2000s. It is important to note that this interval covers two structurally significant sub-periods: the economic recovery before the pandemic (2017–2019/2020) and the COVID-19 crisis, followed by recovery (2020–2023). This makes this period valuable from an analytical perspective, as it combines both cyclical shock effects and medium-term structural adjustments.

Materials and methods of research

To calculate GHG emissions by region, a hybrid methodology was proposed and tested. It combines standard calculations where primary data are available and the distribution of country estimates by region using markers of activity scale in monetary, physical, and volume terms (Shampurov 2024). For example, in the energy sector, emissions from fuel consumption are calculated using the 4-TER form, fugitive emissions from oil and



Source: National Emissions Inventory

Fig. 1. Greenhouse gas emission dynamics in the Russian Federation compared to GDP dynamics

gas production are calculated using the hydrocarbon emissions marker, and emissions from coal production are calculated using production marker indicators in physical terms. Emissions from industrial processes (metallurgy, chemical industry), agriculture, land use, land use change, and forestry are also taken into account. Calculations in previous studies were based on a single slice for 2020, regional differences were analyzed statically, and the direction and degree of stability of trends over time were unidentified. For the purposes of this article, calculations were also made for 2017 and 2023.

A comparison of the authors' calculations with national inventory data reveals similar dynamics, with differences in levels due to differences in category coverage. In 2017, the total emissions according to the authors' methodology amounted to 1,756.1 million t CO₂-eq. versus 1,912.4 in the inventory (a difference of 156.3 million t, -8.2%); in 2020, they were 1,704.3 versus 1,887.4 (-183.1 million t, -9.7%); and in 2023, they were 1,826.2 versus 1,995.0 (-168.8 million t, -8.5%). At the structural level, the differences are concentrated in the industry and agriculture blocks, where the inventory takes into account a wider range of subcategories. Fugitive emissions were taken into account completely with distribution by markers; therefore, the values of calculations and the inventory coincide (Fig. 2).

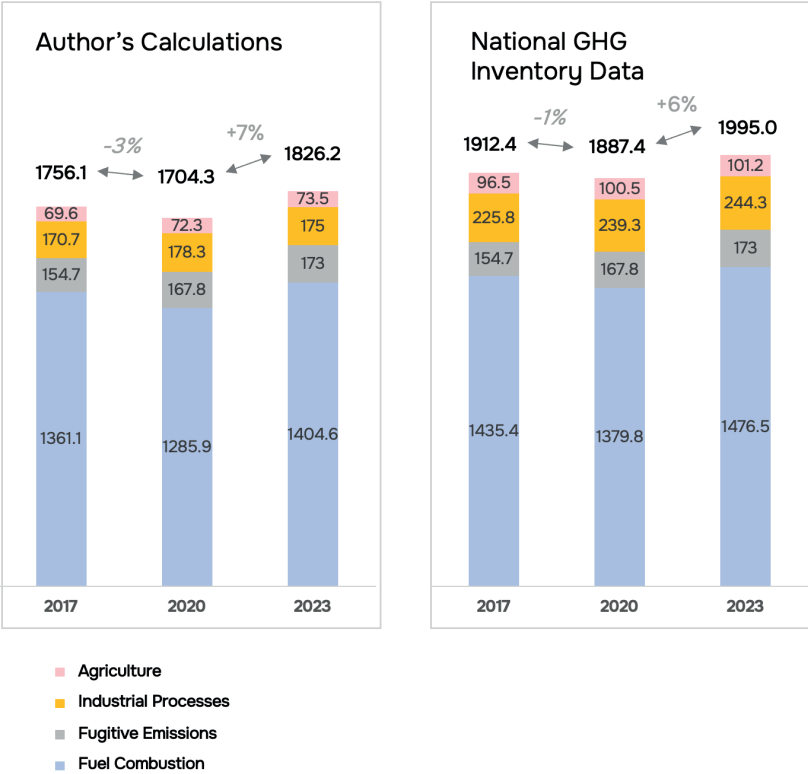
The time dynamics in both calculations are comparable. A decrease was recorded in 2017–2020: -51.8 million tons (-3.0%) according to calculations and -25.0 million tons (-1.3%) according to the inventory; the main contribution came from a decrease in emissions from fuel combustion. An increase was observed in 2020–2023: +121.9 million tons (+7.2%) according to calculations and +107.6 million tons (+5.7%) according to the inventory, with the leading factor again being the increase in emissions from fuel combustion.

RESULTS

To capture regional dynamics, the analysis is structured around two sub-periods: 2017–2020 and 2020–2023. This division reflects distinct shifts in economic trends: during the first sub-period, GRP at 2016 constant prices declined in 20% of Russian

regions, whereas in the second, such a decline was recorded in only two regions. A more systematic analysis of structural shifts and trends in the divergence of economic dynamics from emission dynamics was conducted over the entire observation period (2017–2023).

Period 2017–2020 was characterized by a general decrease in emissions against the backdrop of reduced economic activity during the coronavirus pandemic. However, the same dynamics were typical for only 48 out of 85 regions under study (56% of the regions in the Russian Federation). The most significant decrease in emissions was registered in the Lipetsk Region (-65%), Sevastopol (-62%), Stavropol Territory (-30%), Moscow Region (-27%), and Kostroma Region (-25%). The dynamics of emission reduction were primarily determined by a decrease in fuel consumption. In only five regions did other sectors serve as the primary driver of emission reductions: the Lipetsk Region (metallurgy), the Altai Republic, the Republic of Kalmykia, and the Republic of Dagestan (all driven by agriculture), and the Tomsk Region (oil and gas production). In 37 regions, emissions increased, with fuel consumption being the main driver as a result of the increase (Fig. 3). The largest increases in emissions were seen in the republics of North Ossetia (+127%), Ingushetia (+80%), the Yamalo-Nenets Autonomous District (+55%), and the Chechen Republic (+50%). Most of the leading regions have a relatively low statistical base, raising concerns that the observed dynamics may partly reflect measurement artifacts rather than genuine emission changes. A more mixed picture is observed in terms of growth drivers. For the Tver, Tyumen, and Smolensk regions, the main growth driver is the chemical industry; for Krasnodar Territory, the Komi Republic, and Astrakhan Region, it is oil and gas operations; for Kursk Region, the Republic of Adygea, Bryansk Region, and Tambov Region, it is agriculture; and for the Republic of Khakassia, Tula, Irkutsk, Sverdlovsk, and Murmansk regions, it is metallurgy. In these regions, growth in specialized industries often outweighed the reduction in emissions from fuel consumption. Thus, for the majority of regions where emissions increased relative to 2017, the primary driver appears to be growth in economic activity within specialized industries.



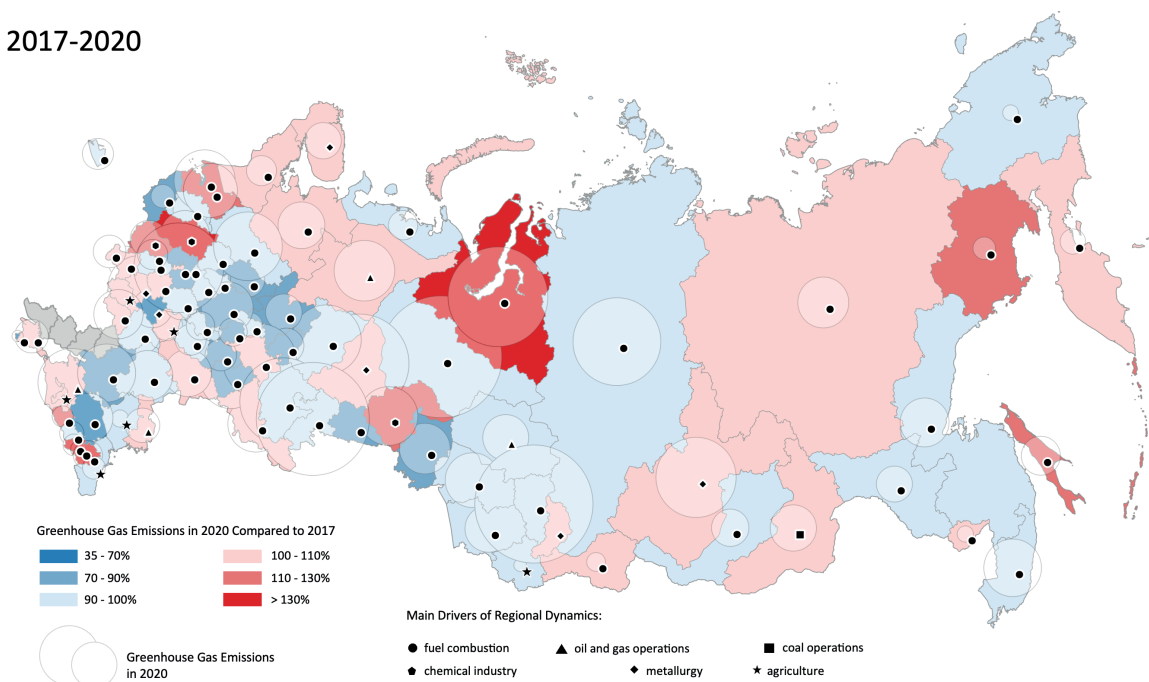
Source: compiled by the author

Fig. 2. Comparison of author's estimates with National Inventory data for 2017, 2020, and 2023 (million tons CO₂-eq)

In 2020–2023 economic trends in the country have changed significantly, with GDP growth already reaching 7.3% in 2021 and a further 5% by 2023. Greenhouse gas emissions increased by 7% by 2023, and the number of regions with increased GHG emissions has increased (72%). These include virtually all eastern regions where GHG emissions from fuel combustion have increased significantly, but for regions with the greatest growth (Yakutia and Amur Region), growth was observed across all sectors. In regions with ferrous and non-ferrous metallurgy (Lipetsk and Orenburg regions, Krasnoyarsk Territory) and oil refining (Moscow, Omsk, Ryazan, Yaroslavl, Novosibirsk, Volgograd, and Sakhalin regions), GHG emissions from the industrial sector have increased significantly. An increase in fugitive emissions of more than 20% is typical for oil and gas-producing regions, both those producing small volumes of oil, for example, at the initial stage of

development (Penza, Volgograd, Irkutsk, Kaliningrad, and Omsk regions, republics of Udmurtia and Adygea, Perm Territory), and the largest ones (Yamalo-Nenets Autonomous District, Nenets Autonomous District, republics of Tatarstan and Bashkortostan). In the Kemerovo Region, the primary driver of emission reductions was a decline in coal mining emissions, attributable to falling production volumes. Metallurgy made the primary contribution to emission reductions in the Chelyabinsk and Vologda regions, where a concurrent decline in fuel combustion emissions may indirectly indicate a contraction in metallurgical output in physical terms. In the Khanty-Mansi Autonomous District, emissions from flammable natural gas combustion and oil and gas operations declined significantly. In the Komi Republic, emissions from fuel combustion as well as processes during oil, gas, and coal extraction have also decreased (Fig. 4).

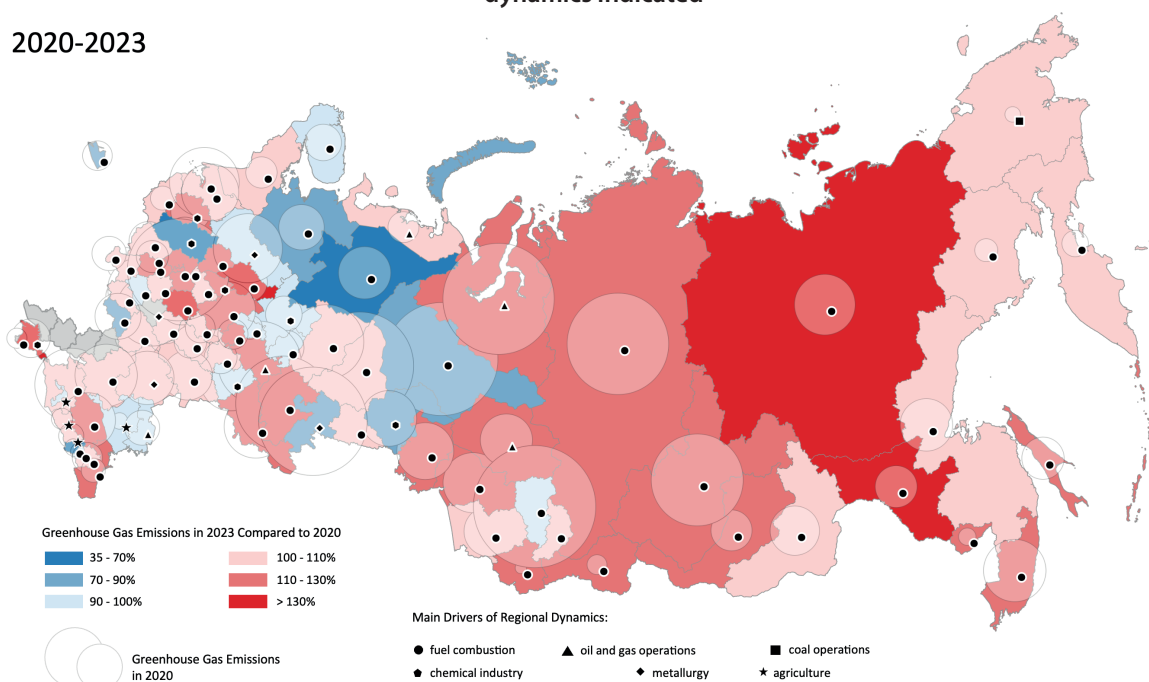
2017-2020



Source: compiled by the authors

Fig. 3. Greenhouse gas emission dynamics by constituent entity of the Russian Federation, with the main drivers of these dynamics indicated

2020-2023



Source: compiled by the authors

Fig. 4. Greenhouse gas emission dynamics by constituent entity of the Russian Federation, with the main drivers of these dynamics indicated

Of all the factors and conditions listed in Table 2, the correlation coefficient reveals a statistically significant relationship between the territorial distribution of GHG emissions and GRP, the amount of heat supplied, population distribution, and electricity consumption. This dynamic, in turn, is explained to a certain extent by changes in electricity consumption, population size, and GRP and to a lesser extent by the dynamics of specific indicators (GRP energy intensity, per capita electricity consumption, and real per capita income) (Table 3).

To explain emission dynamics over the periods 2017–2020 and 2020–2023, a regression model was constructed using the indicators presented in Table 3. No significant results were obtained for certain time periods, which can be attributed to the nature of the dependent variable (GHG emission dynamics), as it is influenced by various types of sources. Explanatory factors for such industries may also differ; for example, emissions from fuel combustion depend on overall energy consumption and the structure of the fuel balance. Fugitive emissions depend on the volumes of oil, coal, and gas production and the parameters of the supporting infrastructure. Agriculture is characterized by specific mechanisms for the formation

of emissions and the response to climate regulation, which requires the use of industry-relevant factors and caution when interpreting results based on aggregated macroeconomic indicators (Svetlov, Kovbashin and Dronin 2025). Accordingly, the value of the dependent variable is formed from a multitude of sector-specific factors, each with varying degrees of severity and indirectly influencing the overall trend through the sector's share of emissions. Intra-sectoral factors and idiosyncratic events may play a particularly significant role, which substantially limits the analytical power of models estimated over such a short time horizon. The analysis presented in Table 3 also shows that the selected factors and indicators for Russian regions are more suitable for explaining regional differences in emissions than for analyzing trends.

However, when moving from aggregated indicators to assessing sector dynamics, the correlations become significantly higher. For example, emission dynamics over different periods are linked to the dynamics of GVA in agriculture at a correlation coefficient of 0.6–0.8, with the strongest link being recorded in the second period (2020–2023). For fugitive emissions, the strongest link is achieved over the full period (2017–2023), while over the two short

Table 3. Correlation coefficients of the volume and dynamics of GHG emissions and indicators used in factor assessments

Indicators	Volume of GHG emissions			Dynamics of GHG emissions		
	2017	2020	2023	2017–2020	2020–2023	2017–2023
Gross value added (GVA) in 2016 prices, thousand rubles.	0.46	0.46	0.50	0.03	0.13	0.29
GRP/capita, thousand rubles	0.16	0.26	0.27	0.02	0.07	0.13
Average annual resident population	0.52	0.49	0.55	0.02	0.21	0.33
Population density, people/sq.km	0.19	0.20	0.25	0.02	0.23	0.09
Volume of household services to the population (thousand rubles)	0.44	0.40	0.47	-0.16	-0.12	-0.10
Thermal energy supplied to consumers (thousand Gcal per year)	0.60	0.48	0.54	0.11	0.01	0.18
Energy intensity of GRP kWh/1000 rub.	0.23	0.23	0.19	0.01	-0.08	0.26
Number of private passenger cars per 1000 people	0.18	0.18	0.19	-0.09	-0.01	0.16
Real per capita monetary income of the population (rubles)	0.21	0.26	0.27	0.17	0.02	0.24
Population consumption expenditure (thousand rubles) in comparable prices	0.40	0.42	0.44	-0.03	-0.09	-0.09
Electricity consumption per capita (thousand kWh/person)	0.39	0.42	0.35	0.02	0.00	0.32
Renewable energy production (megawatt-hours)	n.d.	0.18	0.24	n.d.	-0.06	-0.13
Electricity production from renewable energy sources without hydroelectric power plants (megawatt-hours)	n.d.	0.01	0.00	n.d.	-0.04	-0.19
Share of renewable energy sources in electricity production, %	n.d.	-0.17	-0.20	n.d.	-0.08	-0.07
Share of renewable energy sources in electricity production without hydroelectric power plants (%)	n.d.	-0.18	-0.21	n.d.	-0.02	-0.13
Urban population	0.52	0.50	0.54	0.39	0.16	0.32
The number of people living in small and medium-sized towns	0.54	0.52	0.56	-0.15	-0.15	-0.15
The number of people living in large cities	0.45	0.43	0.46	0.21	0.19	0.19
Share of urban population, %	0.39	0.34	0.40	0.46	0.14	0.26
Share of population living in small and medium-sized towns, %	-0.09	-0.07	-0.08	-0.18	-0.18	-0.18
Share of population living in large cities, %	0.33	0.32	0.34	0.23	0.23	0.19

Source: compiled by the authors

periods the link is negative and insignificant. A comparison of GVA dynamics across sectors with emission dynamics from fuel combustion alone supports the thesis that the relationships between sector-specific dependent variables and their determinants are stronger and strengthen further as the analytical horizon extends (Table 4).

More pronounced relationships for the factors presented in Table 2 were obtained for the full analyzed period 2017–2023. After converting the original values of the indicators into natural logarithms, the dynamics of emissions turned out to be statistically dependent on changes in economic activity (GVA dynamics in constant prices) and energy intensity of GRP (EI). ($\beta_{\text{GVA}}=0.76$; $\beta_{\text{EI}}=0.44$; $p<0.01$). The model as a whole is significant (F-test $p<0.001$) and explains about 18% of interregional variation ($R^2=0.18$) (Tables 5 and 6).

The obtained results fit into the Kaya logic that the dynamics of emissions is explained by the effects of the “scale” and “intensity” indicators⁶. The scale effect is revealed through GRP: an increase in the size of the economy increases energy demand and process volumes, which increases emissions. And intensity (efficiency) is revealed through the energy intensity of GRP: improvements or deteriorations in energy efficiency, holding economic scale constant, translate directly into corresponding decreases or increases in emissions. For future studies, it is logical to hypothesize that over longer time series, the dependence of emissions on scale and intensity factors should manifest itself more consistently and statistically clearly.

Structural shifts in greenhouse gas emissions were analyzed for the entire period 2017–2023 using the Gatev Structural Breaks Index. Almost all regions (87%) showed values <0.1 , and all of them fell within the threshold

of <0.23 . This points to modest structural changes, with no fundamental shifts in the regional emission structure having taken place. The figure below reveals no discernible relationship between structural shifts and emission dynamics. Changes are occurring within key sectors themselves, rather than through a redistribution of emissions across sectors.

The highest and lowest dynamics of emissions were shown by regions where the structure of emissions remained virtually unchanged (Yamalo-Nenets Autonomous District, Sakhalin Region, Yakutia, Jewish Autonomous District, Republic of Crimea, Udmurtia and Komi, Khanty-Mansi Autonomous District).

Compared to other regions, the structure of emissions has changed most significantly either in regions with a pronounced specialization in carbon-intensive industries (Tyumen, Vologda, Volgograd regions, Nenets Autonomous District), or in underdeveloped republics, where the low base effect causes significant shifts even with small changes (republics of Altai and Kalmykia, Chukotka Autonomous District).

In the Tyumen Region, structural shifts occurred in the fugitive emissions sector, which decreased by 19 percentage points and 80% (calculations were performed using a proxy indicator for hydrocarbon emissions, which is where a decrease of this magnitude was recorded). In contrast, in the Nenets Autonomous District, fugitive emissions increased by 30%, while emissions from fuel consumption decreased by 12%. A similar pattern was observed in the Chukotka Autonomous District, where the share of fugitive emissions in the structure increased from 5% to 16%, which is explained by the growth of coal production in the region from 0.5 million tons in 2017 to

Table 4. Sector-specific correlation coefficients

Dynamics of gross value added in sectors	Dynamics of emissions in agriculture			Dynamics of fugitive emissions (oil, gas, coal)			Dynamics of emissions during fuel consumption		
	2017–2020	2020–2023	2017–2023	2017–2020	2020–2023	2017–2023	2017–2020	2020–2023	2017–2023
Agriculture	0.60	0.80	0.58						
Mining				-0.17	-0.16	0.40			
Total							0.05	0.16	0.34

Source: compiled by the authors

Table 5. Model parameters

Parameter	Meaning
Number of observations	85
R^2	0.198
Adjusted R^2	0.179
F-statistic	10.148

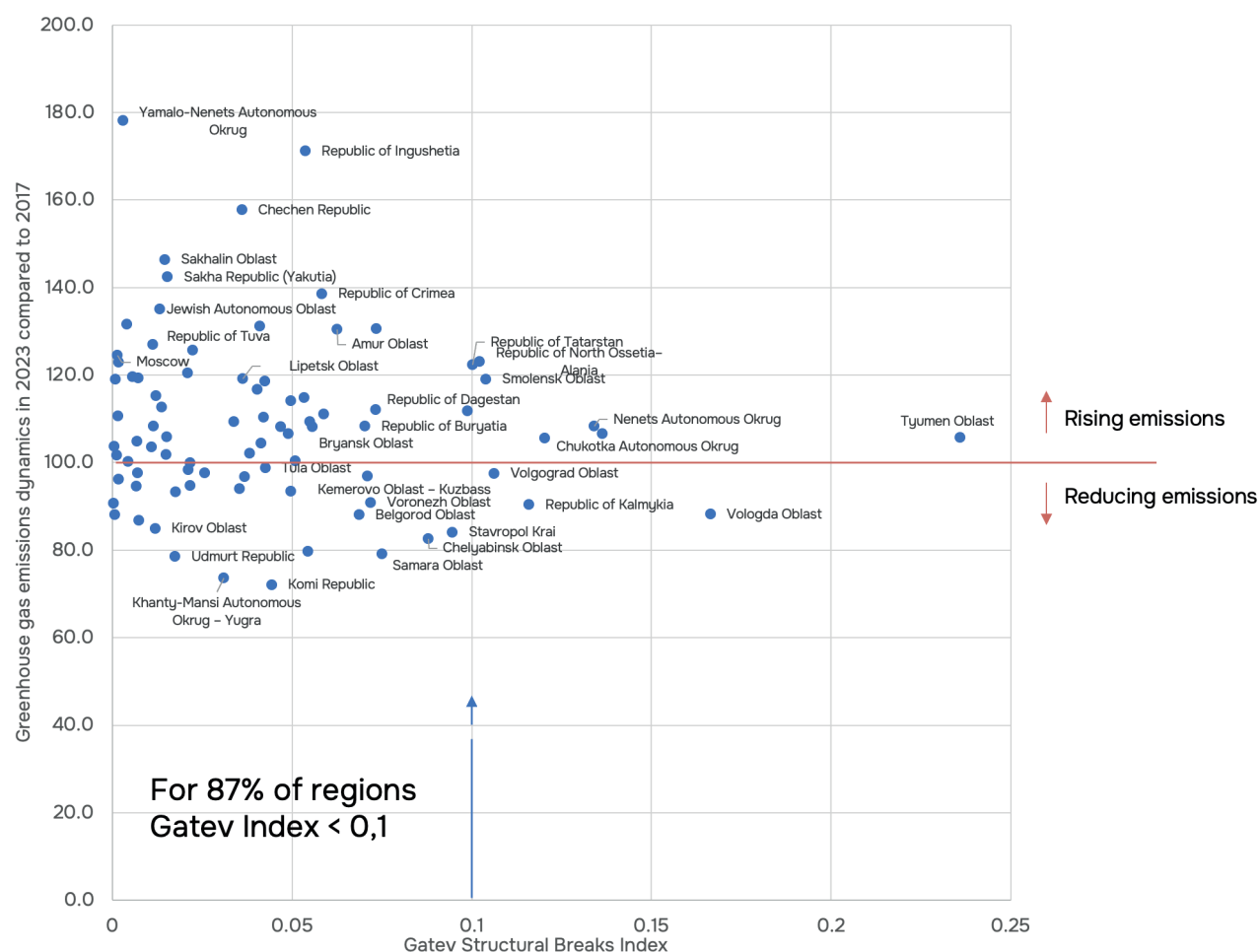
Source: compiled by the authors

Table 6. Coefficient estimates

Variable	Coefficient (β)	Std. Error	p-value
Constant	-0.0258	0.0308	0.404
$\ln(\text{GVA}(2023)/\text{GVA}(2017))$	0.758	0.194	0.00019
$\ln(\text{EI}(2023)/\text{EI}(2017))$	0.440	0.136	0.00180

Source: compiled by the authors

⁶https://archive.ipcc.ch/publications_and_data/ar4/wg3/en/ch1s1-3-1-2.html?



Source: compiled by the authors

Fig. 5. Comparison of the Gatev structural breaks index and the dynamics of greenhouse gas emissions in 2017–2023

1.6 million tons in 2023. In the Vologda Region, the driver of structural changes was a 33% reduction in emissions from fuel consumption, with a 10% increase in emissions from industrial processes. As a result, the share of industrial emissions increased from 49% to 61%. In the Volgograd region, the share of emissions from fuel consumption decreased from 88% to 78%, while the share of emissions from agriculture and industrial processes increased.

In the republics of Altai and Kalmykia, agricultural emissions declined by 15% and 36%, respectively, resulting in a higher share of fuel combustion in the overall emissions. In the Smolensk Region, emissions from industrial processes (chemical industry) increased by 46%, reducing the share of emissions from fuel consumption.

Overall, of the 11 regions with the Gatev Structural Breaks Index >0.1, seven showed major changes in their specialized sectors (fugitive emissions, industrial processes, and agriculture). Among the remaining regions, 80% of changes were in the fuel consumption emissions sector, which is the main sector in the emissions structure of most regions. Thus, for most regions, emission dynamics are explained by changes within the dominant sector (most often, fuel consumption). Structural shifts are more often manifested by changes in activity in non-fuel accounting sectors, such as fugitive emissions (oil, gas, and coal production), industrial processes (metallurgy, chemical industry), and agriculture. The most significant structural shifts are found in regions with ferrous metallurgy (Vologda and Lipetsk regions), chemical industry (Smolensk, Samara, and Volgograd regions, Stavropol Territory), and regions with old oil and gas production development (Republic of Tatarstan and the Nenets Autonomous District).

The decoupling effect, showing the level of consistency between changes in the identified factors of economic development and GHG emissions, was determined by the Eq. 1:

$$D_t = \frac{(V_t - V_0)/V_0}{(E_t - E_0)/E_0} \quad (1)$$

where V_0 and V_t are the volume of GHG emissions in the initial and final years of the period under consideration, respectively, and E_0 and E_t are economic parameters (GDP at base prices, electricity and heat consumption). The concept of ecological modernization serves as a fundamental theoretical basis for the idea of decoupling. Therefore, pollution dynamics can be compared with GDP, whose growth is an indicator of positive processes.

In this case, a distinction is made between absolute decoupling, when a real discrepancy between production and pollution trends occurs, and relative decoupling (Table 7).

Since GRP increased in most regions, two types of scenarios predominate: absolute decoupling and emissions growth faster than GRP.

Absolute decoupling is considered the most positive scenario, being typical for 29 regions. This group's contribution to GHG emissions is the largest, slightly higher than the country's GDP, population, and fuel consumption. Average per capita GRP and real income in this group are the lowest among the identified types, but they are growing at the fastest rate. The energy intensity of GRP is quite high, but it is declining.

In regions where fuel combustion accounts for over 85–90% of total emissions — including Arkhangelsk,

Table 7. Contribution of groups of regions with different decoupling scenarios to the volume of greenhouse gas emissions, GDP, and fuel consumption

Absolute decoupling effect										No decoupling effect									
Emissions are declining with GDP growth - 29 regions $D_t \leq 0$										Emissions rise in the absence of economic growth – 1 region $D_t \leq 0$									
Share of a group of regions in %										Share of a group of regions in %									
1	2	3	4		5					1	2	3	4		5				
37	29	36	29		33					0.33	0.27	0.03	0.02		0.03				
Relative decoupling										Specific emissions are growing									
Emissions are growing slower than GRP in 27 regions. $0 \leq D_t \leq 1$					Emissions are declining faster than GRP $D_t \geq 1$					Emissions are growing faster than GRP in 28 regions. $D_t \geq 1$					Emissions are declining more slowly than GRP $0 \leq D_t \leq 1$				
Share of a group of regions in %										Share of a group of regions in %									
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
29	29	34	35	31						34	42	30	36	36					

Note: Share of a group of regions in (1) the volume of GHG emissions, (2) gross value added, (3) population, (4) population consumption costs, and (5) thermal energy supplied

Source: compiled by the authors based on Tapio (2005)

Moscow, Pskov, Vladimir, Ulyanovsk, and Kurgan regions and the republics of Chuvashia and Mari El — structural shifts manifest as either an increased share of industrial emissions, typical of more industrialized regions such as Volgograd, Murmansk, Belgorod, and Chelyabinsk regions and the Republic of Udmurtia, or an increased share of agricultural emissions in agrarian regions such as Stavropol Territory, Voronezh region, and the republics of Chuvashia, Mordovia, Kabardino-Balkaria, and Adygea. The highest level of decoupling is characteristic of the Vologda Region, where the contribution of industrial emissions increased to 60%, primarily due to the chemical industry and, to a lesser extent, metallurgy. At the same time, fuel consumption in the region decreased. Similarly, in the Khanty-Mansi Autonomous District, a significant decrease in fuel intensity is not offset by an increase in fugitives.

Relative decoupling is typical for 27 regions where emissions grew at a rate more slowly than their GRP. This group's contribution to GHG emissions is equal to its contribution to other indicators. This group has the lowest levels of GRP energy intensity, per capita electricity consumption, motorization, and the share of urban and large-city populations. It can be divided into two subtypes:

– D_t ranges from 0 to 0.5, indicating that GDP growth of 10–30% is associated with emissions growth of 1–3%. In most regions of this group, fuel combustion remains the dominant factor, with its share in the emission structure staying relatively stable in areas with large thermal power plants and combined heat and power plants — including St. Petersburg, Kostroma, Nizhny Novgorod, Omsk, Novosibirsk, and Penza regions; Primorsky and Altai territories; and the Republic of Buryatia. The share of fuel emissions is decreasing in the Chukotka Autonomous District as a result of the launch of a floating nuclear power plant, and in the Astrakhan Region / Oblast as a result of a twofold increase in the share of industrial emissions. The share of fuel emissions increased in the Zabaikalsky Territory, reaching 84%, and in the Altai Republic, where emissions from agriculture grew faster than from fuel.

– D_t ranges from 0.5 to 1, i.e., where GDP growth is similar in terms of emissions growth rates. Among these regions, there are significantly fewer where fuel combustion accounts for more than 85% of emissions; these are primarily regions with large urban populations

(Leningrad and Sverdlovsk regions, Khabarovsk Territory). In most regions, the share of fuel as a source of emissions decreases slightly, favoring emissions from agriculture in developed agricultural regions (Krasnodar Territory, Kursk and Oryol regions) or fugitives in oil-producing regions (Bashkortostan and Tyumen Region).

Lack of absolute decoupling is typical for the Nenets Autonomous District, where emissions increased by 8%, mainly due to fugitive emissions, with a reduction in GRP.

Lack of relative decoupling is observed when emissions grow faster than GRP; this trend is observed in 28 regions. This group contributes 34% to total GHG emissions, 42% of GDP, 36% of fuel consumption, and 36% population consumption. Per capita GRP, real income, and energy intensity of GRP are the highest in this group. Based on the structure of GHG emissions, this group can be divided into three subtypes:

– regions where fuel combustion accounts for more than 90% of GHG emissions. These include relatively underdeveloped regions with cold climates and coal-fired power generation (republics of Tuva and Karelia, Jewish Autonomous Region, Magadan Region, and Kamchatka Territory), as well as machine-building regions of the European part with gas-fired power generation and a significant share of district heating (Moscow, the Yaroslavl, Ryazan, and Kaluga regions), as well as the republics of the North Caucasus, where energy is almost the only source.

– regions where the fuel factor accounts for 60–85% of emissions comprise two main types: powerful industrial regions combining fuel-based energy with a high share of hydroelectric and nuclear power, alongside developed metallurgy — such as Krasnoyarsk Territory, Irkutsk and Orenburg regions, and the Republic of Sakha (Yakutia) — and major oil and gas producing regions, such as the republics of Komi and Tatarstan, and Sakhalin Region. A high share of agricultural emissions, reaching up to a quarter of total GHG emissions, is characteristic of Tambov Region and the Republic of North Ossetia, while a pronounced industrial component is typical of regions where gas-fired energy is complemented by developed chemical and metallurgical industries, such as Novgorod and Smolensk regions and the Republic of Crimea.

– regions where the fuel factor accounts for 25–45% of total emissions, which is attributable either to the predominance of fugitive emissions in the GHG structure

— characteristic of regions with intensive hydrocarbon production such as the Yamal-Nenets Autonomous District and Tomsk Region — or to the dominance of ferrous metallurgy (Lipetsk Region), agriculture (the Republic of Dagestan), or hydroelectric generation in the electricity supply mix (the Republic of Khakassia).

In general, despite the decoupling effect in most regions, it is mainly characteristic of regions with lower per capita GRP and per capita income since economic growth trends are mainly characteristic of relatively small regions; the higher the energy intensity of the GRP, the higher the decoupling effect D_i .

CONCLUSIONS

GHG emission dynamics in Russia over the study period 2017–2023 were multidirectional across sub-periods and highly heterogeneous across regions:

- regional analysis revealed internal negative trends resulting from insufficient modernization, whereby emissions decline more slowly than production during economic downturns, while during growth, emissions increase across the board. The pandemic-induced recession of 2020 led to emission declines in the majority of regions (48 out of 85) while the subsequent recovery over 2020–2023 was reflected in rising emissions across 72% of regions;

- the period 2017–2020 is characterized by a more diverse picture of growth drivers, with emissions from industrial processes in specialized industries outweighing the decline/increase in fuel emissions. During the recovery phase of 2020–2023, fuel combustion represented the dominant source of emission growth, reflecting the energy-intensive nature of the Russian economy. Overall, across the full study period, the spatially heterogeneous pattern gradually gives way to an east–west divide, driven by the predominance of fuel-based energy generation, particularly coal;

- aggregated socioeconomic indicators, selected based on international studies, poorly explain the interregional dynamics of total GHGs due to excessive

aggregation of the dependent variable, sectoral specificity with its own drivers, and the short-term analysis horizon. However, for the entire period 2017–2023, the dynamics of GHG emissions by Russian regions are statistically correlated with the dynamics of GVA at constant prices and the energy intensity of GRP and explain approximately 18% of the interregional variation. These results are consistent with the classical Kaya framework, whereby emissions grow with expanding economic scale, modulated by the indirect influence of intensity and efficiency factors;

- there has been no significant change in the structure of emission factors in the regions, while the emission dynamics themselves are not determined by structural changes; no clear connection between the magnitude of the structural shift and the overall emission dynamics is observed. In regions with the most significant emissions growth, the sectoral structure of emissions has remained virtually unchanged;

- for most regions, GHG emission dynamics are driven by changes within the dominant sector, most often fuel consumption. Notable structural shifts are observed only in isolated non-fuel accounting sectors, primarily in specialized industries (fugitive emissions from oil, gas, and coal production, industrial processes (metallurgy, chemicals), and agriculture);

- despite a country-wide decoupling effect, the divergence between economic indicators and GHG emission dynamics is geographically heterogeneous. With GRP growing in the majority of regions, they were divided almost equally into three groups: those exhibiting absolute decoupling (emissions declining despite GRP growth), those exhibiting relative decoupling (emissions growing more slowly than GRP), and those showing the absence of relative decoupling (emissions growing faster than GRP). The hypothesis that decoupling is more pronounced in wealthier regions with higher GVA per capita was not confirmed. The diversity of trajectories suggests that, in the context of catch-up modernization, economic dynamics alone do not determine emission changes across regions; in most cases, sector-specific factors exert a stronger influence. ■

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