DOI: 10.17747/2618-947X-2023-3-262-271
UDC 658.5:330.341

Mapping the links between resource efficiency and the innovative capacity of national economies

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Abstract

The article examines studying the relationship between the level of innovation in different countries and the efficiency of their resource use, in order to better understand the potential impact of increased adoption of new technologies on the responsible use of resources in the future. Two country's samples were created for the study: the first includes 36 world economies, with calculations of energy and labour resource use efficiency, taking into account the size of the economy and the level of innovation achieved; the second sample includes data on the material footprint of 121 countries, along with levels of innovation and economic development. The empirical confirmation of the hypothesis that there is a relationship between the level of economic innovation achieved and the efficiency of resource use is a key finding. Furthermore, the results of the correlation analysis indicate a direct and close relationship between a country's economic innovativeness and its consumption volume of natural resources. This relationship can be described by a linear function. The analysis also confirms that as the population's welfare and economic innovativeness grow, the state's material footprint increases. The study is of theoretical and practical importance, encouraging the improvement of tools to ensure innovative development based on responsible production and consumption of resources. This approach aims to achieve better results at the same cost. Identifying the necessary factors related to innovative activity and efficient resource use by enterprises, as well as establishing functional dependencies between these variables, represent prospective areas for further research. In addition, a detailed examination of the experiences of Russian companies and their implications regional differentiation in terms of innovation and resource efficiency is a logical next step.

Keywords: resource efficiency, innovation, energy efficiency, labor productivity, material footprint, country, level of development, economy.

For citation:

Kravchenko S.I. (2023). Mapping the links between resource efficiency and the innovative capacity of national economies. *Strategic Decisions and Risk Management*, 14(3): 262-271. DOI: 10.17747/2618-947X-2023-3-262-271. (In Russ.)

绘制资源效率与国民经济创新之间的关系图

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简介
这篇文章研究了不同国家的创新发展水平与个人资源使用效率之间的关系，以进一步确定未来更多地引进新技术对负责任地处理资源的情况可能产生的影响。为了进行研究，我们形成了两个国家样本：第一个包括36个世界经济体，计算了它们利用能源和劳动力资源的效率指标，并考虑了经济规模和达到的创新水平；第二个样本包含121个国家的物质足迹数据，以及它们的创新和经济发展水平。 经验证实了一个假设，即国家经济的创新水平与资源利用效率之间存在关联。而且，相关分析的结果表明，国家经济的创新水平与自然资源消耗量之间存在着直接密切的关系，可以用线性函数描述，并且证实了随着人民福祉和经济创新水平的增长，政府留下的物质足迹也在增加。 研究的理论和实践意义在于促进基于负责任生产和消费原则的工具提供的创新发展程度的合理性，从而在相同成本下实现更好的结果。未来研究的潜在方向可能包括确定与企业创新活动和资源利用效率相关的必要和充分因素，以及建立所选变量之间的功能关系。对俄罗斯企业经验的详细研究及其对区域创新性和资源利用效率指标的差异化影响也是合乎逻辑的。
关键词： 资源效率、创新能力、能源效率、劳动生产率、物质足迹、国家、发展水平、经济。

引用文本:
Kravchenko S.I. (2023). 绘制资源效率与国民经济创新之间的关系图。战略决策和风险管理，14(3): 262-271. DOI: 10.17747/2618-947X-2023-3-262-271。(俄文 。)

Introduction

The ever-increasing needs of humanity and the desire to improve the well-being of the economy in every way possible are leading to the rapid depletion of limited resources and their scarcity. This leads, on the one hand, to fierce competition and higher prices for resources and, on the other, to the problem of resource conservation, i.e. more rational consumption. The problem is further complicated by the fact that intensive production and consumption (sometimes driven by rapid technological development) not only drive the economy, but also have a destructive impact on the environment. In this context, the Sustainable Development Goals (SDGs) adopted by the UN General Assembly[1], call for countries to move towards rational consumption and production models (Goal 12) in order to ensure greater efficiency in the use of resources. The implementation of this goal is primarily aimed at breaking the link between economic growth and environmental degradation.

It should be noted that increasing the efficiency of resource use covers a wide range of interrelated aspects and is a boundless field of scientific research for many scientists (e.g. [Barrett, Scott, 2012; Bach et al., 2016; Hatfield-Dodds et al., 2017; Trofimova, 2022; Salmanov, 2023]). For example, [Barrett, Scott, 2012] examines the relationship between climate change mitigation and resource efficiency in the UK. The publication [Singh et al., 2024] examines the relationship between economic development and mineral rents in the BRICS countries. The models constructed in this paper, based on empirical data, confirm the existence of a relationship between the level of trade turnover, the volume of GDP, as well as foreign direct investment on the amount of mineral rent. Based on this, the authors recommend that when planning policies and measures aimed at ensuring inclusive and sustainable development, increasing GDP, facilitating trade and increasing GDP in the BRICS countries, issues of mining rent (including taxation of mineral rent, royalties on mining, conflicts between mining companies, etc.) should be taken into account.

Another equally important area of scientific research is the issue of ensuring the innovative character of the development of the economy, its industries and enterprises (for example, [Kravchenko, 2021; Trachuk, Linder, 2021; Kosolapova et al., 2023]). Thus, in the work of [Trachuk, Linder, 2021], based on the analysis of the activities of

[1] Transforming our world: The 2030 agenda for sustainable development (2015). United Nations. https://www.un.org/sustainabledevelopment/ru/sustainable-development-goals/.

more than a hundred manufacturing enterprises, the authors identify key indicators of the effectiveness of innovation activity depending on the innovation regime to which the enterprise belongs. The team of authors in [Kosolapova et al., 2023] makes an attempt to identify the drivers of the formation of a circular economy, among which scientists highlight the innovative activity of organisations, the digital technologies used, as well as the volume of investments in fixed capital.

In recent years, research on specific aspects of a combined topic - active implementation of innovations and efficient use of resources - has become increasingly popular (e.g. [Diaz Lopez et al., 2019; Sun et al., 2023; Tang et al., 2023; Fan, Wang , 2024; Rahmani et al., 2024]). For example, the work [Rahmani et al., 2024] examines the impact of digital innovations on increasing the efficiency of resource use and sustainable development in the metallurgical industry. The results showed that the ability to absorb technological innovations and the existing digital capabilities of the company have a positive and significant impact on the company's intentions to carry out digital transformations in the metallurgical sector. In addition, the authors propose a set of measures aimed at improving the state policy regulating the introduction of digital innovations in the activities of small and medium-sized enterprises in the metallurgical industry.

The publication [Tang et al., 2023] focuses on the importance of studying the impact of green innovations and resource use efficiency to achieve zero carbon emission targets. The authors conclude on the important role of the Green Economy Innovation Index and show that even a small increase of 1% results in a measurable increase of about 0.25-0.39% in the Net Zero Emissions Index, highlighting its significant environmental impact. The author concludes that the adoption of green innovations and technologies is crucial to move developed economies towards sustainable development.

However, despite significant scientific and practical developments in the field of increasing the efficiency of resource use and ensuring innovative development of the economy, the complexity and versatility of these problems determine their constant relevance. At the same time, one of the most promising areas of scientific research is the study of the links between the efficiency of resource use and the level of innovative development of the world's economies. In this context, it is proposed to empirically test the hypothesis that the most developed innovative economies are associated with the highest consumption of natural resources and a negative impact on the environment, using quantitative methods of data analysis.

The purpose of the work is to analyse the relationship between the level of innovative development achieved by different countries and the efficiency of their use of individual resources, in order to determine the consequences that the increased introduction of new technologies may have on the situation of responsible management of resources in the future.

1. Methodology and data

This was achieved in two stages: (1) analysis of the resource efficiency of the economies of different countries around the world, taking into account their size and level of innovation; (2) study of the relationship between a country's material footprint, determined by the ratio of global resource production to domestic final demand, and its level of innovation and economic development.

To carry out the first stage - comparing the resource efficiency of the economies of different countries - indicators such as gross value added, labour productivity and energy output of GDP were selected. In addition, the level of innovativeness of countries' economies (according to the Global Innovation Index 2023, GII-2023) was analysed as a factor associated with the extent of use of different types of innovation, including resource saving.

The indicators selected reflect the size or scale of the economy (gross value added in current US dollars) and the efficiency of the use of energy and labour resources. The energy efficiency of the economy was assessed by the ratio of GDP produced at purchasing power parity to the level of expenditure on energy resources. Although this indicator has certain shortcomings (such as the inability to take into account climatic, infrastructural, territorial and other characteristics), it is currently relatively universal and provides a means of comparing the energy efficiency of different economies.

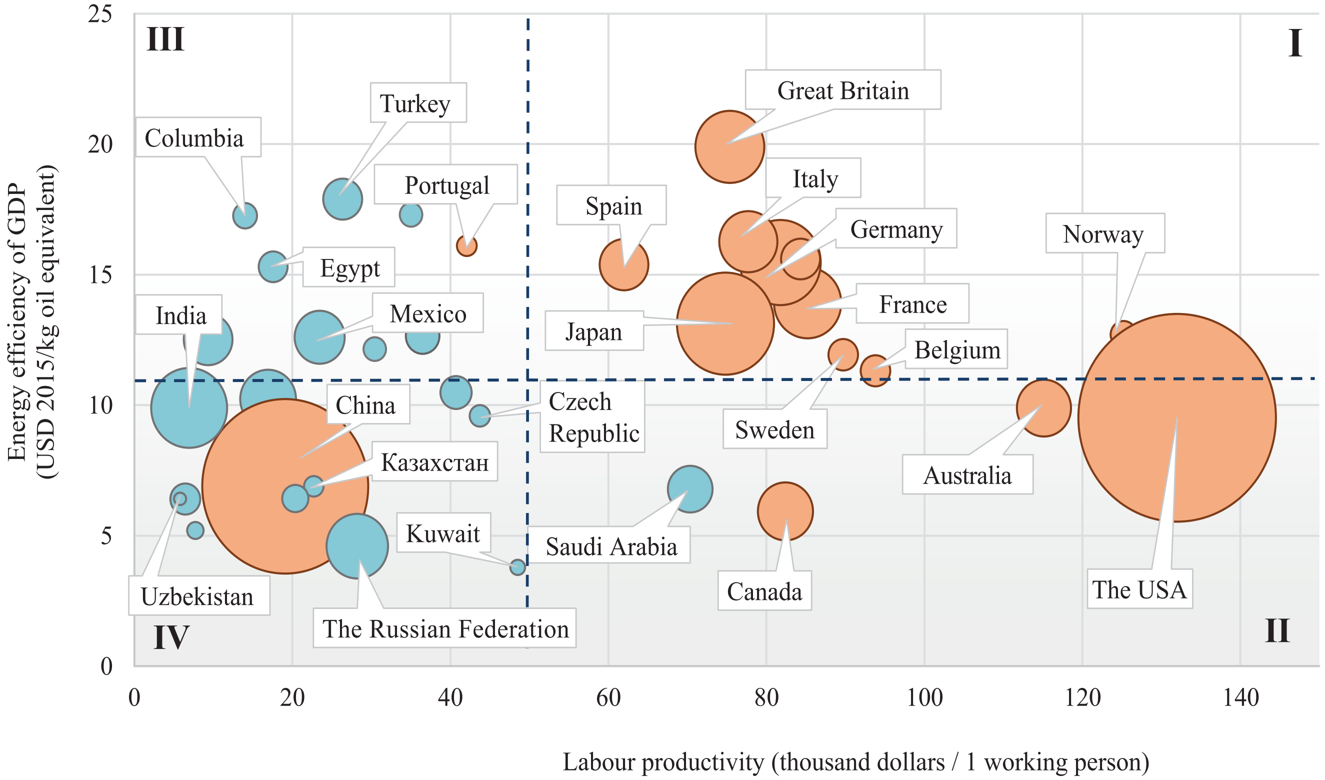
The efficiency of the use of labour resources is calculated using the labour productivity indicator as the ratio of GVA to the number of persons in employment (persons in employment include all persons of working age who, for a short period of time, were in one of the following categories: employees or self-employed).

These indicators have been calculated for 36 countries in the world, located on different continents, with different levels of development and resource endowment, and a matrix of the distribution of world economies by resource efficiency has been constructed. The limited size of the sample of countries is largely due to the availability of publicly available statistical information on the efficiency of energy resource use (namely the data published in the annual report of the Enerdata organisation[2]).

In the second stage, when studying the relationship between the material footprint of a state and its level of innovation as well as economic development, 121 countries were selected. For each country three indicators were collected from open sources of statistical information (including two quantitative ones: the rating score in points according to GII-2023, the value of the material footprint per capita - and one qualitative one: the distribution of countries' economies into groups according to their income level, proposed by the World Bank [Hamadeh et al., 2023]). Based on the quantitative data generated, the strength and direction of the correlation relationship was assessed by determining the linear Pearson correlation coefficient (r_{xy}):

[2] Global energy statistical yearbook (2023). Enerdata. https://yearbook.enerdata.net/total-energy/world-energy-intensity-gdp-data.html.

Fig. 1. Matrix of the distribution of world's economies by labour and energy efficiency



Note. The diameter of the bubbles characterises the value of GVA at basic prices; countries in the top 30 of the GII-2023 ranking are marked in lighter colours.
Source: Calculated and compiled by the author from data provided: Gross value added at basic prices (current US $). https://data.worldbank.org/indicator/NY.GDP.FCST.CD; Global energy statistical yearbook. https://yearbook.enerdata.net/total-energy/world-energy-intensity-gdp-data.html; Employment statistics. https://ilostat.ilo.org/topics/employment; [Dutta et al., 2023].

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \overline{x}) \times (y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \times \sum_{i=1}^{n}(y_i - \overline{y})^2}}, \tag{1}$$

where n – the number of observations, x_i, y_i – observation data, $\overline{x}$, $\overline{y}$ – Mean values of variables x and y.

The Pearson correlation coefficient varies from -1 to +1, with a value of -1 indicating a complete (functional) linear feedback, a value of +1 indicating a complete (functional) linear direct relationship, and a value of 0 indicating the absence of a linear correlation (but not necessarily a relationship).

The significance of the correlation coefficient for the relationship found was tested using Student's t-test where the null hypothesis is that the correlation coefficient is zero. To test the null hypothesis, the calculated value of the t-statistic (t_{calc}) is compared with the tabulated (critical) value (t_{table}) at a given significance level (α) and number of degrees of freedom. The calculated value of the Student's t-test is given by the formula

$$t_{calc} = \frac{r_{xy}}{\sqrt{1 - r_{xy}^2}}\sqrt{n-2}. \tag{2}$$

The null hypothesis is rejected if the calculated value, taken modulo, exceeds the critical value, and the probability of error is less than $\alpha \times 100\%$.

2. Research findings

The calculated characteristics of the efficiency of the use of labour and energy resources, as well as the resulting volume of GVA and the achieved level of innovativeness of the economies of the countries selected for further analysis are presented in Table.

The diagnosis of the sample of countries analysed in terms of the indicators of efficiency in the use of resources, which characterise the ability to achieve maximum results with minimum effort, made it possible to divide the economies into four groups (Fig. 1).

The visual distribution of countries between the sectors of the matrix (Fig. 1) shows that the developed European countries (Belgium, United Kingdom, Germany, Spain, Italy, the Netherlands, Norway, France, Sweden) and Japan have become representatives of the first quadrant. These economies are characterised by high labour productivity and high energy efficiency. All countries have relatively large volumes of gross value added (the maximum

Table
Resource efficiency and innovation characteristics of the world's economies in 2022–2023

Item number	Country	Labor productivity, (thousand dollars/ person)	Energy efficiency of GDP (2015 dollars/ kg oil equivalent)	Gross value added (billion $)	Rating according to GII-2023
1	Australia	115.12	9.89	1566.1	24
2	Algeria	17.00	7.86	184.0	119
3	Argentina	40.71	10.49	524.4	73
4	Belgium	93.80	11.31	468.1	23
5	Brasil	16.95	10.23	1659.4	49
6	Great Britain	75.38	19.89	2526.6	4
7	Germany	81.76	15.46	3477.3	8
8	Egypt	17.57	15.30	453.3	86
9	India	6.94	9.89	3074.4	40
10	Indonesia	9.33	12.51	1261.3	61
11	Spain	61.98	15.38	1263.9	29
12	Italy	77.72	16.26	1795.3	26
13	Kazakhstan	22.71	6.89	203.7	81
14	Canada	82.41	5.93	1622.9	15
15	China	19.10	6.89	14722.8	12
16	Columbia	14.02	17.26	309.0	66
17	Kuwait	48.52	3.78	112.4	64
18	Mexico	23.47	12.60	1344.2	58
19	Nigeria	6.44	6.40	470.2	109
20	Netherlands	84.33	15.60	808.4	7
21	Norway	125.21	12.70	358.0	19
22	Poland	36.49	12.65	611.0	41
23	Portugal	42.08	16.10	206.6	30
24	The Russian Federation	28.22	4.59	2031.4	51
25	Romania	35.02	17.30	273.4	47
26	Saudi Arabia	70.36	6.78	1052.0	48
27	The USA	132.00	9.51	20893.8	3
28	Turkey	26.38	17.89	811.1	39
29	Uzbekistan	5.78	6.40	74.9	82
30	Ukraine	7.71	5.19	141.6	55
31	France	85.21	13.91	2414.8	11
32	Czech Republic	43.73	9.59	226.3	31
33	Chili	30.44	12.15	270.2	52
34	Sweden	89.72	11.93	471.6	2
35	Republic of South Africa	20.37	6.42	363.8	59
36	Japan	74.81	13.12	5029.8	13

Source: рассчитано и составлено автором по данным: Gross value added at basic prices (current US $). https://data.worldbank.org/indicator/NY.GDP.FCST.CD; Global energy statistical yearbook. https://yearbook.enerdata.net/total-energy/world-energy-intensity-gdp-data.html; Employment statistics. https://ilostat.ilo.org/topics/employment; [Dutta et al., 2023].

value belongs to Japan - $5029.8 billion, the minimum value belongs to Norway - $358 billion) and are highly innovative economies as they belong to the top 30 of the GII-2023 rating. In terms of labour productivity, Norway is the leader - one person employed in the country's economy creates GVA in the amount of $125.21 thousand; in terms of energy efficiency - Great Britain, whose energy consumption is only 0.05 kg of oil equivalent to create 1 dollar of GDP.

The second quadrant includes the economies of countries such as Australia, Canada, Saudi Arabia and the US. This group is characterised by above-average labour productivity (for the sample of countries studied) and below-average efficiency in the use of energy resources. Among countries of this type, the highest GVA value belongs to the United States (more than USD 20 trillion). The highest labour productivity in this group of countries is found in the United States, where one person employed in the economy generates a GVA of $132.0 thousand; the highest energy efficiency value is found in Australia, where 0.101 kg of oil is consumed to generate $1 GDP. eq. of energy resources. The countries in this sector are in the top 30 according to the GII-2023 rating (the exception is Saudi Arabia - 48th).

The third quadrant is represented by Chile, Egypt, Indonesia, Colombia, Mexico, Poland, Portugal, Romania, Turkey. Countries of this type are characterised by labour productivity below the average level for the sample of countries analysed and above-average efficiency in the use of energy resources. Among these countries, Mexico has the highest gross value added - $1344.2 billion; the lowest value of labour productivity is in Indonesia, where one worker employed in the economy generates $9.33 thousand of GVA. Turkey is characterised by a high level of efficiency in the use of energy resources, where 0.056 kg of oil is used to generate $1 GDP. eq. The countries in this cluster are ranked from 30th to 66th in the GII-2023 ranking (with the exception of Egypt, which is ranked 86th).

The fourth quadrant included Algeria, Argentina, Brazil, China, India, Kazakhstan, Kuwait, Nigeria, the Russian Federation, Uzbekistan, Ukraine, the Czech Republic and South Africa. Economies of this type are characterised by energy efficiency and labour productivity levels below the average of the sample. In terms of labour productivity, the worst value among the countries in this group is Uzbekistan, where one person employed generates USD 5.78 thousand of GVA. Among the countries in this group, the Chinese economy is characterised by the highest volume of GVA (around USD 15 trillion) and the highest level of innovation, ranking 12th in the GII-2023 ranking. Other countries are much less innovative and do not appear in the GII-2023 top 30.

Separately, it should be noted that some countries with a relatively high level of innovation (e.g. industrial giants such as China and the US) are leaders in terms of gross value added, but in terms of efficiency in the use of labour and energy resources they are in the catching-up groups (e.g. the level of energy resource use in the US is below the average for the sample of countries analysed). For China, both resource use efficiency indicators analysed are below average.

The distribution of countries according to the efficiency of the use of labour and energy resources (Fig. 1) shows that countries with a high level of innovation, which usually generate higher volumes of GVA, are characterised by higher values of resource efficiency indicators. Thus, the existence of a relationship between the level of innovative development achieved by the country and the efficiency of resource use has been empirically documented, which is undoubtedly logical. Obviously, new technologies make it possible, ceteris paribus, to use fewer resources to produce a similar amount of goods as with outdated technologies. What is of particular scientific and practical interest, however, is the impact that the widespread diffusion and implementation of innovations by developed and developing countries may have in the future on the situation with regard to the responsible use of resources.

The Intelligence Study also analysed the relationship between a country's Material Footprint (MF) and the innovativeness of its economy. The total Material Footprint is the sum of the Material Footprints of biomass, fossil fuels, metallic and non-metallic ores and is calculated as the resource equivalent of imports plus domestic production minus the resource equivalent of exports. In turn, the per capita MF describes the average material use for final demand [Giljum et al., 2015; Wiedmann et al., 2015; Matuštík, Kočí, 2021]. It should be noted that the material footprint is an indicator for the achievement of sustainable development goals, which include the desire to gradually increase the global efficiency of resource use in consumption and production systems and to ensure that economic growth is not accompanied by environmental degradation[3].

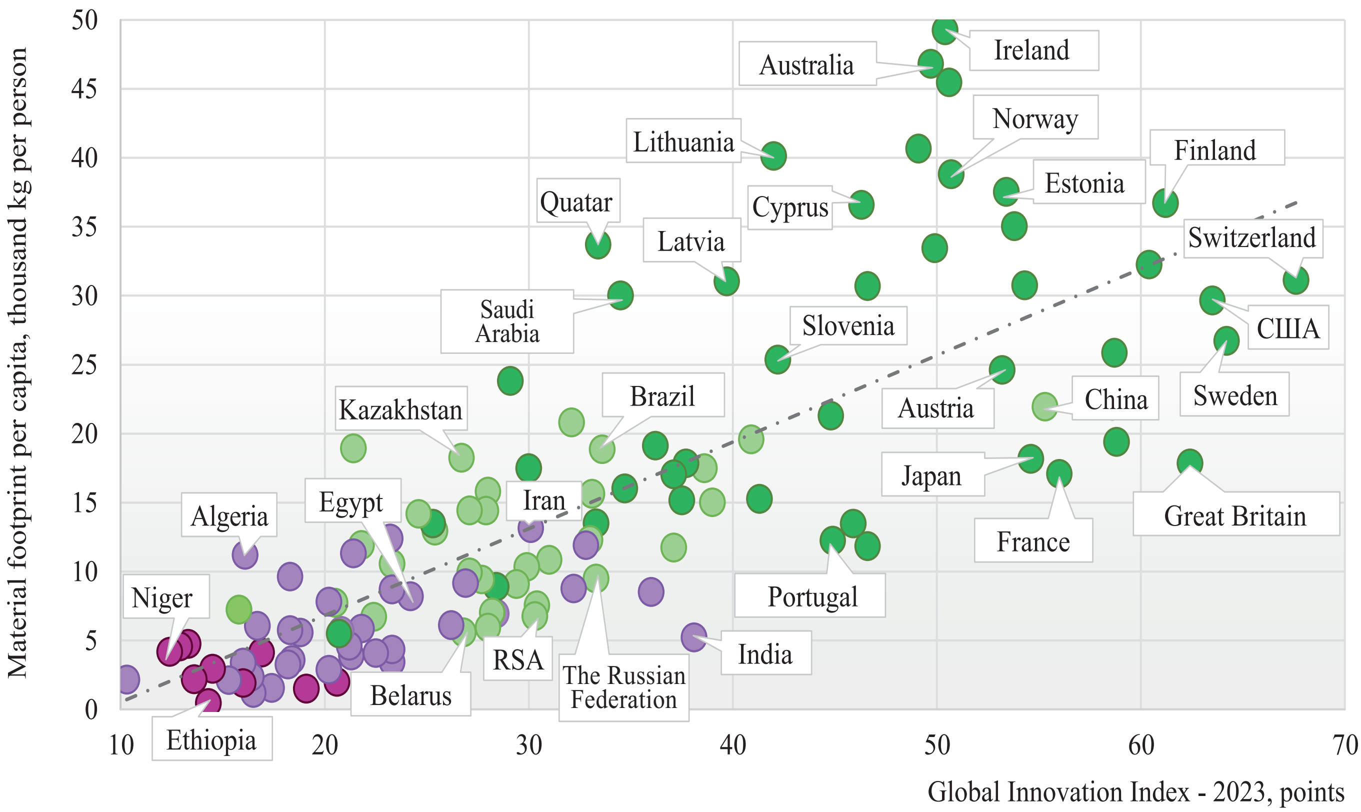
In order to establish the existence of a relationship between these indicators, a correlation matrix was provided covering 121 economies in the world (Fig. 2). The construction of this field has also taken into account the classification of economies into groups (according to income level) proposed by the World Bank, namely:

- high-income countries (GNI per capita greater than $13,845);
- upper middle-income countries (GNI per capita between $4,465 and $13,845);
- lower middle-income countries (GNI per capita between $1,136 and $4,465);
- low-income countries (GNI per capita less than $1,135).

Based on the visual analysis of the correlation field, it is possible to assume the existence of a relationship, its form and its closeness. Thus, according to Fig. 2, it can be argued that the relationship between the variables under

[3] Transforming our world… (2015). United Nations. https://www.un.org/sustainabledevelopment/ru/sustainable-development-goals/.

Fig. 2. Correlation field of the interdependence between the material footprint and the level of innovative development of the world's economies



Note. Dark green indicates high-income countries, light green indicates upper-middle-income countries, light purple indicates lower-middle-income countries and dark purple indicates low-income countries.
Source: constructed by the author from data: Material resources. Material footprint per capita. https://stats.oecd.org/Index.aspx?DataSetCode=MATERIAL_RESOURCES; [Dutta et al., 2023; Hamadeh et al., 2023].

study can be linear, direct and close, i.e. an increase in one indicator is characterised by an increase in another. A more detailed analysis was carried out by calculating correlation indicators based on statistical data.

Based on the calculated data, the close relationship between the volume of the material footprint of countries' economies and their level of innovation was determined according to formula (1):

$$r_{xy} = \frac{15061.35}{\sqrt{15623.77 \times 23964.7}} = 0.778.$$

Pearson's linear correlation coefficient is positive, i.e. the relationship between the variables studied is direct, and when the coefficient is close to 1, it indicates the presence of a linear correlation. The interpretation of the tightness (strength) of the relationship based on the rxy value obtained is carried out using the Chaddock scale, which makes it possible to convert a numerical indicator or quantitative value into a qualitative parameter. Thus, the strength of the relationship between the volume of the material footprint of a country's economy and the level of its innovativeness can be characterised as high.

Using formula (2) and the previously determined value of the correlation coefficient, the calculated value of the t-criterion was obtained:

$$t_{calc} = \frac{0.778}{\sqrt{1-0.778^2}}\sqrt{121-2} = 72.71.$$

The critical value (t_{table}) at $\alpha = 0.001$ is 3.373, i.e. the null hypothesis of no relationship between the variables is rejected, since $t_{calc} > t_{table.}$ The correlation coefficient is therefore statistically significant.

In summary, several points should be noted: firstly, the results of the correlation analysis indicate the existence of a direct close relationship between the level of innovation of the economy of a country and the volume of consumption of natural resources, which can be described by a linear function. Secondly, in accordance with Fig. 2, we can conclude that, moving from the origin along the trend line, there is a gradual transition from developing countries to developed countries. Thirdly, a high level of resource consumption, as well as a higher value of the GII index, is characteristic of developed countries. This confirms that the most developed innovative countries consume more resources. Consequently, further research should be conducted on the assumption that the widespread diffusion of innovative technologies (in both developed and developing countries), aimed at ensuring economic growth without taking into account the resource consequences, may in the future lead to a reduction in resource reserves and increased competition among buyers for the right to own them, with consequent rising prices on commodity markets and negative environmental consequences for humanity.

3. Conclusions and limitations

The study confirms that countries that have achieved a high level of innovation in their development are characterised by higher indicators of efficiency in the use of resources (i.e. there is a direct relationship between these parameters), which creates their competitive advantage, allowing them to produce more goods by attracting new technologies, other things being equal.

At the same time, the results obtained indicate that the widespread dissemination and implementation of innovations by developed and developing countries can contribute both to their economic growth and to an increase in their material footprint, thus leading to the depletion of natural resources in the future. In such conditions, the economic development of all economic entities should be based on the principles of lean production and its intensification, which will help to increase the return on the use of available factors of production with a constant volume of resources consumed or their reduction.

This empirical study is based on quantitative methods of data analysis, but it did not include the identification of functional dependencies between the parameters studied, which is its main limitation. The economies of the countries are characterised by various features (e.g. geographical and climatic conditions affecting the level of energy consumption by households for final consumption and by business entities for the maintenance of production and other premises; the presence of natural resource reserves in the country and the possibility of their extraction, etc.), but such factors have not been taken into account in the analysis.), but these factors were not taken into account in the analysis. In addition, the analysis was carried out in the context of country samples whose representativeness was not statistically verified.

Thus, promising areas for further research may be the identification of the necessary and sufficient number of factors associated with the innovative activity of enterprises and the efficiency of their use of resources, as well as the establishment of functional dependencies between selected variables. It also seems logical to conduct a detailed study of the experience of Russian enterprises and its impact on the differentiation of regions in terms of innovation and resource efficiency.

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The article was submitted on 16.10.2023; revised on 04.11.2023 and accepted for publication on 15.11.2023. The author read and approved the final version of the manuscript.

文章于 16.10.2023 提交给编辑。文章于 04.11.2023 已审稿．之后于 15.11.2023 接受发表。作者已经阅读并批准了手稿的最终版本。