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Evaluating the Eco-Intensity Dynamics of the Mining Industry in Russia: Towards a Circular Economy

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Abstract: One of the main tasks of the circular economy is the decoupling between economic growth and natural resource consumption at the input and the volume of generated waste at the output. The effectiveness of this process can be assessed by the dynamics of the eco-intensity indicators at the macro-, meso- and micro-levels. The article presents the assessment results of the decoupling and growth color of the mining sector in Russia, which show the dynamics of eco-intensity indicators and may reflect the trend towards a circular economy. For the period 2010–2021, it was revealed that negative expansion decoupling and "Black" growth have been observed in terms of generated waste and atmospheric pollution, strong decoupling and "Green" growth in terms of hydrosphere pollution, weak decoupling and "Brown" growth in terms of electricity consumption, and according to water intake from natural water bodies, expansion coupling and "Black" growth. During the study period, the gross value added (GVA) of the mining industry in Russia in comparable prices increased by 77%, while the industry's negative impact on the atmosphere increased by 34%; the volume of production and consumption waste generation increased by 131%, and the negative impact on the hydrosphere decreased by 51%. The growth of the environmental and economic efficiency of any system can be achieved by influencing the drivers and barriers to moving towards a circular economy, so it is important to identify the most significant factors of influence for a particular industry, region or country in the current conditions. Using the ordinary least squares (OLS) method, it was revealed that factors reflecting innovative activities of the mining industry have a significant impact on reducing eco-intensity in the field of electricity consumption and water intake from natural water bodies. The significance of these factors' influence has been confirmed not only at the macro-level, but also at the micro-level.

Keywords: circular economy; decoupling; "green growth" model; eco-intensity

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1. Introduction

The demand and relevance of scientific research in the field of circular economy by the world scientific community is confirmed by a significant increase in scientific publications. Thus, over the past 5 years, the keyword "circular economy" in SCOPUS and Web of Science bases could be found in more than 10,000 scientific articles [1]. Modern world trends of movement towards a circular economy are due to the growth in the use of production resources to achieve the goals of economic development, the depletion of fossil resources, and the increase in anthropogenic burden on the ecosystems of territories. Circular economy (CE) is the antipode of the linear model of the economy, organically built into the concept of sustainable development—the coordinated ecological, socio-economic development of enterprises, industries and territories. For any managed model, it is necessary to be able to measure its parameters and factors influencing these parameters in order to monitor and develop corrective measures. The movement towards a circular economy can be measured and evaluated using the decoupling model and the "Green growth" model by P. Victor [2].

The term "decoupling" within the framework of environmental economics was proposed by the OECD in 2000 in the Indicators to Measure Decoupling of Environmental Pressure from Economic Growth Organization for Economic Co-operation and Development [3] and means "the process of sustainable long-term, predictable and manageable mismatch of economic growth, consumption of natural resources and environmental pollution at all stages of the product life cycle, while not accompanied by a redistribution of environmental risks in time and space" [4]; an improved methodology for using decoupling on the example of the transport sector was described in the paper written by P. Tapio [5]. Currently, this methodological approach is used to assess the environmental impact of the economic growth of countries or regions, the growth of industrial production in general or for individual industries/sectors of the economy.

A number of studies have researched the factors affecting the decoupling process, including energy intensity, intensity of CO_2 emissions, structural changes in the economy and economic activity [6–8], energy consumption [9–12], industrialization and urbanization processes [13–18], industrial water consumption [19], renewable and non-renewable energy consumption, trade openness and financial development [20,21], agricultural development, oil production [22], structural and technological changes [23], economic structure, energy structure [23], foreign direct investment [24,25], rent from natural resources, population growth, human capital, financial integration [26], digitalization processes [27,28], real income population [29,30], economic complexity, green investment [31], research and innovation potential [32], corruption [33,34], and environmental regulation [35,36]. A number of regional studies determined the discrepancy between the rates of economic development through the dynamics of gross regional product (GRP) and the rate of change in the negative impact on the environment [37–42].

To assess the movement towards "Green growth" [43], various modifications of the P. Victor model [2] are used, which determine the color of the ecological and economic development of a country or region.

In this article, an assessment of decoupling and the "color" of economic growth will be carried out using the example of the mining sector of the Russian economy.

The choice of the mining industry of Russia as a subject of study is due to the fact that this sector has a negative impact on all components of the environment: subsoils, lands, soils, surface and ground waters, atmospheric air, flora and fauna. The extraction of resources and their processing is a source of approximately half of the world's greenhouse gas emissions and more than 90% of water stress and biodiversity loss [44].

The main types of negative impact of mining activities on the environment include: alteration/destruction of natural landscapes, destruction of habitats, emissions of pollutants into the atmospheric air (dust, methane and other gaseous substances), wastewater discharges into water bodies (mine and quarry drainage, wastewater from enrichment), change in the level of groundwater as a result of drainage of mine workings, generation and disposal of large-tonnage waste, noise and vibration during the operation of equipment and drilling and blasting [45].

The share of the mining industry in the total volume of generation of production and consumption waste in Russia is about 90%; in the total volume of emissions from stationary sources into the atmosphere of pollutants, it is about 40%. In addition, this sector is a resource-intensive one: it accounts for 12% of the total electricity consumption, and in the structure of water intake from natural water bodies, the mining industry accounts for 8% [46].

According to one of the interpretations of the circular economy, CE "operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond)" [47]; however, we did not find scientific studies in which the methods discussed above would be used at the micro-level.

In order to close this gap and better understand the relationship between the factors influencing the process of moving towards a circular economy in the mining sector, to identify the most significant drivers and barriers, the following research questions (RQ) were formulated in this article:

- RQ1: What are the characteristics of impact decoupling and resource decoupling and the color of industrial production growth in the mining sector in Russia?
- RQ2: What are the most significant factors affecting the dynamics of the eco-intensity indicators of the mining industry?
- RQ3: What are the potential uses of the proposed indicators and models for assessing the movement of the mining industry towards a circular economy for application at macro-, meso- and micro-levels?

The purpose of this study is to assess the environmental and economic development of the mining industry in Russia using decoupling models and a modified model by P. Victor and OLS method to study the factors influencing this process.

2. Materials and Methods

This research includes several stages. At the first stage, the decoupling of the development of the mining industry and its environmental burden is assessed, and the color of the growth of the mining industry in Russia is determined using the model of "Green growth" by P. Victor that was modified for this study.

As part of the decoupling methodology, resource decoupling is distinguished, which reflects the efficiency of resource use at all stages of the production process, and impact decoupling, which reflects the use of waste-free technologies and the efficiency of treatment facilities. The presence of resource decoupling and impact decoupling indicates a movement towards a circular economy and "Green growth".

The decoupling index is calculated using the absolute eco-intensity indicators of the mining industry (E_i), presented in Table 1, the specific indicators of eco-intensity (EI_i) (Equation (1), and Table 2, the economic result of the mining sector (ER_m), which is determined through the gross value added (GVA) by type of economic activity "Mining" in comparable prices.

Table 1. Absolute indicators of the eco-intensity of the mining industry.

Designation	Indicators	Applied Assessment Methods
E_1	Generated production and consumption waste by type of economic activity "Mining", million tons.	Impact decoupling, modified model of "color" of economic growth
E_2	Discharge of polluted wastewater into surface water bodies by type of economic activity "Mining", million cubic meters.	
E_3	Emissions into the atmosphere of pollutants from stationary sources by type of economic activity "Mining", thousand tons.	
E_4	Electricity consumption by type of economic activity "Mining", million kilowatt-hours.	Resource decoupling, modified model of "color" of economic growth
E_5	Water intake from natural water bodies by type of economic activity "Mining", million cubic meters.	

This study defines three absolute and specific eco-intensity indicators that reflect the impact on the environment and two absolute and specific indicators that characterize resource consumption.

Table 2. Specific indicators of the eco-intensity of the mining industry.

Designation	Indicators	Applied Assessment Methods
EI_1	The ratio of generated production and consumption waste by type of economic activity "Mining" to GVA in this industry, tons/RUB 1000.	Impact decoupling, modified model of "color" of economic growth
EI_2	The ratio of the discharge of polluted wastewater into surface water bodies by type of economic activity "Mining" to the GVA in this industry, cubic meters/RUB 1000.	
EI_3	The ratio of air emissions of pollutants from stationary sources by type of economic activity "Mining" to the GVA in this industry, tons/RUB 1,000,000.	
EI_4	The ratio of electricity consumption by type of economic activity "Mining" to the GVA in this industry, kilowatt-hours/RUB 1000.	Resource decoupling, modified model of "color" of economic growth
EI_5	Ratio of water intake from natural water bodies by type of economic activity "Mining" to the GVA in this industry, cubic meters/RUB 1000.	

When selecting indicators, the following requirements were used: objectivity, the importance of the indicator, and possibility of quantitative expression; relevance, i.e., the structure and composition of indicators should correspond to the structure of the "Environment Pressure" category (reflect the negative impact on the main components of the environment: subsoil and land, water, atmospheric air); be representative enough for cross-country and cross-regional comparisons; availability of indicators, the possibility of comparison in dynamics, and taking into account industry and regional specifics; the ability to integrate with real business practices (enterprises or individual projects) in the mining sector.

Specific indicators of eco-intensity (EI_i) are calculated according to the general Equation (1) and are presented in Table 2.

$$EI_i = \frac{E_i}{ER_m} \quad (1)$$

where E_i—absolute indicators of the eco-intensity of the mining industry; ER_m is the economic result of the mining sector in the base and estimated periods (GVA for the type of economic activity "Mining" in comparable prices).

The decoupling index was calculated using Equation (2).

$$DI_i = \frac{E_{it}/ER_{mt}}{E_{i0}/ER_{m0}} \quad (2)$$

where E_{i0}, E_{it}—absolute indicators of the eco-intensity of the mining industry in the base and estimated periods; 2010 was chosen as the base period; ER_{m0}, ER_{mt}—the economic result of the mining sector in the base and estimated periods (GVA for the type of economic activity "Mining" in comparable prices).

Our sample covers data on the mining industry of the Russian Federation for 2012–2021. The data for the first and second phases of the study were taken from Federal State Statistics Service of Russia, Statistical Compilation "Environmental Protection In Russia", Statistical Compilation "Industrial Production in Russia", the Unified Interdepartmental Information and Statistical System (EMISS). To exclude the influence of inflation, the values of cost indicators are adjusted to the level of 2010.

Further, the modeling of the environmental and economic dynamics of the development of the mining industry in the Russian Federation was carried out on the basis of the "Green growth" model of P. Victor [2].

The visualization of the model is shown in Figure 1. The horizontal axis represents the eco-intensity indicator (EI); the vertical axis represents the economic result (ER). The intersection point of the curves on the graph (I_0) reflects the initial relationship between EI and ER, and the red curve is determined by Equation (3).

$$EI \times ER = const \quad (3)$$

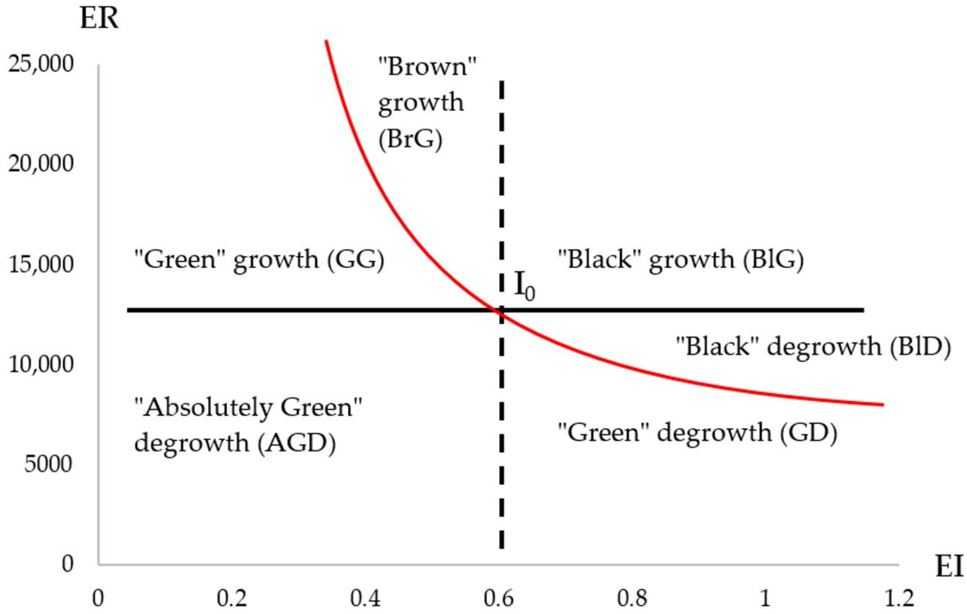

Figure 1. Zones of ecological and economic development of mining in accordance with the modified model of P. Viktor.

Since this model was used for temporal analysis, to assess the environmental and economic dynamics, I_0 is taken to be the values of indicators that assess the environmental and economic state of the mining industry in Russia at the zero point in time (2010).

Table 3 presents the characteristics of the ecological and economic development zones in mining in the Russian Federation according to the proposed model.

Table 3. Interpretation of ecological and economic zones according to the modified model of P. Victor [2].

Eco-Economic Zones in the Concept of "Green Growth"	Change of Indicator ER	Change of Indicator E_i	Change of Indicator EI_i
"Green" growth (GG)	increase	decline	decline
"Green" degrowth (GD)	decline	decline	increase
"Absolutely Green" degrowth (AGD)	decline	decline	decline
"Brown" growth (BrG)	increase	increase	decline
"Black" growth (BlG)	increase	increase	increase
"Black" degrowth (BlD)	decline	increase	increase

At the second stage, a regression analysis is carried out to determine the most significant factors influencing the eco-intensity indicators of the mining sector of the Russian Federation.

Eco-intensity indicators (EI_1–EI_5) were chosen as the variables to be explained.

Based on the literature analysis, independent variables were determined, which are represented by 4 groups of factors. Operating and investment costs aimed at environmental protection measures; the innovative activity level of the mining industry was measured by the share of organizations implementing technological innovations, the use of advanced technologies and the costs of research and development; the quality of management was measured through qualitative proxy indicators, such as imperfection of regulatory and legal bases, lack of skilled workers, average salary in the industry; and the quality of the fixed assets involved in the production process was measured through the age of the fixed assets and the amount of investment in fixed assets. Table 4 shows the list of variables used in this study.

Table 4. Description of the independent variables.

Groups of Factors	Independent Variable	Definition
Financing of environmental measures	OpexWater	Operating costs for wastewater collection and treatment, RUB 1,000,000.
	CapexWater	Investments in fixed assets aimed at the protection and rational use of water resources, RUB 1,000,000.
	CapexProtect	Investments in fixed assets aimed at environmental protection and rational use of natural resources, RUB 1,000,000,000.
Innovative activity level of mining industry	Innov	The share of organizations implementing technological innovations.
	AdvTechn	The number of advanced production technologies.
	RND	Research and development costs, RUB 1,000,000.
Quality of management	Right	The imperfection of the regulatory framework, the proportion of respondents who noted this factor as limiting the activities of the mining organization.
	Worker	The lack of skilled workers, the proportion of respondents who noted this factor as limiting the activities of the mining organization.
	Salary	Average monthly salary of mining industry workers, in RUB.
	Cirlul	The volume of circulating and re-sequential water supply, billion cubic meters.
Quality of the fixed assets	AgeEq	Average age of machinery and equipment, years.
	Capex	Investments in fixed assets, RUB 1,000,000.

Since the ordinary least squares (OLS) regression model is considered as a standard approach in the literature for analyzing economic and environmental variables, it was used in this study. To calculate the standard error of a regression coefficient in a regression model, a robust standard error was used. The construction of the model and the calculation of statistical indicators were carried out using the Gretl program.

At the third stage, an assessment of resource decoupling and determination of the "color" of the introduction of innovative technology for cluster separation of well products and utilization of produced water at a particular oil field was carried out. Table 5 presents eco-intensity indicators of an innovation project.

Table 5. Indicators of eco-intensity of the project for the introduction of a new oil production technology.

Designation	Indicators	Applied Assessment Methods
E_6	Electricity consumption costs, RUB 1000.	Resource decoupling, modified model of "color" of economic growth
E_7	The cost of collecting and transporting water, RUB 1000.	
EI_6	Electricity consumption costs per unit of economic result (EBITDA), in RUB.	
EI_7	Water collection and transportation costs per unit of economic result (EBITDA), in RUB.	

The calculation of the decoupling index of the introduction of the proposed technology is carried out according to Equation (4).

$$DI_i = \frac{E_{it}/ER_t}{E_{i0}/ER_0} \quad (4)$$

where ER_0, ER_t—the economic result (EBITDA) before and after the introduction of an integrated technology for cluster separation of well products and utilization of produced water; E_{i0}, E_{it} are absolute indicators of eco-intensity (E_6 and E_7) before and after the introduction of an integrated technology for cluster separation of well products and utilization of produced water.

Determining the "color" of the proposed technology implementation is carried out similarly to the first stage using Table 3.

3. Result

3.1. Evaluation of Decoupling and Color of the Economic Growth in the Mining Industry in Russia

Throughout the entire period, negative expansion decoupling was observed in terms of the rate of waste generation and GVA of the industry (Table 6), which indicates that measures aimed at minimizing waste in this industry should be a priority both for the federal and regional governments and for mining enterprises.

Table 6. Impact decoupling indicators of the mining industry in the Russian Federation for 2010–2021.

Year	DI_1	Decoupling Type	DI_2	Decoupling Type	DI_3	Decoupling Type
2011	1.32	Negative Expansion Decoupling	0.17	Weak decoupling	0.73	Weak Decoupling
2012	2.64	Negative Expansion Decoupling	0.17	Weak decoupling	1.22	Negative Expansion Decoupling
2013	2.61	Negative Expansion Decoupling	−0.44	Strong Decoupling	0.08	Weak Decoupling
2014	3.28	Negative Expansion Decoupling	−0.80	Strong Decoupling	−0.37	Strong Decoupling
2015	1.68	Negative Expansion Decoupling	−0.34	Strong Decoupling	−0.36	Strong Decoupling
2016	1.85	Negative Expansion Decoupling	−0.54	Strong Decoupling	−0.25	Strong Decoupling
2017	1.77	Negative Expansion Decoupling	−0.21	Strong Decoupling	−0.13	Strong Decoupling
2018	1.37	Negative Expansion Decoupling	−0.18	Strong Decoupling	−0.09	Strong Decoupling
2019	1.59	Negative Expansion Decoupling	−0.33	Strong Decoupling	−0.06	Strong Decoupling
2020	3.51	Negative Expansion Decoupling	−1.76	Strong Decoupling	1.15	Negative Expansion Decoupling
2021	1.70	Negative Expansion Decoupling	−0.66	Strong Decoupling	0.44	Weak Decoupling

GVA of the mining sector in Russia for the period from 2010 to 2021 increased by 77%, and the level of waste generation increasedby 131%, which was reflected in the "Black" color of the economic growth of the industry (Figure 2).

In terms of E_2 and GVA of the mining industry of the Russian Federation, strong decoupling and "Green" growth according to the modified model have been observed since 2013, reflecting the movement towards a "green" economy in 2011 and 2012. Decoupling type was weak decoupling, and the decoupling index was 0.73 and 1.22, respectively, which was also reflected in the "Brown" color of the ecological and economic dynamics of mining and discharge of polluted wastewater in these years (Figure 3).

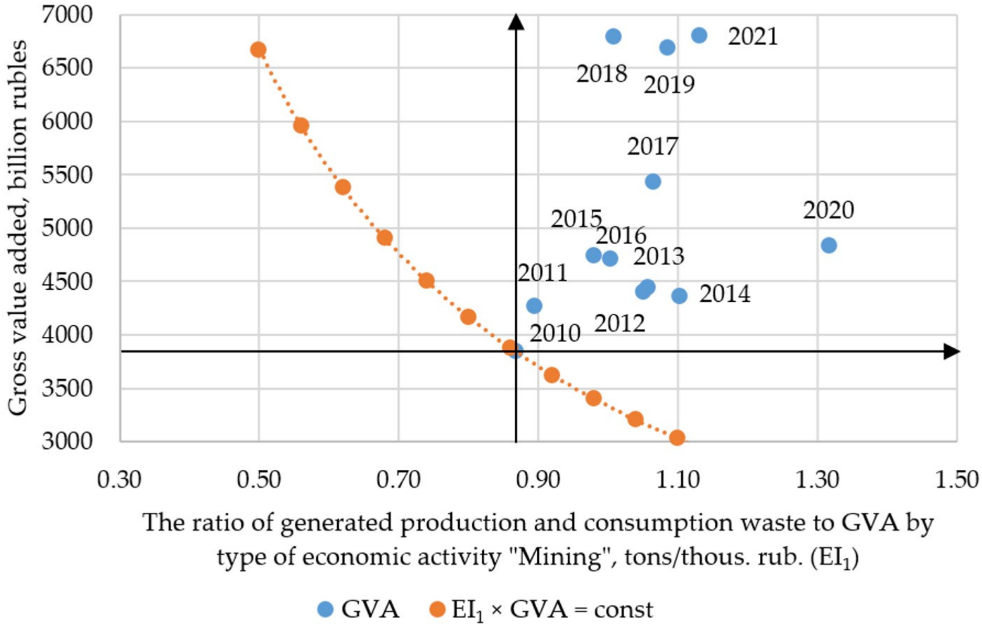

Figure 2. The color of environmental and economic development in terms of production and consumption waste generation by type of economic activity "Mining" in the Russian Federation for the period 2010–2021.

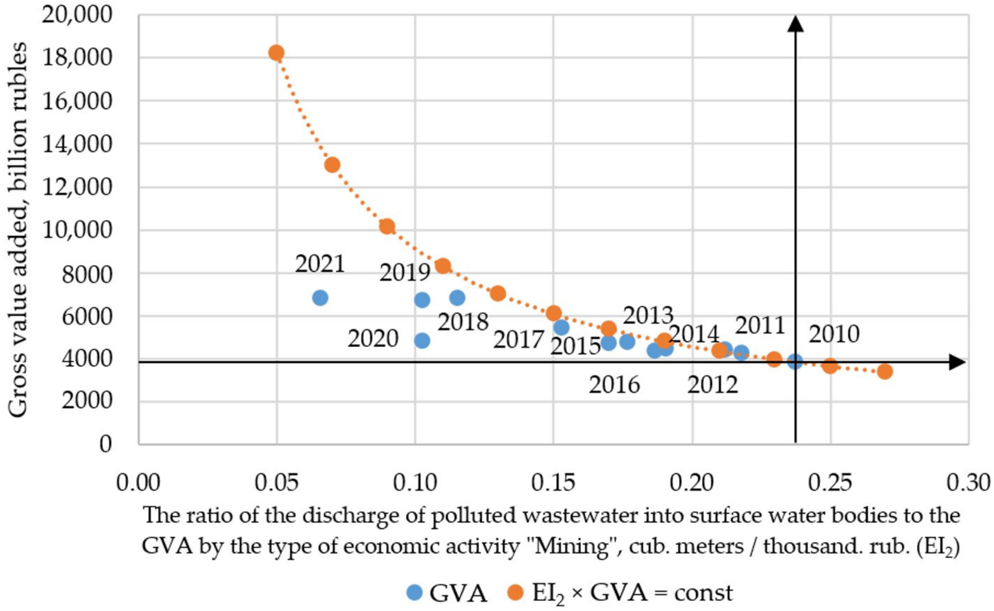

Figure 3. The color of environmental and economic development in terms of discharge of polluted wastewater into surface water bodies by type of economic activity "Mining" in the Russian Federation for the period 2010–2021.

In general, over the entire period under study, the negative burden of mining in Russia on the hydrosphere decreased by 51%, while the GVA of the industry grew by 77%.

In terms of the negative impact of the Russian mining industry on the atmosphere from 2014 to 2018, strong decoupling is observed. Weak decoupling was observed in 2011, 2013 and 2021, and 2012 and 2020 were characterized by negative expansion decoupling. Such different trends for different years of the study period indirectly characterize the lack of consistency and complexity in solving the problem of reducing the level of negative impact on the air. It should be noted that the "Black" growth of the industry in 2020 and the

"Brown" growth in 2021 are observed against the backdrop of the implementation of the Clean Air federal project since 2018, which involves large industrial complexes in Russia.

For a deeper and more detailed analysis, of particular interest are the periods in which there were sharp changes in the eco-intensity indicator (both an increase and a decrease)—2012 and 2020; this is necessary to identify the causes of such volatility and develop corrective measures. If we consider the entire period of the study, then with an increase in the GVA of the industry over 12 years by 77%, the volume of air polluting emissions increased by only 34%, which led to weak decoupling and the "Brown" color of the environmental and economic dynamics of the industry in terms of E_2 (Figure 4).

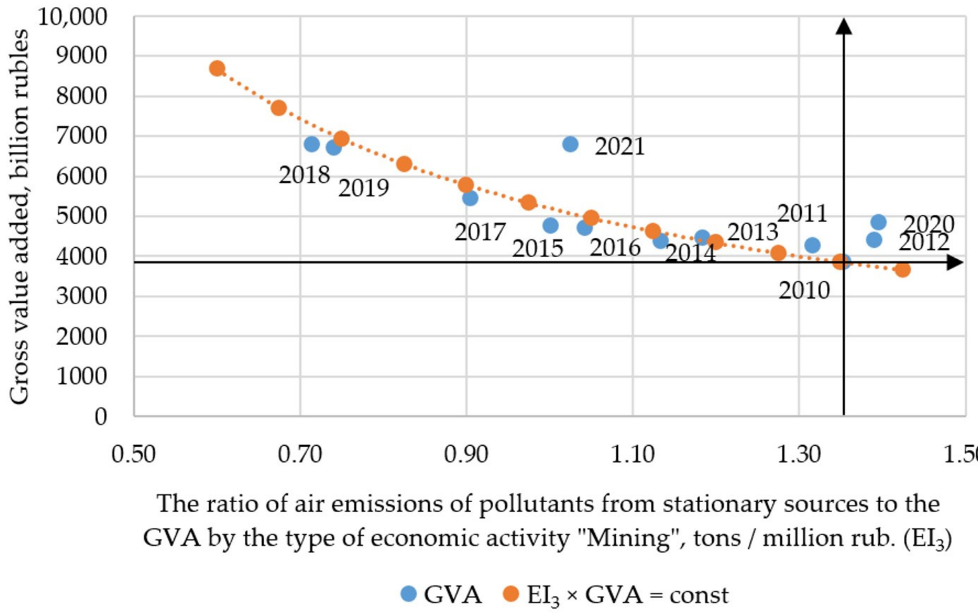

Figure 4. The color of environmental and economic development in terms of emissions into the atmosphere of pollutants from stationary sources by type of economic activity "Mining" in the Russian Federation for the period 2010–2021.

Table 7 shows the resource decoupling indexes and decoupling types for the period being evaluated.

Table 7. Resource decoupling indicators of the mining industry of the Russian Federation for 2010–2021.

Year	DI_4	Decoupling Type	DI_5	Decoupling Type
2011	0.22	Weak Decoupling	0.59	Weak Decoupling
2012	0.24	Weak Decoupling	0.87	Expansion Coupling
2013	0.49	Weak Decoupling	0.93	Expansion Coupling
2014	0.64	Weak Decoupling	3.54	Negative Expansion Decoupling
2015	0.46	Weak Decoupling	2.70	Negative Expansion Decoupling
2016	0.62	Weak Decoupling	3.95	Negative Expansion Decoupling
2017	0.26	Weak Decoupling	2.27	Negative Expansion Decoupling
2018	0.16	Weak Decoupling	1.22	Negative Expansion Decoupling
2019	0.21	Weak Decoupling	1.25	Negative Expansion Decoupling
2020	0.43	Weak Decoupling	3.06	Negative Expansion Decoupling
2021	0.16	Weak Decoupling	1.09	Expansion Coupling

In terms of electricity consumption in the mining industry, weak decoupling and "Brown" growth has been observed for all 12 years (Figure 5) (the growth in electricity consumption over the period was 13%). In terms of water consumption, expansion coupling is observed (during the study period, the growth in water consumption exceeds the growth in the GVA of the industry, 84% and 77%, respectively).

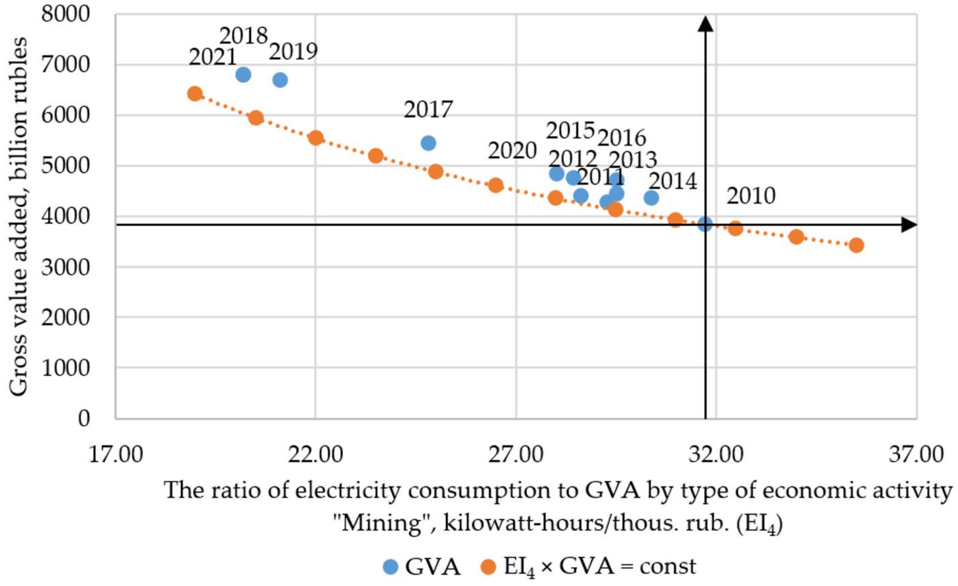

Figure 5. The color of environmental and economic development in terms of electricity consumption by type of economic activity "Mining" in the Russian Federation for the period 2010–2021.

If we evaluate the color characteristic of the resource intensity of the development of mining according to this indicator, then we can distinguish three years of "Brown" growth (2011–2013), and "Black" growth has been observed since 2014 (Figure 6).

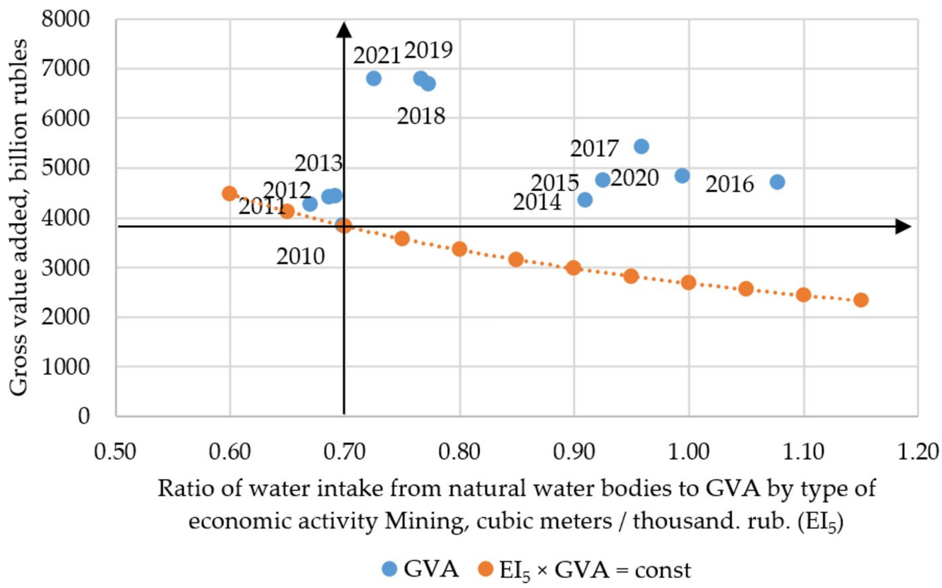

Figure 6. The color of environmental and economic development in terms of water intake from natural water bodies by type of economic activity "Mining" in the Russian Federation for the period 2010–2021.

According to the results of the first stage of the study, it can be seen that the most problematic areas for the movement of the mining industry in Russia towards a circular economy from the standpoint of the environmental burden in the form of environmental pollution are the high rates of waste generated, which, on the one hand, is due to the specifics of the industry, and, on the other hand, should be a zone of special attention from the state.

If we evaluate the change in resource consumption per unit of the economic result of the industry (in terms of electricity and water) for the estimated period, then water consumption could be considered as the most problematic, the growth rate of which exceeds the growth rate of GVA by 1.09 times, but either "Brown" or "Black" growth is observed in both indicators.

Despite the adoption and implementation of many legislative environmental initiatives at the federal and regional levels that contribute to the transition to the CE, the targets that were reflected in them have not yet been achieved. Therefore, for example, in the period 2012–2020, it was planned to reduce waste per unit of gross domestic product (GDP) by 1.6 times; in fact, there was an increase in this indicator. In our opinion, eco-innovations are among the tools that will reduce waste generation, as well as carry out waste recycling, so the state needs to develop a set of measures to stimulate them.

3.2. Results of OLS Estimation

At the second stage of our study, five regression models were built. Eco-intensity indicators (EI_1–EI_5) were chosen as explained variables, but since resource decoupling indicators were the most problematic at the first stage of the study, two indicators were chosen as explained variables for further analysis of eco-intensities reflecting the consumption of electricity and water per unit of economic result (EI_4 and EI_5).

Table 8 defines the descriptive statistics of all the variables along with different measurements and a probability section.

Table 8. Summary of Descriptive Statistics.

Variables	Mean	Median	Minimum	Maximum	Std. Dev.	Variation	Skewness	Kurtosis
EI_4	26.818	28.536	20.20	31.716	4.143	0.154	−0.727	−1.044
EI_5	0.823	0.770	0.670	1.077	0.141	0.172	0.473	−1.248
OpexWater	11,883.0	10,276.0	8787.6	17,441.0	3361.8	0.283	0.973	−0.807
CapexWater	5210.5	5233.0	4076.1	6118.4	582.8	0.112	−0.447	−0.384
CapexProtect	21.453	20.190	15.602	40.629	6.920	0.323	1.968	3.076
Innov	10.949	10.574	9.000	13.088	1.432	0.131	0.153	−1.497
AdvTechn	9997.9	9758.0	7914.0	13,062.0	1465.4	0.147	0.582	−0.359
RND	0.330	0.054	0.023	1.216	0.493	1.495	1.143	−0.640
Right	5.681	5.750	2.500	7.583	1.309	0.230	−0.977	1.113
Worker	15.167	14.500	10.000	21.500	3.737	0.246	0.350	−1.030
Salary	69,001	66,816	39,895	103,473	20,540	0.298	0.237	−1.145
Cirlul	140.14	140.55	126.98	145.720	4.902	0.035	−1.565	2.478
AgeEq	8.058	8.050	7.200	8.900	0.425	0.053	−0.046	0.433
Capex	1581.6	1568.5	1264.0	1820.5	178.060	0.113	−0.367	−0.960

In the Russian mining industry, the mean value of the electricity consumption to GVA ratio (EI_4) is 26.8 kilowatt-hours per thousand rubles and the mean varies from 20.20 to 31.716 kilowatt-hours per thousand rubles. The mean water withdrawal from natural water bodies to GVA ratio (EI_5) is 0.823 cubic meters per thousand rubles and varies from 0.670 to 1.077 cubic meters per thousand rubles. The variation of values for dependent variables does not exceed 18%.

Since OLS regressions are considered as a standard approach in the literature for analyzing economic and environmental variables, Table 9 shows the main results from OLS estimation. To calculate the standard error of a regression coefficient in a regression model, a robust standard error was used.

Table 9. Results of OLS estimation.

Variables	Coefficient	t-Statistics	*p*-Value
		EI_4	
Constant	46.0675	17.640	0.000000109 ***
CapexProtect	−0.2009	−2.678	0.0280 **
AdvTechn	−0.0014	−4.289	0.0027 ***
RND (Science)	−5.3455	−3.354	0.0100 **
R-squared (R^2)	0.8752	F-Statistic	63.3452
Adjusted R-squared	0.8284	*p*-Value (F)	6.45×10^{-6}
		EI_5	
Constant	4.68010	6.602	0.0000991 ***
Innov	−0.0865	−3.938	0.0034 ***
RND (Science)	−0.28590	−2.523	0.0326 ***
R-squared (R^2)	0.4453	F-Statistic	7.8026
Adjusted R-squared	0.3220	*p*-Value (F)	1.08×10^{-2}

Notes: Values in parentheses are the estimated *p*-values. **, and *** indicate significance level at the 10%, 5%, and 1% levels, respectively. R^2 is the coefficient of determination, which represents the ratio of "explained" variance to the "total" variance of the dependent variable y.

The specification of the models is correct according to the Ramsey test; a VIF value < 10 indicates the absence of multicollinearity.

Three exogenous variables have a negative, as expected, and significant impact on the ratio of electricity consumption to GVA in the mining industry of the Russian Federation. Increasing investments in fixed assets aimed at environmental protection by 1 billion rubles will result in a reduction of consumed electricity by 0.0865 kilowatt-hours per thousand rubles of GVA. The presence of a statistically significant dependence indicates the effectiveness of investments in environmental assets.

An increase in research and development costs by one billion rubles leads to a decrease of consumed electricity by 5.35 kilowatt-hours per each thousand rubles of GVA. In addition, an increase in number of advanced production technologies in the practice of mining enterprises by one thousand units leads to a decrease in consumed electricity by 1.4 kilowatt-hours per each thousand rubles of GVA. Thus, research and development financing and the implementation of the results into the practice of mining industry companies will reduce the resource intensity.

An increase in research and development by one billion rubles leads to a decrease of water withdrawal from natural water bodies by 0.296 cubic meters per thousand rubles of GVA. An increase in the share of organizations implementing technological innovations by one percent will lead to a decrease in water withdrawal from natural water bodies by 0.087 cubic meters per thousand rubles of GVA. Thus, in order to reduce pressure on the environment, attention should be focused on involving mining industries in innovative activities.

Statistically significant factors influencing the movement towards a circular economy through resource conservation are CapexProtect, AdvTechn, Innov and RND. Therefore, at the third stage, the possibility of using the methodological approaches and indicators proposed at the first stage for assessing the movement towards a circular economy at the micro-level was assessed using the example of an innovative project of an oil-producing enterprise.

3.3. Assessment of the Environmental and Economic Characteristics of the Project Using the Decoupling Model and the P. Victor Model

The last stage of the study included an environmental and economic assessment of the project to introduce an innovative technology for cluster well separation and disposal of associated water at the Yarino-Kamennolozhskoye field of LUKOIL-PERM company.

This technology is a decentralized system for managing the treatment, injection and disposal of produced water and is used in fields at the third and fourth stages of development, with a large volume of produced water several times greater than the volume of oil produced.

With the traditional collection and transportation system, associated water is separated from the oil product in special equipment located at a great distance from production and injection wells, which leads to an increase in the cost of transporting oil products to collection points, water discharge and an increase in the cost of returning purified water to the system facilities maintaining reservoir pressure for the purpose of further injection into the well.

In order to reduce these costs and reduce the environmental burden, this technology is being introduced, which consists of separating the produced product into oil and water directly at the well cluster, while the discharged water is again sent to the reservoir pressure maintenance system, and partially dehydrated oil is sent to the system for collection of this deposit. This process is carried out through the development and implementation of a mobile block unit of cluster separation [48].

On the basis of literature sources, it is possible to single out such advantages of the cluster separation technology as reducing the load on aerial oilfield facilities for collecting, transporting, and preparing oil and water; reducing the cost of electricity for the transportation of well products and the consumption of reagents to ensure the process; reduction of capital costs for the modernization and construction of aerial facilities and field pipelines; additional oil production by reducing the pressure in the collection system; improving the quality of oil treatment [49–51].

As a result of pilot tests at the Yarino-Kamennologskoye field, 114 m^3 of ballast-produced formation water was discharged daily, which made it possible to reduce operating costs for electricity, transport the volume of ballast water from a cluster of production wells to an oil pre-treatment unit and back for injection into injection wells, increase the flow rate of oil production from the well by 5.9 tons/day and improve the quality of treatment of produced water.

All of the above indicates the environmental and economic efficiency of the introduction of technological innovations in the oil production process.

Table 10 presents the data for calculating the eco-intensity indicators of the project (EI_6, EI_7), decoupling indexes and determining the color of the environmental and economic results of the project.

Table 10. Initial data for the environmental and economic assessment of the project for the implementation of cluster separation technology for well products.

Indicators	Before Project Implementation	After Project Implementation
Electricity costs, total, RUB 1000/month (E_6)	1181	742
including:		
electricity costs for the collection and transportation of liquid, RUB 1000/month	982	727
electricity costs for oil preparation, RUB 1000/month	21	15
electricity costs for artificial reservoir stimulation, RUB 1000/month	178	0
Pumping volume (oil and ballast water), m^3/day	439.7	325.7
The volume of water to be injected into the formation	114	preparation at the well cluster
Water collection and transportation costs, RUB 1000/month (E_7)	976.13	723.05

Current operating costs for electricity decreased by 37%; the cost of collecting and transporting water was reduced by 26%. The 1.8% increase in EBITDA was achieved not only due to a reduction in the cost of production of 1 ton of oil, but also due to an increase in revenue due to both an increase in oil production by almost 6 tons per day and an improvement in oil quality.

According to Table 10, based on Equations (1) and (4), EI_6, EI_7, DI_6, DI_7 were calculated; the type of decoupling and the color of the environmental and economic results of the project were determined (Table 11).

Table 11. Resource decoupling indicators of the project and the "color" of the project.

Indicators	Before Project Implementation	After Project Implementation
EI_6, rub/rub	0.022	0.014
EI_7, rub/rub	0.0177	0.0128
DI_6 and (Decoupling Type)	-	−20.55 (Strong Decoupling)
DI_7 and (Decoupling Type)	-	−14.44 (Strong Decoupling)
Color according to EI_6	-	«Green» growth (GG)
Color according to EI_7	-	«Green» growth (GG)

The data given in Table 11 indicate a decrease in the resource intensity of oil production with the introduction of this technology and at the micro-level confirm the results of regression analysis, indicating the presence of a statistically significant feedback between indicators of eco-intensity and indicators reflecting the level of innovative activity of enterprises in the mining sector and investments in fixed assets aimed at protecting the environment and rational use of natural resources.

4. Discussions and Future Research Perspectives

The decoupling methodology and the "Green growth" model of P. Victor were applied in this study, which are characterized by universality from the standpoint of conceptual applicability at the macro-, meso- and micro-level (can be used in diagnosing the environmental friendliness of the economic development of a country, region, industry, and enterprise, using different sets of assessment indicators with a common methodological approach), clarity and simplicity in terms of the availability of tools.

The article shows the possibility of applying these methodological approaches at the macro-level (on the example of the mining sector of Russia) and at the micro-level (on the example of a specific project of an oil-producing enterprise).

As for the further prospects for using these methodological approaches, they can be used for cross-country comparison of trends in the greening of economic development, at the regional level, assessing the heterogeneity of the environmental and economic dynamics of regional development as a whole or comparing clusters of regions united by industry specifics, climatic conditions or any other clustering parameters to determine similar and different characteristics of ecological and economic development.

The use of panel data (data on countries, regions, etc.) will also expand the mathematical tools used in regression analysis and improve the quality of the model.

Since a series of dynamics was used in this study, the OLS regressions method was used to assess the influence of factors on the eco-intensity of the mining industry. To calculate the standard error of a regression coefficient in a regression model, a robust standard error was used. The ratio of electricity consumption by type of economic activity "Mining" to the GVA in this industry (EI_4) and ratio of water intake from natural water bodies by type of economic activity "Mining" to the GVA in this industry (EI_5) was used as the dependent variable.

Based on the analysis of the literature, we identified four groups of factors (12 variables) that could potentially have an impact on the dependent variables. Using the OLS regressions method, regression models were built. The quality of the models was verified using the Akaike and Schwartz criteria. The specifications of the models are correct according to the Ramsey test; all outcomes were validated. The VIF test results indicated no multi-collinearity issue in the data as all the values are less than 10.

The novelty of this study lies:

- Firstly, in assessing the degree of circularity (environmental friendliness) of the economic development of the mining sector in Russia (both from the position of entry—resource consumption and from the position of exit—the burden on the environment);
- Secondly, in the use of a synthesis of various methodological and instrumental approaches that logically complement each other and allow one to obtain a more complete picture of the subject of research;
- Thirdly, in the adaptation of the methodology traditionally applied at the macro-level to the micro-level and its approbation on a specific project (implementation of a new technology) of a mining sector enterprise.

The use of this methodological apparatus at the micro-level will make it possible to formulate the criteria for a “green enterprise” or “green project” using eco-intensity indicators that will allow us to assess not only the economic but also the environmental effect of the project, which is in line with the modern ESG agenda.

The use of this toolkit at the macro-level will allow diagnosing and subsequent monitoring of the process of greening the economic growth of a country, region and industry, identifying problem areas of environmental and economic development in order to develop an algorithm and tools for making managerial decisions, and it can be used to update state, regional or sectoral policies, taking into account modern environmental requirements and challenges.

In addition to the contributions and implications, our research work has a few limitations.

First, there were limitations when choosing indicators for calculating resource decoupling. For example, data on the consumption of fuel and energy resources by types of economic activity in Russian statistics have been presented only since 2012.

Secondly, when choosing independent variables, it was necessary to abandon the assessment of the impact of the level of digitalization on the environmental and economic development of the mining sector, since the “Index of Digitalization of Economic and Social Spheres”, which reflects the level of use of digital technologies, digitalization of business processes, digital skills of personnel, costs for the implementation and use of digital technologies and cybersecurity, is calculated only from 2019.

Also, this study did not assess the impact of the quality of the industry’s labor resources on its eco-intensity, since the HDI is not calculated by type of economic activity.

For some indicators that were used in the study, there were also restrictions on the availability of data, which determined the study period—2010–2021.

Thirdly, the methodological limitation of the OECD decoupling model is its arbitrariness in relation to the choice of the base period [8]. To assess the environmental and economic dynamics of the development of the industry, when calculating the decoupling index, 2010 was chosen as the base year (we did not use chain indicators of time series), since in this study we were interested in the general trend in the movement of the mining industry towards CE; also, choosing 2010 as the baseline is consistent with the temporal analysis of the environmental and economic situation in the industry, carried out using the modified model of P. Victor and the generated database for regression analysis.

Fourthly, as a result of the regression analysis, there was no statistically significant influence of the “Quality of management” group of indicators on the eco-intensity of the mining industry, which can be explained by the fact that the first two indicators of this group are based on expert assessments, which are subjective and cannot fully reflect the real situation in the industry. However, they assess the quality of the institutional environment (institutional barriers) by industry and, in the absence of other data reflecting the institutional conditions for the functioning of the mining sector, were selected as independent variables.

In addition, future researchers may consider other variables not included in the model.

However, these limitations do not diminish the significance of the study.

5. Conclusions

In this study, it was revealed that throughout the entire estimated period, negative expansion decoupling and "Black" growth was observed in terms of generated waste and GVA of the mining industry in Russia.

Emissions into the atmosphere of pollutants from stationary sources and GVA of the mining sector in 2011, 2013 and 2021 were weak decoupling and "Brown" growth; in the period 2014–2019 strong decoupling and "Green" growth were observed, and in 2012 and 2020 these indicators demonstrated negative expansion decoupling and "Black" growth.

According to electricity consumption and GVA of the mining industry, weak decoupling and "Brown" growth were observed throughout the study period.

Only one indicator clearly shows a movement towards CE: discharge of polluted wastewater into surface water bodies (according to this indicator and the GVA of the industry, strong decoupling and "Green" growth has been observed since 2013).

According to water intake from natural water bodies and GVA of the industry, weak decoupling was observed in 2011; in 2012, 2013 and 2021,expansion coupling was observed, and in the period 2014–2020, negative expansion decoupling, according to the modified model of P. Victor, saw three years of "Brown" growth (2011–2013) which could be distinguished, and since 2014, "Black" growth has been observed.

At the same time, a sharp increase in the environmental burden in the form of an increase in environmental pollution per unit of economic result and resource consumption per unit of economic result during the years of economic crises (2014 and 2020) should be noted. For all five indicators of eco-intensity, a significant increase in the decoupling index has been observed in these years. In our opinion, this is due not only to a decrease in the volume of industrial production in the industry (in 2020, the volume of industrial production in Russia decreased by 2.1%), which will have almost the same effect on the rate of change in GVA and absolute indicators of eco-intensity, but also by a decrease in prices for final industry products (for example, the average price of Urals oil in January–December 2020 was USD 41.73 per barrel against USD 63.59 per barrel in January–December 2019 and set an anti-record since 2004) (answer to RQ1).

The identification of statistically significant factors influencing eco-intensity indicators (answer to RQ2) was the result of the second stage of the study; however, the absence of a statistically significant relationship between dependent variables (we considered two models) and indicators for which we assumed the existence of a relationship also needs further analysis.

According to the constructed models, it was found that the ratio of electricity consumption by type of economic activity "Mining" to the GVA in this industry (EI_4) is influenced by the following factors which have a statistically significant impact: investments in fixed assets aimed at environmental protection, research and development costs and number of advanced productions, which is consistent with previous studies.

The ratio of water intake from natural water bodies by type of economic activity "Mining" to the GVA in this industry (EI_5) is also influenced by research and development cost and the share of organizations implementing technological innovations.

Since both explanatory variables (EI_4, EI_5) showed a statistically significant influence of indicators included in the group "Innovative activity level of mining industry", it is possible to suggest to the government to consider the possibility of reducing taxes on environmental RND or increase public funding of such scientific developments.

In both regression models, there is no statistically significant relationship between AgeEq, Capex, Right, Worker, Salary, and dependent variables.

The lack of connection between the state of equipment and investments in the fixed capital of mining enterprises may be due to the fact that it is important not only to invest in updating the equipment fleet of enterprises in the industrial sector, but to invest in environmental modernization of production based on the principles of the best available technologies, which is also confirmed by this study and previous works of other researchers [52].

As for the lack of a statistically significant impact of the "Quality of management" group of indicators on the eco-intensity of the mining industry, this may be due to the fact that the first two indicators of the group are based on subjective expert assessments (for a more detailed explanation, see Section 4. Discussions and Future Research Perspectives), underrepresentation of the sample of respondents, and the lack of association between salary overlaps with a number of studies that also found no association between economic growth, environmental health and income.

The answer to RQ3 is embodied in the application of the decoupling methodology and the "Green growth" model of P. Victor in assessing the environmental and economic characteristics of a project to introduce a new oil production technology for one of the enterprises in the industry under study.

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