Adapting Innovation Development Management Processes to Improve Energy Efficiency and Achieve Decarbonization Goals

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Abstract

The study focuses on decarbonization problems as a systemic priority for the innovative transformation of the national economy at the time when the global economy faces new challenges. The research hypothesis confirms a dual effect in the scope of the "innovation - energy efficiency - decarbonization" triad, with each item being affected by the two others. We applied econometric models, testing them using data from 83 Russian regions for 2016-2020. The identified effects are critical for developing a conceptual framework to adjust management goals related to the energy efficiency and decarbonization of the Russian economy. The paper suggests that Russian regions should adopt the triad approach in drafting their energy efficiency and decarbonization plans. It also provides a deeper understanding of the relations between the triad elements. The results can be useful for practitioners aiming to improve the sustainability of national economies. Importantly, our findings could be applied by countries at different economic development levels using a different mix of energy sources to accomplish decarbonization or carbon neutrality goals.

Keywords: innovative development; improving energy efficiency; decarbonization; dual influence effects; managing energy system transition

Citation: Melnik A., Naoumova I., Ermolaev K. (2023) Adapting Innovation Development Management Processes to Improve Energy Efficiency and Achieve Decarbonization Goals. *Foresight and STI Governance*, 17(1), 51–66. DOI: 10.17323/2500-2597.2023.1.51.66

Introduction

An appreciable increase in the international community's attention to the green climate agenda has set a new global trend toward the decarbonization of national economies. The devastating effects of climate change are becoming so apparent, including in the Russian Federation, that denying them no longer seems to be possible (Porfiryev et al., 2021). Moreover, in our country, the climate change issue is more acute than on average across the planet (Zhigalov et al., 2018). The emerging trend towards decarbonization matches the sustainable development paradigm which combines global environmental, socioeconomic, and science and technology goals and outlines the prospects for global economic development (Bohra et al., 2022; Hernan, et al., 2022; Ye et al., 2022).

Despite the global nature of the problem under consideration, when determining one's attitude toward the climate agenda and predicting the scale of potential changes in the economy, one should proceed primarily from national interests (Gatto et al., 2021; Levenda et al., 2021; Porfiriev, 2021). At the same time, the uncertainty of the relevant processes, further aggravated by the changes in the geopolitical situation, should be fully taken into account. Many of the previously proclaimed and seemingly unshakable global economic development priorities, such as, for example, the complete rejection of the use of coal in the short term or replacing traditional fuels with alternative energy sources, are gradually being disavowed.[1]

Under the current circumstances, denying the existence of major challenges when making strategic decisions about Russia's future is fraught with unpredictable and irreversible consequences for national security (Pakhomova et al., 2021). Due to ongoing attempts to use the green agenda as a new tool for applying economic and political pressure, the level of potential threats has dramatically increased, which can lead to serious problems in various industries and activity areas (Kryukov et al., 2021; Makarov et al., 2021). All this creates the need to promptly deal with a wide range of new issues related to the decarbonization of the global economy, as a key prerequisite of achieving carbon neutrality (Bashmakov, 2020).

Given the current disagreements about the approaches to solving the existing problems, most researchers recognize the special role of innovative energy efficiency improvement strategies in the interests of decarbonization. However, so far the mechanisms for their implementation essentially remain undeveloped, while the possible effects of mutual impact in the scope of the "innovation - energy efficiency - decarbonization" triad are understudied.

Literature Review

The problems associated with introducing energy-efficient innovations are discussed in the context of different national economy levels, with a particular emphasis upon assessing the impact of various factors including the dynamics of fuel and energy prices (Brutschin et al., 2016), the export-import orientation of the economy (Urpelainen, 2011), the scope for transferring advanced technologies (Wan et al., 2015), the amount of foreign investments, and so on. Considerable attention is paid to supporting energy efficiency-related innovation, among other ways through government initiatives to promote innovation in the field of energy technologies (Winkler et al., 2011; Fri et al., 2014). Despite the existence of numerous approaches to improving energy efficiency through innovation, researchers from different countries agree on the importance of dealing with this issue to promote economic development (Patterson, 1996; Bobylev et al., 2015; Costantini et al., 2017).

Research aimed at achieving the sustainability of energy systems based on, in particular, innovative solutions such as smart grids, smart devices (Hyytinen et al., 2015), and other technologies received a serious impetus. Effort taken in this area promoted the development of advanced data collection, processing, and analysis technologies to support managerial decision-making (Luong, 2015), improve energy infrastructure (Thoyre, 2015), and develop energy efficiency strategies based on new opportunities (Liu et al., 2016; Ruiz-Fuensanta, 2016). To date, the approach that assesses the increase in energy efficiency of national economies on the basis of the reduction in energy resources consumed to produce products/services, and sees this area as the most important for meeting current development challenges, continues to prevail (Bolson et al., 2021; Panait et al., 2022; Wu et al., 2021). The effect of energy conservation and energy efficiency improvements on achieving strategic development goals is frequently ignored (Zakari et al., 2022).

Researchers addressing the improvement in the energy efficiency of national economies tend to see innovation as the most important factor of and a necessary condition for such changes (Newell et al., 1999; Popp, 2002; Urpelainen, 2011). Enterprises which pursue active innovation policies demonstrate higher levels of energy efficiency and tend to apply the best available technologies (Song et al., 2015; Sohag et al., 2015). Examples of major technological projects in this area include the international Energy Star program (Boyd et al., 2008; Qiu et al., 2019) and the Chinese Top 100-1,000-10,000 Enterprises program (Lewis, 2011; Zhao et al., 2016; Qi et al., 2020). All this allows one to conclude that increasing energy efficiency based on the broad adoption of innovations remains a key priority for the development of national economies.

Due to the aggravation of the climate agenda in recent years, decarbonization issues have become particularly relevant (Table 1). Reducing the environmental impact of production activities not only does not contradict the goal of increasing its efficiency, but on the con-

[1] https://www.vedomosti.ru/business/articles/2022/04/26/919731-globalnaya-energetika-vozvraschaetsya-k-ugolnoi-generatsii , accessed 25.08.2022.

Table 1. **Main Areas of Decarbonisation Research**

Research area	Literature
Achieving competitive advantages through the introduction of green technologies	(Kuhn et al., 2022; Lenox, 2021; Wang et al., 2022)
The relationship between energy production and consumption on the one hand, and carbon emissions on the other	(Dalla Longa et al., 2022; Natali et al., 2021; Pandey et al., 2022)
Increasing energy efficiency as a key area of national economies' decarbonisation	(Mier et al., 2020; Obrist et al., 2022; Pakhomova et al., 2021)
The relationship between investments in renewable energy sources and CO2 emissions	(Acheampong et al., 2019; Ikram et al., 2020; Mehmood et al., 2022)
The Impact of government initiatives to promote decarbonisation on economic performance	(Al Mamun et al., 2022; Rissman et al., 2020; Stephenson et al., 2021)
Managing companies in the context of "carbon tax" introduction	(Dixit et al., 2022; Domon et al., 2022; Reaños et al., 2022)
Rebound effect of energy efficiency	(Chen et al., 2021; Baležentis et al., 2021; Berner et al., 2022)
Source: authors.	

trary serves as an important development incentive (Dell'Anna, 2021; Koval et al., 2021; Sarkar et al., 2021).

Despite the differences in the current approaches to many of the fundamental energy transition issues (Gatto, 2022; Shahbaz et al., 2022; Bompard et al., 2022), most experts agree on the critical contribution of energy efficiency improvements to achieving carbon neutrality (Zeka et al., 2020; Nam et al., 2021; Khan et al., 2022). At the same time, their positions are often reduced to simply noting a significant contribution of increased energy efficiency to solving climate problems, without disclosing management mechanisms applied to accomplish decarbonization objectives in terms of identifying mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad.

A review of the current state of the problem under consideration reveals that, despite the attention the scientific community pays to various green agenda aspects, no consensus has yet been reached on possible ways to adapt the existing government mechanisms to meet the current global challenges and overcome threats.

Methodology

Methodologically, this study is based on the results of our previous research (Melnik et al., 2021). Using data from various Russian regions, it first of all confirmed the presence of a mutual impact of increased energy efficiency and innovation-based development processes; secondly, it revealed its basic nature, which largely determines additional positive effects in various industries and activity areas; and thirdly, through the empirical testing of the proposed assumption, one of these effects was assessed, which confirmed the potential for stepping up Russian regions' exports as their energy efficiency increases.

Further development of the previously suggested methodology is aimed at adapting it to address decarbonization problems. A hypothesis was put forward in the course of the study about the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad. To confirm it, it was proposed to divide the study into two stages. In the first stage, the existence of the triad itself is postulated for subsequent consideration of the effects arising within it. The objective of this stage is to avoid randomly including any other intuitively obvious parameters in the triad without sufficient grounds to expect the presence of paired relationships between its elements. To accomplish the set goals and confirm the above effects, paired direct and paired inverse models were used.

Compared with the previous ones, the proposed approach proceeds from a broader understanding of the nature of paired relationships between the processes under consideration. This allows one to assess not only the effects of the direct paired impact, e.g., of innovation in the dependencies "innovation → energy efficiency" and "innovation → decarbonization", but also those of the inverse one: "energy efficiency → innovation", and "decarbonization → innovation" (Figure 1). This statement also holds true for the effects of direct and inverse paired impact in "energy efficiency → decarbonization" dependencies. By modeling the impact of a factor attribute on the resulting one, one could assess the effects of direct and inverse paired impact in the dependencies under consideration, presented as follows:

a) direct and inverse paired impact in the "decarbonization – innovation" relationship:

$$D = f(I); \quad I = f(D), \tag{1}$$

b) direct and inverse paired impact in the "decarbonization - energy efficiency' relationship:

$$D = f(E); \quad E = f(D), \tag{2}$$

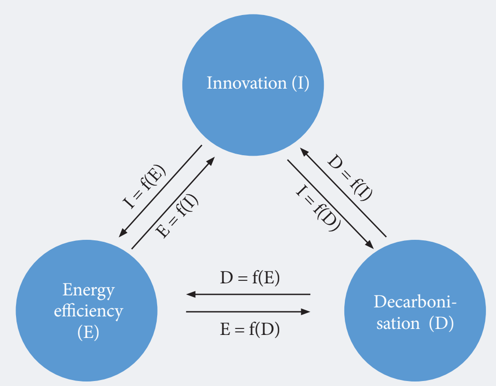
c) direct and inverse paired impact in the "innovation - energy efficiency" relationship:

$$I = f(E); \quad E = f(I), \tag{3}$$

where I are indicators applied to assess the innovation-based development level; E are indicators applied to assess energy efficiency; and D are indicators applied to assess the level of harmful emissions.

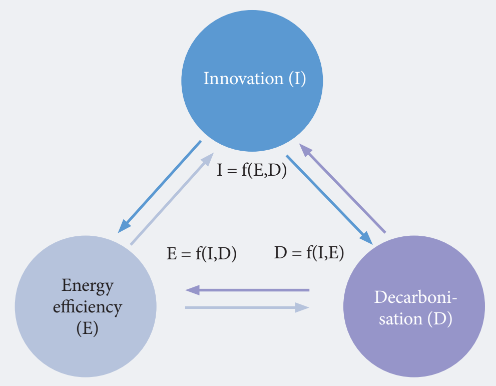
At the second stage, after substantiating the composition of the triad, an econometric approach was applied to confirm the suggested hypothesis about the dual ef-

Figure 1. **Paired Impact in the Scope of the "Innovation-Energy efficiency–Decarbonization" Triad**



Source: authors.

Figure 2. **Dual Effect of Mutual Impact in the Scope of the "Innovation–Energy Efficiency–Decarbonization" Triad**



Source: authors.

fects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad. A system of interrelated equations describing the impact was used for this purpose.

The validity of the applied approach is confirmed by the fact that, as follows from dependencies (1) - (3), each of the presented components of the "innovation-energy efficiency–decarbonization" triad is affected by two parameters, which implies the presence of complex relationships between the processes under consideration: e.g., innovation and energy efficiency simultaneously impact decarbonization, energy efficiency is simultaneously impacted by innovation and decarbonization, while innovation – by energy efficiency and decarbonization. Along with a direct impact (e.g. by innovation on the solving of decarbonization problems), there is also an indirect one: of energy efficiency improvements achieved through the application of energy efficient innovations. In this case, to test the suggested hypothesis, the assumed dependencies in the triad can be presented as a system of interrelated (concurrent) equations:

$$\begin{cases} D = f_D\,(I, E) + \varepsilon \\ E = f_E\,(I, D) + \varepsilon \\ I = f_I\,(E, D) + \varepsilon \end{cases} \qquad (4)$$

where f are functions linking the triad indicators to a set of exogenous factors, and ε is random error.

In this case all three indicators D, E, I are endogenous; in the course of solving system (4), the equations will be supplemented with exogenous variables to ensure the system's solvability. A two-step least squares method (2LSM) was applied to solve the constructed simultaneous equations system.

For simulation purposes, the simultaneous impact of two factors on the third one (the resulting one in the triad under consideration) will be called the "dual effect of mutual impact". The starting point for further reasoning is the hypothesis that each of the two factors make both direct and indirect impacts on the resultant one, by changing the other factor (Figure 2). In the actual study, the target model will be selected depending on which triad component is considered the resulting one, and which are the factorial ones. Thus in the context of decarbonization, assessing the direct impact of innovation on accomplishing this goal involves taking into account its indirect impact too (through increased energy efficiency).

The suggested methodology can be applied to make decisions aimed at achieving the decarbonization of the Russian economy to promote sustainable global development (Figure 3).

Effects of the Paired Direct and Inverse Impact in the Scope of the "Innovation-Energy Efficiency–Decarbonization" Triad

In the framework of the chosen methodology, at the first stage empirical calculations were conducted to identify the effects of paired relationships in the "innovation-energy efficiency–decarbonization" triad. They were based on panel data for 83 Russian regions for 2016-2020. To assess the innovation performance at various life cycle stages (including research and development (R&D), application of innovations, commercialization, and scaling of the results obtained), official statistical data published by the Russian Federal State Statistics Service (Rosstat) were used.[2] At the first stage of the life cycle, innovation activities were identified using such indicators as number of R&D per-

[2] https://rosstat.gov.ru/statistics/science, accessed 25.08.2022.

sonnel, internal R&D expenditures, and expenditures specifically on environmental innovation. Regional enterprises' efforts at the implementation stage were assessed via the share of companies which have implemented technological, organizational, and marketing innovations in the reporting year in the total number of surveyed companies, and the number of advanced production technologies applied by Russian regions. Finally, at the commercialization and scaling stage the performance was calculated on the basis of the value of shipped innovative products/provided services, and their share in the total value of all shipped products/provided services.

Rosstat data also served as the source of information for assessing regions' energy efficiency. It was calculated as the ratio of gross regional product (GRP)[3] (in constant 2016 prices) to electricity consumption in the region.[4]

Indicators for assessing regional pollutant emissions into the environment were based on Rosstat and the Federal Service for Supervision of Natural Resources data.[5] The key indicator is atmospheric emissions from stationary and mobile pollutant sources, including sulphur dioxide, nitrogen oxides, carbon monoxide, volatile organic compounds, ammonia, etc., which largely determine decarbonization targets. Stationary sources are understood as immovable technological units (installations, devices, apparatus, etc.) emitting air pollutants during operations; mobile sources primarily mean road and rail transport. In the absence of alternative and equivalent statistics, pollutant emissions fit the context of our study best. Thus, some authors note that reduction in greenhouse gas emissions directly correlates with a decrease in the concentration of other pollutants in the atmosphere (Rauner et al., 2020; Bobylev et al., 2022).

During the second stage of work, various indicators used in the empirical calculations can be applied in models as control or instrumental variables. These include, in particular, GRP (Baev et al., 2013; Frenkel et al., 2013; Safiullin, 2021), electricity consumption (Solovieva, Dzyuba, 2016), value of in-house-produced shipped goods (Strizhakova, 2019), per employee electricity consumption (Yakunin, 2017), etc. All variables included in the calculations are presented in Table 2.

To accomplish the objectives set for the first stage of the study, random effect (RE) and fixed effect (FE) models were applied, which allowed for taking into account unquantifiable individual differences between objects (Hsiao et al., 2010). These differences are interpreted as an extra parameter to be excluded. The use of such models allows one to confirm a direct relationship between the parameters under consideration. To improve the models' reliability, key variables' lags and unobservable time effects were taken into account. In the model itself, robust standard errors were used to level the explanatory variables' autocorrelation. The model specification was tested using the Hausman test to compare fixed and random effects models, and the Breusch-Pagan test to compare the random effects and linear models (Greene, 2003). The simulation results are presented in Table 3, the interpretation of the empirical calculations in Table 4.

The results obtained at the first stage of the study using data on Russian regions' economic development allowed the authors to substantiate the actual existence of the "innovation-energy efficiency-decarbonization" triad for the subsequent study of the dual effects of mutual impact arising within its scope.

The Study of the Dual Effects of Mutual Impact in the Scope of the "Innovation-Energy Efficiency–Decarbonization" Triad

In accordance with the chosen methodology, at the second stage of the study, empirical calculations were carried out to assess the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad using panel data for 83 Russian regions for 2016-2020. Based on the analysis of the correlation matrix of indicators (the results are presented in Table 2), the constructed system of interrelated equations (4) takes the following form:

$$\begin{cases} D\_L\_vibros = E\_L\_eef + I\_L\_inproduct + L\_vrp + I\_L\_pers + I\_L\_cost + I\_L\_mantech + \varepsilon_1 \\ E\_L\_eef = D\_L\_vibros + I\_L\_inproduct + L\_vrp + I\_L\_pers + I\_L\_cost + I\_L\_mantech + \varepsilon_2 \\ I\_L\_inproduct = D\_L\_vibros + E\_L\_eef + L\_vrp + I\_L\_pers + I\_L\_cost + I\_L\_mantech + \varepsilon_3 \end{cases} \quad (16)$$

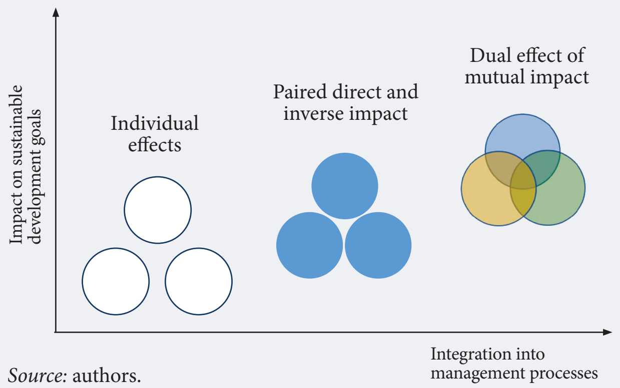
The endogenous variables to assess the level of innovation development, energy efficiency, and harmful emissions were defined as D_L_vibros, E_L_eef and I_L_ inproduct, respectively, and the control variables as follows: GRP as L_vrp, number of R&D personnel as I_L_pers, internal R&D expenditures as I_L_cost, developed advanced manufacturing technologies as I_L_mantech. The following indicators were used as instrumental variables: shipped in-house-produced products L_product, in-house-produced products shipped in the previous period L_product(t-1), electricity consumption L_electropotr, electricity consumption in the previous period L_electropotr(t-1), GRP in the previous period L_vrp(t- 1), per employee electricity consumption L_electro, specific expenditures on environmental innovation in the previous period L_ecocost(t-2), innovation activity in the previous period L_innactiv(t-2).

[3] https://rosstat.gov.ru/statistics/accounts, accessed 25.08.2022.

[4] https://rosstat.gov.ru/regional_statistics, accessed 25.08.2022.

[5] https://rosstat.gov.ru/folder/11194, accessed 25.08.2022.

Figure 3. **Effect of Mutual Impact in the Scope of the "Innovation–Energy Efficiency–Decarbonization" Triad**



Source: authors.

The presented system of simultaneous equations is over-identifiable, so 2LSM can be used to estimate its parameters. The estimates are presented below, excluding variables which did not significantly impact the resulting one:

$$\begin{cases} D\_L\_vibros = -5.832 - 0.947 * E\_L\_eef - \\ 0.144 * I\_L\_\ inproduct + 1.144 * L\_vrp + \varepsilon_1 \\ E\_L\_eef = -5.442 - 0.995 * D\_L\_vibros - \\ 0.15 * I\_L\_\ inproduct + 1.156 * L\_vrp + \varepsilon_2 \\ I\_L\_\ inproduct = -31.305 - 4.265 * D\_L\_ \\ vibros - 4.251 * E\_L\_eef + 5.45 * L\_vrp + \varepsilon_3 \end{cases} \quad (17)$$

According to Student's t-test, for the given variables the statistical significance threshold is 1%. The model is also adequate at significance level of 1% according to Fisher's F-test. The tools applied to construct a multiple regression must be, firstly, exogenous (i.e., they must not correlate with the model's random errors), and secondly, relevant (i.e., they must correlate with endogenous regressors). Tools meeting both these requirements are considered as valid, while the use of a two-step LSM ensures validity of the coefficient estimates obtained.

During the calculations, the requirements for the selected instrumental variables were checked, and their validity substantiated (Table 5). To assess the relevance, reference values for the corresponding F-statistics were obtained by testing the hypothesis about the significant contribution of the applied tools to explaining the changes in the endogenous variable. In practice, the following rule is typically used: tools are considered to be relevant if the calculated reference value of the F-statistic for testing this hypothesis exceeds 10 (Stock et al., 2002). As the calculations carried out in line with this principle show, all the applied tools are relevant.

The tools' exogeneity was tested with the Sargan test (the overidentifying restrictions test), which is only possible if the number of applied tools exceeds the number of endogenous regressors. The test's null hypothesis is that all of these tools are exogenous, and the alternative one is that at least one of them is endogenous. At a 1% significance level, all the tools applied in the calculations are exogenous. An additional Hausman test allows one to decide about the advisability of using 2LSM, or applying ordinary LSM. The confirmed validity of the applied tools is a prerequisite for this test. Its null hypothesis is that the least squares estimates of the model coefficients are consistent. If it is not rejected, the ordinary least squares method is suitable for estimating the coefficients: the results will be valid. If the null hypothesis is rejected, it means LSM is not suitable for assessment, so 2LSM should be used. On the basis of the test results, the hypothesis was rejected, which confirmed the need to use 2LSM. To assess indicators' elasticity in a system of interrelated equations, a 95% confidence interval (17) was built.

No variable's confidence interval contains a zero value; this confirms that corresponding indicators impact the explanatory variable, which for a number of variables is elastic. The interpretation of empirical calculations' results is presented in Table 7.

The quality of the calculations was assessed using the first equation in system (17) as an example, which reflects the dual effects of the impact of improvements in innovation development and energy efficiency on accomplishing decarbonization goals. A plot of observed and calculated values of the D_L_vibros variable (Figure 4) shows that statistics (marked by the red "+" symbol) and data obtained from the constructed models (marked by the blue "x" symbol) are close enough to each other, which reflects the high predictive potential of the constructed regression equation. Deviations of the calculated values from the actual ones observed for some equations can be caused both by errors in the initial data and by factors not taken into account in the model. Without refuting the statistical reliability of the obtained empirical regression equations, this necessitates further research.

The partial elasticity coefficients E calculated below show the change in the dependent variable (as a percentage) when the corresponding factor changes by 1% (Florens, 2007). In particular, the comparison showed that the first equation in system (17) which describes the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad has a 1.85% higher energy efficiency elasticity coefficient than the mutual impact model (5) (Table 8). That is, if in model (17), which describes the dual effects energy efficiency, changes by 1%, emissions will decrease by 1.96%, while in the mutual impact model (5) they will only decrease by 0.109%. A similar ratio of effects was found for the second equation in system (17) and model (9) for innovation activity, and for the third equation in system (17) and model (15) for emis-

Table 2. **Indicators Applied in the Calculations**

Indicator	Designation	Unit
Energy efficiency	E_L_eef	roubles/kwh.
Atmospheric pollutant emissions from stationary and mobile sources	D_L_vibros	thousand tons
Number of R&D personnel	I_L_pers	people
Internal R&D expenditures, by Russian region	I_L_cost	roubles
Specific expenditures on environmental innovation	I_L_ecocost	roubles
Developed advanced production technologies, by Russian region	I_L_mantech	units
Regional organisations' innovation activity compared to all organisations'	I_L_innactiv	%
Value of shipped innovative products/provided services	I_L_ inproduct	roubles
Share of innovative products/provided services in total value of shipped products/provided services	I_L_vesproduct	%
Shipped in-house-manufactured products	L_product	million roubles
Per employee electricity consumption	L_electro	kwh
GRP	L_vrp	thousand roubles
Electricity consumption	L_electropotr	million kwh
Share of investments made for restructuring/modernisation purposes in total amount of capital investments	L_invest	%
Share of investments in machinery, equipment, and vehicles in total amount of capital investments for restructuring/modernisation purposes	L_investm	%
Labour productivity index, by Russian region	L_trud	% of previous year
Actual household monetary income	L_dohod	% of previous year

Source: authors.

sions. The obtained data indicates that in terms of impact, dual effects in the scope of the considered triad exceed paired effects, which is particularly important for choosing investment strategies aimed at promoting decarbonization.

The results obtained using data for Russian regions confirm the suggested hypothesis about the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad.

The further application of the proposed methodology has significant potential for accomplishing various applied objectives of meeting decarbonization targets and addressing a wide range of research issues. We are talking about forecasting various factors, in particular total greenhouse gas emissions (or individually sulphur dioxide, nitrogen oxides, carbon, etc.), returns on innovations created to promote decarbonization, and constructing dynamic models of innovation activity indicators related to the implementation of sustainable development goals at various levels. Solving analytical problems related to strategic development seems to be a promising area, which combines academic feasibility studies for meeting various decarbonization targets under different science and technology development scenarios with regulatory forecasting, and identifying necessary conditions for such development.

The list of possible objectives and application areas can be expanded or adjusted to meet specific management levels, priorities, and time periods.

How Energy Efficiency and Decarbonization Objectives are Reflected in Russian Regional Innovation-Based Development Programs

The identified dual effects of mutual impact of the processes under consideration provided the basis for further research. An analysis of the progress in increasing energy efficiency and accomplishing decarbonization objectives, and of their reflection in the published innovation development programs of 83 Russian regions revealed the following areas for more detailed consideration:

1. Inclusion of measures aimed at increasing energy efficiency and decarbonization into these programs.
2. Inclusion of the results of implementing measures aimed at increasing energy efficiency and decarbonization in the list of key performance indicators for these programs.
3. Evaluation of the contribution of the implemented measures aimed at increasing energy efficiency and decarbonization to meeting regional innovation development targets.
4. Evaluation of the division of responsibility for the results of innovation activities, and for improving energy efficiency and decarbonization at the regional level.

The analysis allowed us to draw the following conclusions. First, innovation development management models implemented in different Russian regions

Table 3. **Simulation Results for Calculating Paired Relationships' Effects in the Scope of the "Innovation-Energy Efficiency–Decarbonization" Triad**

Model No.	Dependent variable	Method	Independent variables	Coefficient	Standard error	P-value	R-square	Hausman test	Breusch-Pagan test
(5)	D_L_vibros	FE	Const	–5.175	2.914	0.079*	0.989	0.159	0.057
			E_L_eef	0.387	0.231	0.098*			
			L_trud	0.503	0.242	0.041**			
			L_vibros_1	0.8	0.19	6.28e–05***			
			Dt_2	0.349	0.054	7.43e–09***			
			Dt_3	0.352	0.054	7.05e–09***			
			Dt_4	0.139	0.044	0.002***			
		RE	E_L_eef	–0.053	0.022	0.016**			
			L_trud	0.381	0.231	0.099*			
			L_vibros_1	1.011	0.03	3.03e–243***			
			Dt_2	0.319	0.037	2.55e–017***			
			Dt_3	0.307	0.032	1.11e–020***			
			Dt_4	0.085	0.013	2.62e–010***			
(6)	E_L_eef	FE	Const	15.612	1.553	4.56e–016***	0.995	6.49e–028	0.978
			D_L_vibros	–0.057	0.010	7.162e–07***			
			L_electropotr	–0.71	0.072	1.65e–015***			
			E_L_eef_1	0.191	0.107	0.077*			
		RE	D_L_vibros	–0.014	0.008	0.099*			
			L_electropotr	0.014	0.007	0.065*			
			E_L_eef_1	0.986	0.008	0***			
		MHK	D_L_vibros	–0.011	0.006	0.092*	0.986		
			L_electropotr	0.013	0.006	0.028**			
			E_L_eef_1	0.992	0.006	1.99e–102***			
(7)	I_L_ecocost	FE	Const	63.154	29.2676	0.0338**	0.43	0.05	6.75e–011
			E_L_eef	–5.381	2.653	0.0457**			
(8)	I_L_ mantech	RE	Const	–2.452	3.018	0.4165	0.85	0.712	5.62e–057
			E_L_eef	0.469	0.275	0.0879*			
(9)	E_L_eef	FE	Const	10.518	0.106	8.81e–089***	0.99	0.003	1.77e–109
			I_L_inproduct	0.06	0.012	6.42e–06***			
			I_L_vesproduct	–0.06	0.013	3.73e–05***			
			I_L_ecocost	–0.002	0.0009	0.02**			
(10)	D_L_vibros	FE	Const	9.227	0.984	1.063e–014***	0.965	1.19e–021	3.94e–019
			I_L_inproduct	–0.442	0.112	0.0001***			
			I_L_vesproduct	0.441	0.106	7.580e–005***			
			I_L_ecocost_2	0.022	0.009	0.02**			
(11)	I_L_pers	FE	Const	7.02	0.143	2.11e–062***	0.995	1.13e–007	2.17e–171
			D_L_vibros	0.109	0.026	0.0001***			
(12)	I_L_cost	FE	Const	8.426	0.236	1.17e–051***	0.99	1.06e–013	5.8e–159
			D_L_vibros	–0.129	0.043	0.0042***			
(13)	I_L_ mantech	FE	Const	4.617	0.959	9.49e–06***	0.857	0.001	1.85e–044
			D_L_vibros	–0.292	0.167	0.0859*			
(14)	I_L_ innactiv	RE	Const	1.342	0.233	8.64e–09***	0.69	0.877	4.39e–068
			D_L_vibros	0.152	0.04	0.0002***			
(15)	I_L_ inproduct	FE	Const	12.133	0.947	1.93e–021***	0.93	3.21e–016	2.62e–095
			D_L_vibros	–0.537	0.176	0.0031***			

Note: ***p < 0.01, **p < 0.5, *p < 0.1. Models (5) and (6) are described in detail, in models (7) - (12) estimated coefficients are presented in accordance with the results of the Hausman and Breusch-Pagan tests.

Source: authors.

largely reproduce the structure and characteristics of the federal governance model.

Secondly, all Russian regions currently pay significant attention to improving energy efficiency. Almost all of them consider this area a priority in their innovation development programs, and the relevant indicators are among the key ones. At the same time, regions' progress in accomplishing decarbonization objectives remains in its infancy, and relevant indicators are not yet directly applied to evaluate innovation development results. Improvements here apparently should be expected only when a number of methodological limitations are overcome at the federal level.

Thirdly, although energy efficiency objectives set in regional programs are declared a priority, in reality in most cases they remain unrelated to the most important innovation development targets, i.e., they apparently are not considered critical from a strategic point of view. Until recently decarbonization was not included among the set of priorities either.

Table 4. **Interpretation of Empirical Calculations to Assess Paired Relationships' Effects in the Scope of the "Innovation-Energy Efficiency-Decarbonization" Triad**

Model No.	Regression equation	Interpretation
	«Energy efficiency – decarbonisation» D = f(E), E = f(D)	
(5)	Direct relationship: D_L_vibros = −1.51 − 0.0528 * E_L_eef − 0.00216 * L_L_product + 0.381 * L_trud + 0.319 * dt_2+ 0.307 * dt_3 + 0.0845 * dt_4 + 1.01 * D_L_vibros_1	Increased energy efficiency contributes to reduced emissions.
(6)	Inverse relationship: E_L_eef = 0.0421 − 0.0116 * D_L_vibros + 0.0134 * L_electropotr + 0.992 * E_L_eef_1	Emissions increase with decreased energy efficiency.
	«Energy efficiency – innovation» I = f(E), E = f(I)	
 (7) (8)	Direct relationships: I_L_ecocost = 63.2 − 5.38 * E_L_eef I_L_mantech = −2.45 + 0.470*E_L_eef	Increased energy efficiency reduces the need to invest in environmental innovation. Increased energy efficiency promotes development of innovative technologies.
(9)	Inverse relationship: E_L_eef = 10.5 + 0.06 * I_L_inproduct − 0.06 * I_L_vesproduct − 0.002 * I_L_ecocost	Increased innovation activities at all life cycle stages contribute to energy efficiency.
	«Innovation – decarbonisation» D = f(I), I = f(D)	
(10)	Direct relationship: D_L_vibros = 9.23 − 0.442 * I_L_inproduct + 0.441 * I_L_vesproduct + 0.0220 * I_L_ecocost_2	Increased innovation activity at various life cycle stages leads to reduced emissions of pollutants. At the same time expenditures on environmental innovations contribute to reducing emissions with a two-year delay.
 (11) (12) (13) (14) (15)	Inverse relationships: I_L_pers = 7.03 + 0.109 * D_L_vibros I_L_cost = 8.43 − 0.129 * D_L_vibros I_L_mantech = 4.62 − 0.293 * D_L_vibros I_L_innactiv = 1.28 + 0.164 * D_L_vibros I_L_inproduct = 12.1 − 0.538 * D_L_vibros	Increased pollutant emissions make a statistically significant impact on increasing innovation activities at various stages of its life cycle, and lead to increased number of R&D personnel, indicate a decrease in innovation expenditures, number of innovative technologies, and production of innovative products.

Source: authors.

Table 5. **Tools' Validity Tests and the Spplication of 2LSM for the Interrelated System Equations (17)**

System (17) equation, dependent variable	F-statistics	P-value (F)	Sargan test, p-value	Hausman test, p-value
D_L_vibros	123.243	5.55e-46	0.069	4.013e-006
E_L_eef	14.638	1.09e-08	0.058	0
I_L_inproduct	20.252	1.46e-11	0.019	3.701e-017

Source: authors.

Table 6. **Interval for Dey Variables of Interrelated System Equations (17)**

System (17) equation, dependent variable	Variable	Coefficient	95% confidence interval	
D_L_vibros	I_L_inproduct	−0.143	−0.251	−0.036
	E_L_eef	−0.947	−1.279	−0.614
E_L_eef	I_L_inproduct	−0.150	−0.246	−0.054
	D_L_vibros	−0.995	−1.328	−0.661
I_L_ inproduct	l_eef	−4.251	−6.298	−2.204
	l_vibros	−4.265	−6.477	−2.052

Source: authors.

Fourth, innovation development programs and reports on their implementation do not reflect the impact of relevant efforts on energy efficiency and decarbonization indicators on the one hand, and the latter's inverse impact on regions' innovation development progress on the other. The existing legal framework does not allow for the monitoring and evaluation of the identified dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization' triad.

Fifth, in all Russian regions, and at the federal level, the organizational systems for managing innovation, energy efficiency, and decarbonization function independently of one another. Various regional executive authorities' divisions are responsible for these areas; they develop and adopt their own program documents and targets, set procedures for planning and implementing them and monitoring the progress, establish mechanisms and formats for providing administrative, financial, economic, and legal decision-making support, and ultimately independently report results. Managing these processes at different levels at the same time leads to inconsistency, which can adversely affect the achievement of the goals.

Sixth, a wide range of issues related to innovation activities aimed at improving energy efficiency and the decarbonization of the economy to date remains unregulated by the Russian legislation. No flexible mechanisms have yet been designed to regulate innovation in the context of the rapid transition of the energy sec-

Table 7. **Interpretation of Empirical Calculations to Assess the Dual Effects of Mutual Impact in the Scope of the "Innovation-Energy Efficiency-Decarbonization' Triad**

Assessed element	System (17) equation	Interpretation
Decarbonisation D = f(I,E)	D_L_vibros = –5.832 – 0.947 * E_L_eef – 0.144 * I_L_ inproduct + 1.144 * L_vrp + ε_1	Increased energy efficiency, and increased production of innovative goods/services simultaneously contribute to reduced emissions.
Energy efficiency E = f(I,D)	E_L_eef = –5.442 – 0.995 * D_L_vibros – 0.15 * I_L_ inproduct + 1.156 * L_vrp + ε_2	Increased emissions, and increased production of innovative products simultaneously impact energy efficiency. Increased emissions indicate a decrease in energy efficiency. Increased production of innovative products has a similar effect.
Innovation I = f(E,D)	I_L_ inproduct = –31.305 – 4.265 * D_L_vibros – 4.251 * E_L_eef + 5.45 * L_vrp + ε_3	Increased energy efficiency, and increased emissions simultaneously affect innovation activity. Decreased energy efficiency indicates an increase in innovation activity. A decrease in emissions has a similar effect.

Source: authors.

tor to a new technological paradigm, and toward decarbonization.

The reflection of initiatives to increase energy efficiency and especially decarbonization in Russian regional (and federal) innovation development programs tends to be rather formalistic. At the same time, accomplishing relevant objectives remains outside the approved strategic priorities and does not set the innovation activity vector in Russia. A simplified approach to increasing energy efficiency and decarbonization in the scope of socioeconomic development still prevails at all government levels. Typically these objectives are seen from a tactical point of view, losing sight of not only strategic economic modernization issues, but also of the global sustainable development agenda based on carbon neutrality policy.

Thus the mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad is not considered when program documents for the development of the Russian economy are prepared at various levels of government,. Stepping up the effort to implement the green agenda requires taking these effects into account when shaping innovation policies to improve energy efficiency and address decarbonization challenges.

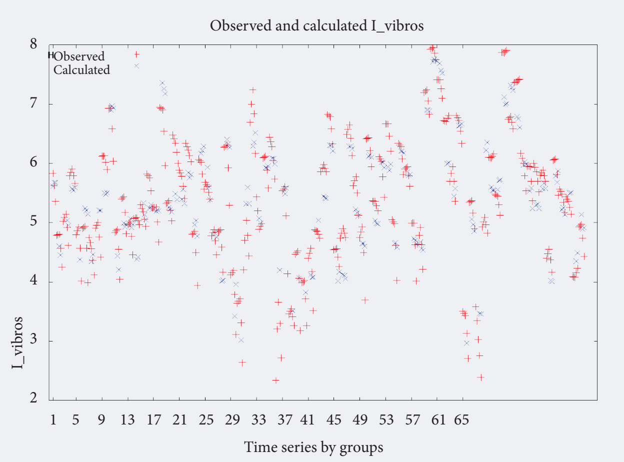
Conceptual Basis for Managing Innovation Development to Increase the Energy Efficiency and Decarbonization of the Russian economy

Adapting the existing system for managing the processes under study, taking into account the revealed effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonisation" triad, requires meeting the following conceptual requirements.

First, shaping policy in this area, one should proceed from the global climate agenda proclaimed at the UN level in line with the sustainable development paradigm. As the largest country in the world in terms of territory, the amount of fuel and energy resources supplied to the world market, the ferrous metallurgy, chemical, petrochemical, and other industries' output, the amount of industrial and natural greenhouse gases emissions into the atmosphere, and a number of other indicators, Russia cannot ignore these processes.

Secondly, developing a conceptual basis for the relevant policy and predicting the possible extent of the expected changes, one should focus on national interests and strategic goals. These are determined by the officially approved government priorities, the historical structure of the economy, the competitive advantages in the global goods and services markets, the achieved technological development level, and the availability of

Figure 4. **Observed and Calculated Values of Variable D_L_vibros for the Studied Panel Data**



Source: authors.

Table 8. **Assessment of Various Ractors' Impact on the Dependent Variable in Constructed Models**

Model No.	Dependent variable	Factor	Partial elasticity coefficient E
(5)	D_L_vibros	E_L_eef	-0.109
(6)	E_L_eef	D_L_vibros	-0.011
(7)	I_L_ecocost	E_L_eef	-15.686
(8)	I_L_mantech	E_L_eef	1.764
(9)	E_L_eef	I_L_ecocost	-0.0006
		I_L_inproduct	0.05
		I_L_vesproduct	-0.005
(10)	D_L_vibros	I_L_ecocost	0.015
		I_L_inproduct	-0.765
		I_L_vesproduct	0.082
(11)	I_L_pers	D_L_vibros	0.076
(12)	I_L_cost	D_L_vibros	-0.089
(13)	I_L_mantech	D_L_vibros	-0.531
(14)	I_L_innactiv	D_L_vibros	0.405
(15)	I_L_inproduct	D_L_vibros	-0.31
(17)	D_L_vibros	E_L_eef	-1.96
		I_L_inproduct	-0.249
	E_L_eef	I_L_inproduct	-0.272
		D_L_vibros	-0.48
	I_L_inproduct	D_L_vibros	-1.234
		E_L_eef	-2.348

Source: authors.

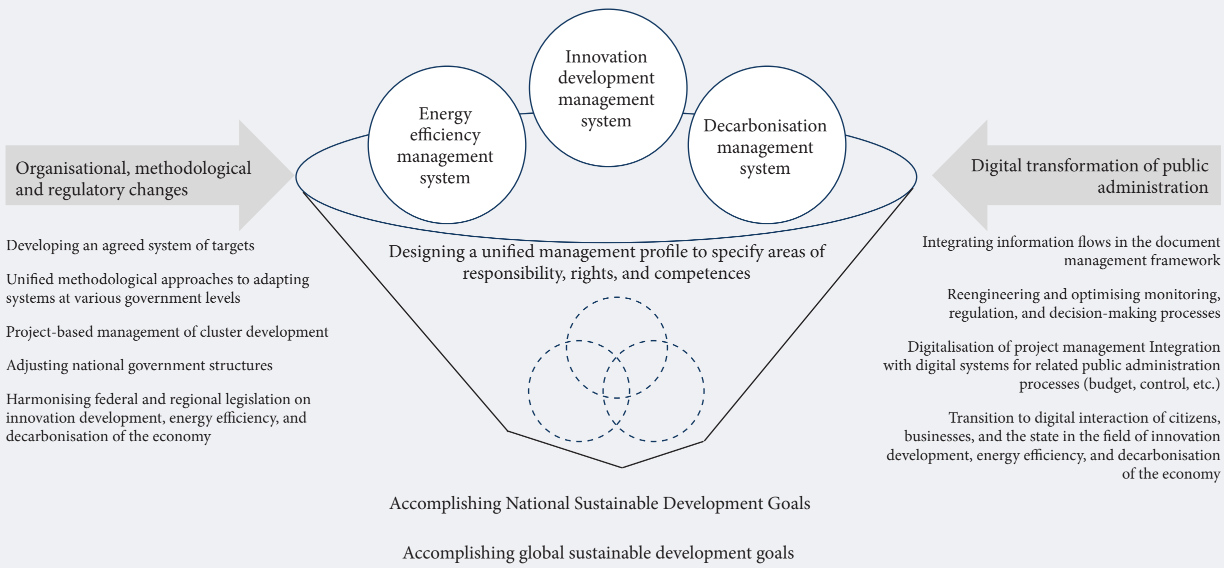
material, financial, human, and other resources for the energy transition.

Thirdly, a unified approach is needed at the federal and regional levels to adapt the mechanism for managing innovation-based development aimed at improving the energy efficiency and decarbonization of the economy. We are talking about developing a coordinated system of target indicators based on a single methodological platform.

Fourth, the adaptation of the administrative mechanism should first of all include integrating energy efficiency and decarbonization management processes into the innovation, science, and technology policy system, to create synergy. Such adaptation should on the one hand contribute to strategic growth of the energy sector, and on the other, to accomplishing decarbonization objectives as part of the Russian economy's transition to an innovative development path.

Meeting the above conceptual requirements implies taking steps to harmonize federal and regional legislation on innovation development, energy efficiency, and decarbonization; coordinating relevant targets, and structuring them by management levels; adopting a systemic approach founded on project- and cluster-based development principles; developing a system for monitoring innovation development, energy efficiency, and decarbonization progress in the scope of a uni-

Figure 5. **Main Areas for Adapting the Mechanism for Managing Innovation Development, Energy Efficiency, and Decarbonization**



Source: authors.

fied management profile, with an appropriate division of responsibilities and competences at each level. The digital transformation of public administration plays key role here, consolidating information flows into a document management system using big data technologies, reengineering, optimization of monitoring, regulation, decision-making, etc. (Figure 5).

The proposed integration of energy efficiency and decarbonization processes with innovation management will ensure the coordination of these three areas in the scope of a single profile covering various regulation levels. Harmonizing legislation on these three areas will optimize the relevant public support mechanisms. Implementing the described approach to adjusting the organizational structure will give priority status to the processes under consideration in a situation when new challenges and threats are emerging.

Conclusion

In recent years, almost all countries have been paying particular attention to various aspects of decarbonization, which has come to the fore of the global green agenda. Numerous studies have been published on choosing approaches to meeting new environmental challenges under various scenarios. Despite their differences, almost all of them emphasize the role of innovation as a tool to increase energy efficiency and promote decarbonization. However, specific mechanisms for their implementation remain insufficiently developed. To fill this gap, our study is the first to implement an integrated approach to addressing decarbonization issues by identifying dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad.

The focus on improving energy efficiency through innovation to facilitate achieving the decarbonization goal is due to the fact that the former is a key parameter of most modern technological processes and a characteristic of various types of products. Concentrating on increasing energy efficiency further will help create a technological foundation for developing basic industries, capable of giving an impetus to the whole economy. From the decarbonization point of view, energy efficiency can become a catalyst for developing technological solutions for entire production chains in various industries, from mining raw materials to final consumption. In its turn, this will allow entities to step up innovation processes throughout the national economy.

The results of the study confirm the suggested hypothesis about the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad. For this purpose, empirical calculations were conducted, using data for 83 Russian regions and yielding statistically significant results.

The theoretical importance of the obtained results is in confirming the dual effects of mutual impact in the scope of the "innovation-energy efficiency-decarbonization" triad and substantiating the need to take them into account when designing a conceptual framework for adapting the innovation development management system to accomplish energy efficiency and decarbonization objectives in the framework of a single management profile. The proposed methodology can support integrated decision-making on the decarbonization of the economy in the interests of global sustainable development, with national development goals having unconditional priority given sanctions pressure. The results of the study expand the scientific understanding of possible approaches to achieving these goals.

More important areas of future research may include, firstly, assessing the potential for the development and industrial application of critical domestic technologies to accomplish decarbonization goals in the context of limited access to advanced foreign technologies. Scientifically and methodologically substantiating strategic investments in sustainable economic development in the context of the decarbonization problem seems to be a productive area for analysis. It would also make sense to develop a mechanism for adjusting science and technology development indicators to match the specified objectives, while maintaining high growth rates of the Russian economy.

The proposed methodology, which was tested using data on the Russian economy, can be also useful for countries at different science and technology development levels and with different availability of resources to address practical problems associated with the energy transition and designing relevant mechanisms, including various aspects of decarbonization.

The study was supported by the Russian Science Foundation grant No. 22-18-00171 (https://rscf.ru/project/22-18-00171/).

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