Journal of Infrastructure, Policy and Development 2024, 8(16), 10396.
https://doi.org/10.24294/jipd10396

Article

Examining the link between GDP growth and raw material usage efficiency in EU nations

László Török

Department of Engineering Management and Enterprise, Faculty of Engineering, University of Debrecen, 4028 Ótemető utca 2-4, Hungary; dr.torok.laszlo@eng.unideb.hu

CITATION

Török L. (2024). Examining the link between GDP growth and raw material usage efficiency in EU nations. Journal of Infrastructure, Policy and Development. 8(16): 10396. https://doi.org/10.24294/jipd10396

ARTICLE INFO

Received: 18 November 2024
Accepted: 3 December 2024
Available online: 27 December 2024

Abstract: Creating products and services that satisfy individual and community needs is impossible without raw materials. This study takes a novel approach by integrating the economic dynamics and raw material consumption indicators of the European Union (EU). The study uses different econometric methods to analyze the relationship between GDP (gross domestic product) and the EU's raw material consumption (RMC) from 2014–2023. Among the results, the panel data analysis model shows that the resource productivity of the EU improved during the period under review, whereas the material intensity decreased significantly. These trends significantly contributed to the relative decoupling of material consumption from GDP in the last decade. The results of the K-means cluster analysis highlight the regional economic differences within the EU. According to the results of the correlation analysis, EU member countries differ significantly in the efficiency of raw material use. Nevertheless, five member countries are robustly vulnerable to large-scale raw material use. The divergence calculation results show that while some countries use raw materials extremely efficiently to produce GDP, others achieve low efficiency. This unique approach and the resulting findings provide a new perspective on the complex relationship between economic growth and raw material use in the EU.

Keywords: economic dynamics; resource productivity; material intensity; decoupling; econometrics

1. Introduction

The relationship between the European Union's (EU) GDP (Gross Domestic Product) and raw material consumption (RMC) is closely related to the natural sciences, especially the ecological sciences. In addition, the natural sciences contribute to developing resource management strategies to achieve sustainable economic growth, manifested in increased GDP. Improving resource efficiency is crucial in mitigating the environmental impacts associated with using materials and achieving the security of supply and job creation goals. Lower material input into various economic activities can also increase competitiveness at the company level and in the national economy. Natural resources are essential for creating products and services, but their quantity is limited. It is impossible to know where the limits of the Earth's natural resources and raw materials are. However, with the current trends, EU member states cannot achieve the same level of well-being as European Union societies without endangering life-sustaining ecological systems (Wackernagel et al., 2004). The amount of natural resources (such as extracted raw materials) is closely related to the value of the ecological footprint (EF). EF is a sustainability indicator that expresses the annual renewable capacity of the Earth's biosphere. In other words, the ecological EF measures the resources required to produce all the goods and services consumed by humanity and to absorb the waste generated (Destek et al., 2018; Ghita et al., 2018).

One of the central issues of sustainability is how to harmonize the dynamics of economic systems with those of ecological systems. One of the tools for this can be the improvement of eco-efficiency, which means an increase in added value while reducing the intensity of resource use, i.e., an increase in resource efficiency is achieved in a way that also benefits business organizations. In principle, improving environmental efficiency makes it possible to reduce the ecological burden without reducing material well-being by using natural resources better. Accordingly, the longer-term environmental strategy of individual countries is based primarily on improving resource efficiency (Zschieschang et al., 2013).

Companies play a significant role in harmonizing economic and ecological systems' dynamics. Companies in national economies want to be competitive and develop sustainably. Corporate sustainability is a business approach that increases the value of the company in the long term by exploiting opportunities and reducing risks at the level of economic, environmental, and social development (Stoenoiu and Jäntschi, 2024) while taking into account economic-social and moral or ethical values (Ikerd, 2024).

Calculating the EF is a complex task, as several factors must be considered. The sustainability methodologies consider five factors during the calculations: 1) resource use, which is equal to the raw materials used to produce GDP; 2) emission, which is the emission of carbon dioxide and other greenhouse gases; 3) biocapacity, which includes the number of biological materials produced by the given area and the regeneration capacity of natural resources; and 4) consumption habits, which are the consumption habits of the country's population; and 5) technological efficiency, which is the country's technological development and energy efficiency and influences how "green" GDP production is (Kalantaripor et al., 2020).

Better technologies can reduce EF even as GDP increases. The previous sentences show that calculating EF is a multifactorial task that gives a complex picture of a country's environmental impact, considering many different aspects. One aspect, perhaps the most important, is the raw materials needed to produce GDP (Wang et al., 2022). **Figure 1** shows what factors influence EF.

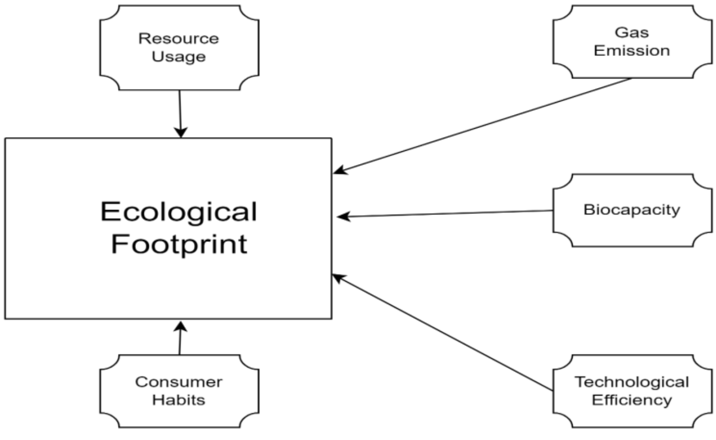

Figure 1. Factors influencing the ecological footprint (FP).

source: Own figure.

The definitions of the factors in **Figure 1** are as follows: Resource Usage: The amount of materials and energy that society uses to meet its needs; Consumer Habits, People's purchasing and consumption habits that determine their demand for natural resources; Gas Emissions: The emission of greenhouse gases from human activities, such as energy use or industrial production; Biocapacity: The ability of a given area to produce natural resources and absorb waste generated by human activities; Technological Efficiency: The extent to which technology is applied to optimize the use of natural resources and minimize the impact on the environment.

In connection with this topic, researchers often use the Ecological Footprint Calculator. The calculator measures how much environmental resources our lifestyle requires, how much land and sea area it requires to sustain ourselves and absorb the waste we produce, and how much impact these have on the natural environment. Its value can be calculated for individual people, groups, regions, countries, or businesses. Ecological footprint data is often used as an argument in discussions about the sustainability of our current lifestyle. This calculator measures the greenhouse gas emissions of our everyday activities and our carbon footprint, which accounts for almost 60% of our ecological footprint. By converting the result, we see the global ecological footprint expressed in hectares.

The present study does not examine the EF but rather its most crucial factor, RMC, with respect to economic output. In this work, the study uses the Eurostat databases for the analyses. The value of the statistical raw material flow account used for calculations includes specific flow aggregates, namely, the domestic extraction of materials, actual imports, and actual exports, in a detailed breakdown according to mandatorily prescribed materials. The raw material flow account of the EU member states includes all materials (except water and air) that cross the system boundaries of the national economy of the reporting country. The study shows how GDP production by EU member states and the amount of raw materials used for it (RMC) were related between 2014 and 2023. The research revealed the differences in the raw material efficiency and economic performance of the European Union member states, particularly regarding the efficiency and material intensity of resource use. In addition, the goal of analyzing the disconnection process between material consumption and economic growth in the EU was achieved, thereby revealing the extent to which the EU can maintain economic growth while reducing the demand for raw materials.

The results of this study can help EU economic policymakers develop sustainable development strategies and improve resource efficiency.

The study's parts are as follows: After the Introduction, the Literature review, and the Materials and Methods sections follow. The Results, Discussion, and Conclusions sections follow the previous ones. The article concludes with a section on the study's limitations and future research directions.

(The names of EU member states are included in the Appendix).

2. Literature review

The literature review section briefly summarizes and evaluates existing research on GDP production and RMCs. Its purpose is to identify gaps, contradictions, and areas that require further investigation while providing an overview of existing knowledge in the study's target area. A brief literature review helps provide context and background information about the research topic and its significance.

The resource intensity of economies has an extensive literary background, as it can be examined at several levels of the economy. For example, the following studies have analyzed resource intensity at the industry level (Kazemzadeh et al., 2023; Kuziboev et al., 2024; Mahmood, 2023; Mahmood et al., 2023; Wandebori and Murtyastanto, 2023). Several studies have examined resource intensity at the national and regional levels (Bithas and Kalimeris, 2018; Bringezu, 2015; Chen et al., 2021; Dogan and Shah, 2022; Du et al., 2020; Huong et al., 2021; Liang et al., 2023; Taguchi and Ganbayar, 2022; Zhang et al., 2016; Zhang et al., 2023; Ziolo et al., 2020).

The study of resource intensity is also a prominent research field in the natural sciences, and numerous studies have analyzed the relationship between the added value of the national economy and the extraction and use of resources (Ashby, 2012; Golam, 2023; Haberl et al., 2020; Kinnaman, 2023; Koskela et al., 2023; Kuemmerle et al., 2013; Min et al., 2022; Mostert and Bringezu, 2019; Pepłowska and Olczak, 2024; Török, 2022; UNEP, 2013; Xu et al., 2016).

A significant proportion of the results of the literature studies indicate that resource intensity is decreasing in most developed national economies due to several factors. These factors include technological innovation, restructuring of the outsourcing of heavy industry toward the service sector, and an increase in the level of production organization (Bánhidi and Dobos, 2023; Bányai, 2013; Eurostat, 2024a, 2024b; Wiedenhofer et al., 2020).

This thesis is significant from a scientific point of view because it provides a comprehensive picture of the economic and raw material consumption performance of the 27 EU member states, highlighting the connections between economic growth and sustainability. The methods used (panel data model, cluster analysis, calculation of correlation and divergence values) enable a detailed and comparative analysis between EU member states, which provides valuable insight into regional economic differences and sustainable resource management.

3. Materials and methods

Before presenting the methodologies, the study describes the databases on which the analyses are performed. One such database is the GDP data of the EU member states between 2014 and 2023.

According to **Table 1**, the GDP data of the EU member states show that continuous economic growth was observed in most countries between 2014 and 2023. Eastern and Central European (CEE) countries show more dynamic growth, whereas Western European countries maintain stable, high GDP values during the period under review. In the examined period, the EU's GDP increased to 144%. Ireland's economy grew the most dynamically (+154%), while Greece's economy grew the least, only +24%. This growth trend highlights the economic differences and structural peculiarities between EU regions. The development of Eastern and Central European countries is partly due to the efficient use of EU funds and economic modernization. In contrast, Greece's lower growth can be traced back to the long-term effects of previous financial crises. Ireland's economic success, however, was built on innovation, the presence of multinational companies, and a favorable business environment during the period under review.

Table 1. GDP data of EU member states in billions of euros (2014–2023).

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	23/14
BE	403	417	430	445	460	479	461	508	554	585	145
BG	43	46	49	53	56	62	62	71	86	94	219
CZ	159	171	179	197	214	229	220	246	287	317	199
DK	266	272	282	294	301	309	312	345	382	376	141
DE	2927	3026	3135	3267	3365	3474	3404	3617	3877	4122	141
EE	20	21	22	24	26	28	27	31	36	38	190
IE	201	273	276	309	335	364	382	449	521	510	254
EL	177	176	174	177	180	183	165	182	207	220	124
ES	1033	1078	1114	1162	1204	1246	1119	1222	1346	1462	142
FR	2154	2201	2232	2292	2355	2432	2318	2508	2655	2822	131
HR	44	45	48	50	53	56	51	59	68	76	173
IT	1627	1655	1696	1737	1771	1797	1661	1822	1963	2085	128
CY	17	18	19	20	22	23	22	25	28	30	176
LV	24	25	25	27	29	31	30	33	38	40	167
LT	37	37	39	42	46	49	50	56	67	72	195
LU	52	54	56	58	60	62	65	72	78	79	152
HU	106	113	116	127	136	147	138	154	169	196	185
MT	9	10	11	12	13	14	13	15	17	19	211
NL	672	690	708	738	774	813	797	871	959	1034	154
AT	333	344	358	369	385	397	381	405	447	478	144
PL	406	430	425	466	499	532	526	576	656	751	185
PT	173	180	186	196	205	214	201	216	242	266	154
RO	151	160	167	186	206	224	220	242	284	325	215
SI	38	39	40	43	46	49	47	52	57	63	166
SK	76	80	81	85	90	94	93	100	110	123	162
FI	207	211	218	226	233	240	238	251	268	275	133
SE	436	452	465	476	467	475	479	539	552	541	124
EU	11,791	12,224	12,651	13,078	13,531	14,023	14,482	14,667	15,954	16,999	144

Source: (Eurostat 2024a).

The study uses Eurostat databases because Eurostat provides reliable and consistent data for all member states. The database is updated regularly, making it an up-to-date and reliable source for analyzing economic and environmental indicators. The wide availability and granularity of the data also allow for annual, country-specific, and aggregated EU-level analyses. The World Bank database could have been used as an alternative database, providing global coverage and detailed economic indicators (Almodóvar-González et al., 2020).

The second database shows the RMCs of EU member states between 2014 and 2023.

Table 2. Raw material flow values of EU member countries, in million tons (2014–2023).

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	23/14
BE	54	49	45	52	49	53	49	49	52	55	102
BG	20	20	19	22	22	22	18	23	23	20	100
CZ	23	22	25	25	25	25	25	24	23	28	122
DK	42	40	42	44	40	44	43	42	43	38	90
DE	266	243	247	261	229	240	242	253	231	230	86
EE	5	6	5	6	5	6	6	5	7	6	120
IE	45	45	44	45	46	46	48	46	46	36	80
EL	34	31	31	30	29	29	28	28	28	25	74
ES	129	130	139	122	143	133	138	139	122	113	88
FR	259	227	213	251	221	228	207	235	194	216	83
HR	13	11	13	12	13	13	13	12	12	13	100
IT	140	127	129	126	130	137	135	131	129	121	86
CY	1	2	2	2	2	2	2	2	2	2	200
LV	6	6	6	6	6	7	8	8	7	6	100
LT	17	18	18	18	16	18	19	18	19	16	94
LU	2	2	2	2	2	2	2	3	3	3	150
HU	40	33	40	33	38	38	35	34	27	38	95
MT	1	1	1	1	1	1	1	1	1	1	100
NL	53	52	48	59	55	58	55	55	58	54	102
AT	41	38	42	39	39	39	42	42	39	37	90
PL	158	135	150	161	144	144	158	158	162	154	97
PT	32	34	34	36	35	35	33	35	38	38	119
RO	62	59	63	72	79	72	59	69	55	55	89
SI	5	5	5	4	5	6	6	5	5	5	100
SK	20	16	19	16	19	18	17	17	15	15	75
FI	35	35	36	35	39	39	38	39	35	32	91
SE	62	58	58	59	58	65	58	59	61	62	100
EU	1565	1445	1476	1539	1490	1520	1485	1532	1437	1419	91

Source: (Eurostat 2024b).

Based on the RMC data of the EU member states in **Table 2**, it can be concluded that larger economies such as Germany, France, and Italy have the highest RMC values. However, these countries also show sustainability efforts by reducing RMCs during this period. In several member countries, the RMC remained relatively stable during the period under review, with minor fluctuations (Denmark, Croatia, and Hungary). These findings indicate that these countries are using their raw materials more sustainably. Smaller economies such as Cyprus, Malta, and Luxembourg have the lowest RMC values. These countries have lower industrial production and a proportionally larger service sector, which results in a lower RMC. The RMC decreased to 91% in the EU during the examined period.

In this part, the study uses different econometric methods to examine the data and reveal complex relationships. Analyzing each dataset (GDP and RMC) separately allows us to observe each variable's temporal behavior, trends, and seasonal patterns. This helps us understand fundamental economic and environmental processes, such as economic cycles or changes in RMCs. The joint examination of GDP and RMC enables the exploration of correlations and interactions. This makes it easier to understand how much EU economic growth burdens natural resources and the environment.

A regression analysis was performed in the study, the results of which are shown in **Table 3**:

Table 3. Results of the regression analysis with the EU GDP (billion euros) and RMC (million tons) data.

Year	Actual GDP	Estimated GDP	Difference (%)	Actual RMC	Estimated RMC	Difference (%)
2014	11,791	11,546	−2.07	1565	1524	−2.61
2015	12,224	12,078	−1.19	1445	1517	4.96
2016	12,651	12,610	−3.32	1476	1509	2.26
2017	13,078	13,142	0.49	1539	1501	−2.41
2018	13,531	13,674	1.06	1490	1495	0.30
2019	14,023	14,206	1.03	1520	1487	−2.16
2020	14,482	14,738	1.77	1485	1480	−0.30
2021	14,667	15,270	4.11	1532	1472	−3.90
2022	15,954	15,802	−0.95	1437	1465	1.94
2023	16,999	16,334	−3.91	1419	1457	2.71

Source: Data from **Tables 1** and **2**.

The R-squared value for GDP is 0.9575. The linear model explains 95.75% of the GDP data, indicating a solid relationship between years and GDP. The model follows the data trend well, with minimal deviation from the actual GDP values for each year.

The R-squared value for RMC is 0.2178. This means that the linear model explains only 21.78% of the variance in the data. This indicates a poor fit, indicating that the trend does not follow the raw material consumption data well and that other factors may also significantly impact the development of RMC.

3.1. Panel data model analysis

Econometric research using panel data has become increasingly widespread in recent years, as it is suitable for various uses (Dziechciarz, 2024; Forchini and Peng, 2016; Salas-Velasco, 2023). This study aims to determine the relationship between economic growth (measured in GDP) and RMCs. Panel Data Model calculates the value of fixed contributions (FEs) using each EU member state's time-constant but unique characteristics.

The model equation is as follows:

$$Y_{it} = \alpha_i + \beta X_{it} + \epsilon_{it} \tag{1}$$

where Yt is the t-th time observation (GDP) of the i-th individual (member country), αi is the individual-specific fixed effect (a fixed factor specific to a given member country, such as geographical location), β is the independent variable Xit is the estimated coefficient of its effect (RMC effect), and $\in it$ is the error term, which includes the factors that the variables of the model cannot explain.

3.2. *K*-means cluster analysis

Researchers often use the K-means clustering methodology (Herman et al., 2022; Malatesta and Breadsell, 2022; Yoder Clark et al., 2021). The *K*-means cluster analysis aims to divide the EU member states into homogeneous groups based on the similarities of GDP and RMC. This allows countries to be grouped into groups with similar internal economic structures and RMC patterns. The clusters formed in this way identify the typical characteristics of the EU member states. The equation for the model (Calculating Centroids) is as follows:

$$\mu_j = 1/C_j \Sigma_{xi \in cj} X_i \tag{2}$$

where μj is the centroid of the jth cluster, Cj is the set of the *jth* cluster, and xi is the ith data point belonging to the jth cluster.

The centroid represents the average of the GDP and RMC data of the countries in a given cluster. This centroid point represents the cluster, i.e., it shows the "average country" of the given group in terms of economic performance (GDP) and raw material consumption (RMC).

3.3. Calculation of correlations

The Pearson correlation coefficients show how much each EU member's GDP and RMC values correlate. The coefficient's value ranges from −1 to 1, where 1 indicates a strong positive correlation, −1 indicates a strong negative correlation, and 0 indicates no correlation.

The model equation is as follows:

$$r = n(\Sigma xy) - (\Sigma x)(\Sigma y) / \sqrt{[n\Sigma x^2 - (\Sigma x)^2][n\Sigma y^2 - (\Sigma y)^2]} \tag{3}$$

where n is the number of data points, x represents the GDP values, and y represents the RMC values.

Pearson correlation is used for linear correlation. However, Spearman and Kendall's correlations also exist (Bolboacâ and Jäntschi, 2006).

3.4. Calculation of the divergence index

Researchers have used divergence indicator calculations to examine differences and efficiency between economic systems or periods (Glawe and Wagner, 2021; Suad et al., 2024). Using the divergence indicator, I examine how different each country's GDP and RMC values are from the average. To do this, we calculate the divergence by comparing the GDP and RMC values of each year with the averages of the respective countries.

The model equation is as follows:

$$D_i = \sqrt{\frac{1}{n}\sum_{t=1}^{n}((GDP_{it} - \overline{GDP_i})^2 + (RMC_{it} - \overline{RMC_i})^2)} \tag{4}$$

where *n* is the number of years, and *GDPit* is the GDP of the *i*-th country in the *t*-th year. *GDPi* is the average GDP of the ith country in the examined period. *RMCit* is the RMC of country *i* in year *t*. *RMCi* is the average RMC of the *i*-th country in the examined period.

4. Results

The study summarizes the results of the individual econometric analyses below.

4.1. Panel data model analysis results

According to the data in **Table 4**, the average GDP in the 27 EU member states hovered approximately 832 billion euros between 2014 and 2023. The average values differ significantly between countries; Germany (DE) has the highest GDP values, whereas Cyprus (CY) and Malta (MT) have the lowest values. The standard deviation of the GDP data was 1036 billion euros, indicating significant differences in the economic performance of individual countries. The largest economies, such as Germany, France, and Italy, differ significantly from smaller economies. The lowest value of GDP was 9 billion euros, whereas the highest value was 4122 billion euros. These values reflect the economic diversity of EU member states and the wide range of economic performance.

Table 4. Summary statistics of the panel data.

Panel feature	GDP	RMC
Average	832. 13	40.04
Spread	1036.44	51.68
Minimum	9.00	1.00
25% Quartile	39.00	5.00
Median	222.00	25.00
75% Quartile	1032.00	43.00
Maximum	4122.00	266.00

Source: Own table.

The average RMC in the 27 member states of the EU during the period under review was approximately 40.04 million tons. The differences in the data per country are significant. Germany had the highest consumption values (261 million tons), whereas Cyprus and Malta had the lowest values (one million tons rounded off). The standard deviation of the RMC was 51 million tons, indicating significant differences between the individual countries. Larger industrial countries have a much higher specific RMC than smaller, service-oriented economies.

Average GDP values: The average GDP value is 832 billion euros, but the data median is 222 billion euros, which suggests that the data distribution is asymmetric and that the high GDP values of some large economies (e.g., Germany) may skew the average. Differences in material use: The median of the RMC is 25 million tons, so more than half of the EU member states use fewer raw materials than this number does, whereas the 75 percent quartile is already 43 million tons, which also shows robust differences in the raw material use of the member states.

Table 5 shows the results of the Fixed Effects calculation. This means that an increase of one unit of RMC leads to an average increase of 12.49 units of GDP, with other variables remaining unchanged. The results are statistically significant (*P* value < 0.05). This finding is likely not a coincidence but a real correlation between GDP and RMCs. The statistical significance confirms that the relationship between RMC and GDP is reliable and worth considering during the EU's economic policy decisions. The values in **Table 5** should be regarded as the EF model, taking into account the specific characteristics of each country, which are constant over time, such as geographical location, institutional framework, and economic structure.

Table 5. Results of the fixed effects (FE) model.

Parameter	Estimated value	Standard error	*t* value	*P* value
Constant	347.55	62.89	5.53	0.00
RMC	12.49	2.16	5.78	0.00

Source: Own table.

Based on the panel data model results, temporal trends also play a significant role in economic growth in the 27 member states of the EU. The analysis of the data revealed that the rate of economic growth was variable in the period between 2014 and 2023. However, the average GDP increase of 12.49 units for each RMC unit showed a stable growth trend. This indicates that the economic utilization of raw materials has improved over time in the EU, and national economies have used the available raw materials increasingly efficiently to increase GDP. Using the panel data model, we determined that the differences between individual countries are based on differences in the economic utilization of the RMC. The EU's resource productivity improved, whereas its material intensity decreased significantly. These trends significantly contributed to the relative decoupling of material consumption from GDP in the last decade.

Based on the results of the fixed effects (FE) model, the following conclusions about the robustness of the data are drawn: 1) There are highly significant effects. The model's constant value (347.55) and the RMC value (12.49) are significant since both *P* values are 0.00. This indicates that the impact of the variables on GDP is statistically significant and highly reliable. 2) High *t* values: The *t* values (constant: 5.53; RMC: 5.78) are also high, which suggests that the parameter estimates are far from zero, i.e., the forecasts are not random results but accurate and robust in terms of their impact on GDP. 3) Low standard errors: The standard errors are relatively low (constant: 62.89; RMC: 2.16), which shows that the model is stable and that the estimates are not sensitive to significant fluctuations in the data. 4) Model robustness: The above results suggest that the model is robust, as the variables are significant, the standard errors are low, and the t values are high. The FE model explains the impact of RMCs on GDP well and provides reliable results.

The data in **Table 6** clearly show that between 2014 and 2023, GDP in the EU significantly increased, increasing from 11,791 billion euros to 16,999 billion euros. In contrast, raw material consumption (RMC) decreased from 1565 million tons to 1419 million tons. The literature calls this phenomenon 'decoupling,' meaning that economic growth is separated from raw material consumption growth. This result suggests that the EU economy can grow increasingly efficiently without proportionally increasing the use of raw materials.

Table 6. GDP growth and RMC reduction (decoupling) in the EU (2014–2023).

Variables	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
GDP	11,791	12,224	12,551	13,078	13,531	14,023	13,482	14,667	15,954	16,999
RMC	1565	1445	1476	1539	1490	1520	1485	1532	1437	1419

Source: Own table.

The separation of the values of the two variables is continuously visible. However, as **Figure 2** shows, the divergence between GDP and RMC has been much more dynamic since 2021.

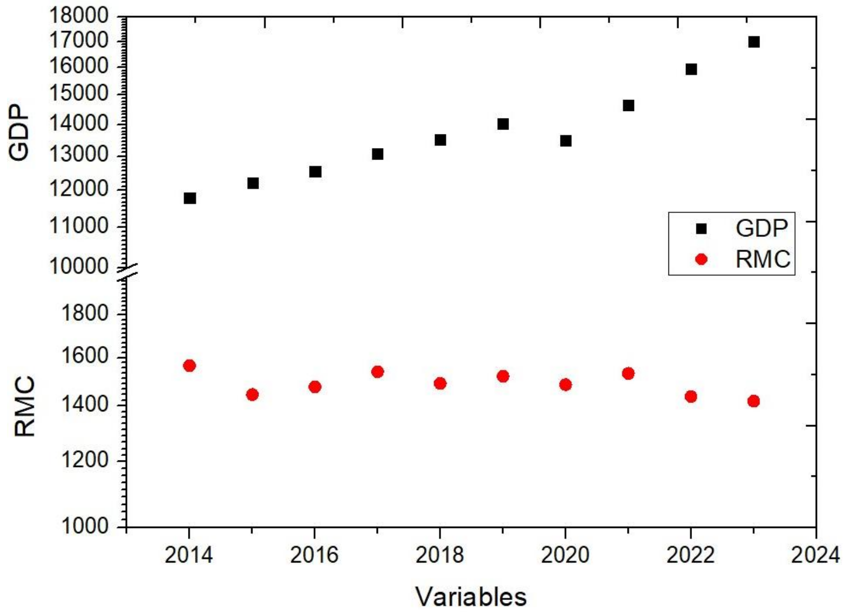

Figure 2. 'decoupling' model of EU GDP and RMC separation.

Source: Own figure (GDP: billion euro/year; RMC: million tons/year).

4.2. *K*-means cluster analysis results

Using this method, four clusters were formed, which I present below:

Cluster 1: Low GDP and RMC. This cluster includes countries with low GDP and low RMC. The countries included Bulgaria, Estonia, Latvia, Cyprus, Malta, Croatia, Latvia, Slovenia, and Slovakia.

Cluster 2: Average GDP and RMC. This cluster includes countries with medium GDP and medium RMC. The countries included are the Czech Republic, Denmark, Greece, Romania, Finland, Hungary, Poland, and Portugal.

Cluster 3: High GDP and low RMC. This cluster includes countries with high GDP but relatively low RMC. The countries included are Germany, Ireland, France, Italy, Luxembourg, and the Netherlands.

Cluster 4: High GDP and RMC. This cluster includes countries with high GDP and RMC, including Sweden, Austria, Spain, and Belgium.

The results of the cluster analysis highlight regional economic differences within the EU. Western and northern European countries typically belong to clusters with higher GDP and RMC efficiency. In contrast, Eastern and Southern European countries have lower economic performance and efficiency (see **Table 7**). This regional distribution highlights that economic development and RMC efficiency are not evenly distributed within the EU and that different regions use different financial strategies.

Table 7. Clusters of EU member states based on GDP and RMC.

Clusters	Cluster characteristic	Member countries classified in a cluster
First cluster	Low GDP and RMC	Bulgaria, Estonia, Latvia, Cyprus, Malta, Croatia, Latvia, Slovenia and Slovakia.
Second cluster	Average GDP and RMC	Czech Republic, Denmark, Greece, Romania, Finland, Hungary, Poland, Portugal.
Third cluster	High GDP and Low RMC	Germany, Ireland, France, Italy, Luxembourg, Netherlands.
Fourth cluster	High GDP and RMC	Sweden, Austria, Spain, Belgium

Source: Own table.

4.3. Results of the correlation calculation

The correlation value between the GDP and RMC of the 27 EU member states was calculated for 2014–2023. (Pearson correlation values are included in **Table 7**). I classified the member countries into clusters based on their correlation values. I classified the countries with published correlation values of 0.5 and 1.0 into the first cluster. The Czech Republic, Estonia, Luxembourg, Malta, and Portugal are these countries. It was placed in the second cluster with a correlation value between 0.0 and 0.5: Belgium, Bulgaria, Croatia, Cyprus, Latvia, the Netherlands, Poland, Slovenia and Sweden. The third cluster included the member countries whose correlation values of 0.0 and −0.5 were published: Denmark, Ireland, France, Lithuania, Hungary, Austria, Romania, and Finland. The fourth cluster included those with published correlation values of −0.5 and −1.0. These countries are Germany, Greece, Spain, Italy and Slovakia.

In the case of the countries in the first cluster, a strong positive correlation can be observed between GDP and RMC. This means that their economic growth is closely related to RMC. These countries rely on industrial or technological sectors where RMC directly impacts economic performance. These countries can use technological innovations and optimize production processes to improve efficiency.

The countries in the second cluster show a moderate positive correlation, indicating some relationship between GDP growth and RMC. However, this relationship is not as strong as in the first cluster. These countries have a more diversified economy, where the service sector and other less raw material-intensive industries also play a significant role in GDP production. Their strategic focus is to maintain economic growth, and they can concentrate on developing services, technological developments, and sustainable resource management.

The countries of the third cluster show a weak negative correlation, which suggests that the increase in RMC does not necessarily go hand in hand with the rise in GDP, and in some cases, a decrease even occurs. These countries have made significant efforts toward sustainability and economic restructuring where economic growth is less dependent on RMCs. An emphasis on sustainable development and green technologies can help these countries increase their economic performance further while minimizing their environmental impact.

The countries in the fourth cluster show a strong negative correlation, which suggests an inverse relationship between GDP growth and RMC. These countries are competitive economies where economic growth is not based on directly using raw materials but is driven by services, technology, and innovation.

A negative correlation indicates that these countries have become more efficient using raw materials and can feed economic growth from other, less raw material-intensive sources.

A distribution test was performed on the correlation coefficients, which confirmed that the (r) values were typically distributed, as shown in **Figure 2**.

The macroeconomic meaning of **Figure 3** is that in most EU member states, the correlations are concentrated around the median value. In contrast, only a few member states show extraordinarily high or low correlations. This allows the conclusions to be generalized and a more reliable analysis of economic trends within the EU.

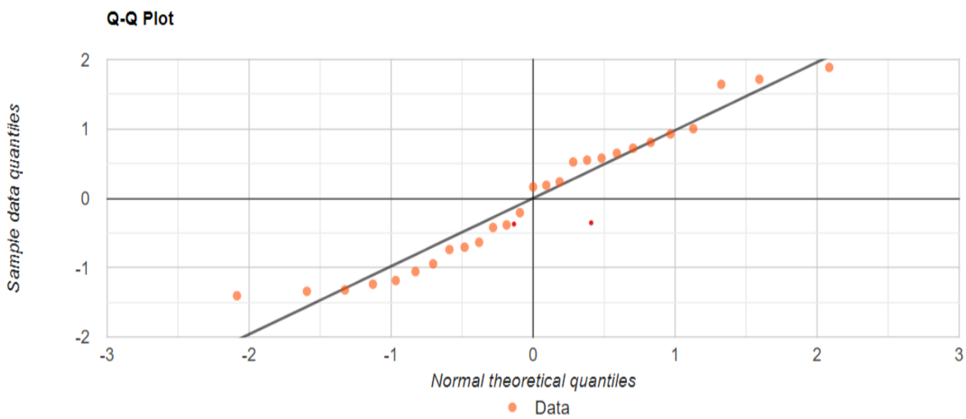

Figure 3. Average distribution test results of the correlation between EU GDP and RMC.

Source: Own figure.

Figure 4 shows the number of EU member states included in clusters 1, 2, 3, and 4 based on strong positive, weak positive, weak negative, and strong negative correlations.

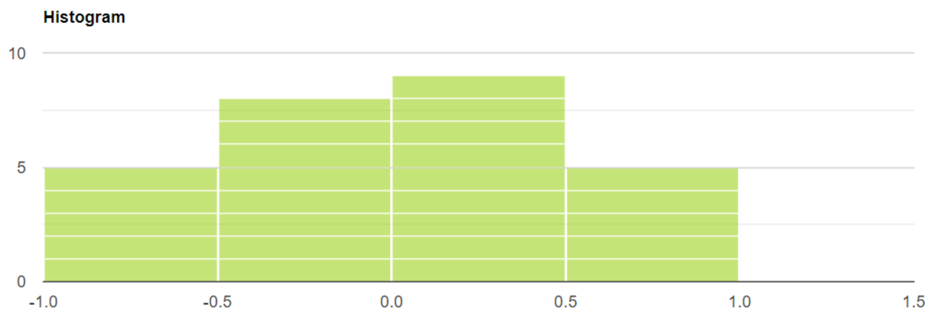

Figure 4. Histogram of clusters formed based on correlation values between GDP and RMCs.

Source: own figure.

The connection between **Table 6** and **Figure 4** is that the table and the following text verbally present the EU member states classified in the same cluster, naming the countries by name. On the other hand, **Figure 4** shows the EU member states classified into each cluster based on the Pearson correlation values calculated with Excel. The same countries are classified in the **Table 6** and **Figure 4** clusters.

Based on examining the correlation coefficients of the member countries classified into clusters, some conclusions can be drawn about the robustness of the model. The broad correlation spectrum between the clusters (from a positive correlation between 0.5 and 1.0 to a negative correlation between −0.5 and −1.0) shows that the differences between individual EU member states are significant, and the relationship between GDP and RMC differs across the countries. 2/The countries in the first cluster, with a strong positive correlation (0.5–1.0), indicate a stable relationship between GDP and raw material consumption, which supports the robustness and reliability of the model for these countries. 3/The third and fourth clusters, which show a negative correlation, suggest that in certain countries, the increase in GDP is associated with a decrease in the consumption of raw materials, which confirms the phenomenon of separation. The different relationships between the variables also confirm the robustness here. 4/Overall, the results from the cluster analysis show that the model is sensitive to the other relationships occurring in different member states, which reflects the model's robustness and versatility in examining EU member states.

4.4. Divergence index calculation results

The data in the second column of **Table 8** show the values of the divergence indicator. During the divergence calculation, the degree of deviation from the GDP and RMC data of the EU member states was determined and compared with the average values of the given member state. Higher divergence index values indicate more significant differences. The divergence indicator shows how stable the economic and RMC indicators of the member countries are during the examined period.

Table 8. Divergence: Deviations of GDP and RMC from the average and their (r) values.

Country	Divergence indicator values	Pearson correlation values
BE	152.94	0.4044
BG	35.11	0.3042
CZ	96.94	0.5457
DK	79.94	−0.1715
DE	1071.12	−0.6354
EE	12.52	0.5076
IE	29.51	−0.3147
EL	3.91	−0.6254
ES	375.35	−0.5568
FR	787.27	−0.4917
HR	28.62	0.1229
IT	601.94	−0.5835

Table 8. (*Continued*).

Country	Divergence indicator values	Pearson correlation values
CY	7.15	0.4467
LV	13.46	0.3322
LT	10.31	−0.0643
LU	6.83	0.9050
HU	74.52	−0.2794
MT	9.52	0.9912
NL	318.75	0.3675
AT	125.52	−0.4354
PL	151.84	0.3177
PT	75.12	0.8682
RO	71.93	−0.3319
SI	23.65	0.1349
SK	30.99	−0.6675
FI	71.26	−0.1530
SE	121.55	0.1592

Source: Own table.

Germany shows the highest divergence index (1071.12), which means that Germany achieves the highest economic performance with each raw material unit. It is followed by France and Italy, which have significant economic performance in proportion to the raw materials used. Luxembourg and Cyprus are located in the lower regions, where economic performance is lower per unit of raw material. The Netherlands, Belgium, and Austria are in the middle, with RMC's stable financial performance. Central and Eastern European countries, such as Poland, the Czech Republic, and Hungary, also perform well in terms of RMC but have lower values than Western European countries.

The results show that while some countries use raw materials extremely efficiently for economic growth (Germany, France, and Italy), others do so only with low efficiency (Bulgaria, Slovakia, Croatia).

For a deeper analysis of the efficiency of raw material use, some methodologies can consider the raw material use of the sectors of a country, especially if the raw material demand of the sectors shows significant differences. Below, I present some of these methodologies, which can be used to analyze the efficiency of raw material use in a national economy at the sectoral level. Such a methodology is SMFA (sectoral material flow analysis). Material flow analysis (SMFA) allows one to examine the raw materials used by individual industries and sectors in a sectoral breakdown. This method makes it possible to measure which sectors use the most raw and resource-efficient raw materials. Another methodology is SI-OA (Sectoral Input-Output Analysis). Input-output analysis is an analysis method that examines how individual sectors use raw materials (inputs) in their production processes. This analysis is instrumental in understanding how much raw materials each industry uses to produce GDP. The methodology aims to assess the extent to which a specific sector depends on raw materials and the cross-links between the sectors regarding raw material consumption. By applying the methodology, it can be seen at the sectoral level which industries are the most significant users of raw materials and which are the largest output emitters. For reasons of scope, this study does not use these methodologies.

5. Discussion

According to one of the robust results of the study, between 2014 and 2023, the relative separation of material consumption from GDP significantly strengthened in the EU, a phenomenon the researchers refer to as 'decoupling' in the literature (see the data in **Tables 1** and **2**). This occurs when the GDP increases while the RMC or environmental load decreases. Farm performance improves in this ideal state without additional raw material use or ecological damage. Decoupling is relevant to global sustainable development, enabling economic growth without depleting natural resources or exacerbating environmental problems.

The decoupling theory has been verified by several studies in connection with GDP and several other economic variables. A paper in Zhejiang Province from 2002–2017 tested the theory. According to the results of the study, the decoupling of economic growth and carbon dioxide emissions increased continuously in all stages, first in the form of "expansive coupling and expansive negative decoupling," then in the form of "weak decoupling," and finally in the form of "strong decoupling" (Li et al., 2023). A study quantified the degree of economic growth measured by GDP and independence from environmental degradation through CO_2 and HFC emissions at the level of individual EU-27 countries in 2008–2012 and 2013–2020. The results showed that most EU-27 countries registered a negative level for the considered variables in the first period, thus entering the negative connection stage. In the second period, the development of the separation process was visible in all countries (Cautisanu and Hatmanu, 2023). The following results show no robust, strong correlation between GDP and the energy consumption of EU member states. According to another result, the decrease in those member states where energy consumption dropped significantly did not hurt economic growth (Török, 2023).

The cluster analysis results presented in the study highlighted the regional economic differences within the EU. Several studies have examined the classification of EU member states into clusters. An article reviewed the level of integration of the European Union's energy markets and its changes over time. The authors also proposed a methodology for creating detailed energy and climate strategies for the selected clusters. Clustering revealed that GHG emissions were not highest in countries where the mix was coal-based. The highest emission level was registered in Denmark. The situation was similar for Luxembourg and Ireland (Rybak et al., 2022). The development trend and analysis of variability and linear dependence helped with the cluster analysis and comparison of EU countries. The cluster analysis reveals two groups of countries: the first has a positive result, with the lowest energy taxes and environmental protection tax burdens, and the second has a negative result, with the highest environmental protection and energy policy tax burdens (Taušová et al., 2021). The clustering method was also used in the study that examined the environmental impact of the EU member states. The EU member states were classified into clusters based on the results, and a linear trend model analysis was performed. The results show that the EU's total environmental impact did not decrease significantly between 2012 and 2022. This study demonstrated that GDP growth was the main driver in maintaining the total ecological load (Török, 2024).

Section 3.3 of this article presents the study's results on the relationship between GDP and RMC of the EU member states. The study revealed very high Pearson correlation coefficients for the Czech Republic, Estonia, Luxembourg, Malta, and Portugal.

According to the results of a previous study, energy and raw materials are increasingly important in industrialized countries and impact the economy, sustainability, and future of people. The research used Pearson's correlation and principal component analysis methods to examine the relationship between energy and the circular economy. The results revealed 12 strong correlations, five of which were relevant (Martins et al., 2023). Researchers have investigated the relationship between energy production and GDP in the EU. The main conclusion of this study is that the correlation measured with the Pearson correlation coefficient is not reflected in the data. The change in energy production independent of the energy source does not directly affect GDP; the relationship was only random in the EU economies (Szustak et al., 2022).

The last question examined in this study was how efficiently EU member states apply the raw materials used to produce GDP. The values of the divergence indicator answer this question. The calculated values showed a significant deviation in the EU member states. Germany, France, and Italy are at a high level, whereas other countries apply only raw materials with low efficiency; these member countries are Bulgaria, Slovakia, and Croatia.

In the next part, the study refers to some studies that analyzed the consumption of raw materials in EU member states. One study analyzes import dependence indicators, net stock growth, domestic material use, resource productivity, and circular material use rates in the EU. Future products and technologies are changing in electromobility, digitalization, Industry 4.0, and energy transformation, and the demand for raw materials is increasing. The article formulates proposals to ensure the EU can use critical raw materials as efficiently as possible (Domaracka et al., 2022). The main goal of the following study is to determine the intensity and impact of eco-innovation and material recycling on raw material consumption in European Union member states. The primary hypothesis of this paper is that eco-innovation and recycling significantly affect the EU RMC. The authors believe that in the long term, by promoting eco-innovation and recycling, EU countries will minimize their RMC (Platon et al., 2023). According to the results of the research for the period between 1970 and 2017, economic expansion was accompanied by an increase in material consumption, primarily due to the side effect of the expansion of consumption. In contrast, an economic recession led to the dematerialization of the economy (Kassouri et al., 2021).

6. Conclusions

Several conclusions can be drawn from the results of the analysis carried out in this study. The article examined the GDP and RMC of 27 EU member states between

2014 and 2023. The results highlight the complexity of the interactions between the economy and nature. Resource use efficiency has indeed increased in the EU, which is well reflected by the decreasing RMC trends of the economies. Technological development creates an opportunity to improve the efficiency of using natural resources in production processes to moderate or even reduce environmental impacts. This helps promote sustainability policies in the EU. While the EU's aggregate GDP increased by 44 percent, the RMC decreased by 9 percent, which indicates the separation of the two variables, i.e., the 'decoupling' phenomenon. This result shows that the EU economy can grow without proportionally increasing its RMC. However, according to future prognoses, the global use of resources may triple, which suggests the economy's growing dependence on resources. In this context, the EU faces increasing challenges in sustainable development and resource management. Technological innovations and effective resource management policies will be critical in the future. The EU should continue improving resource efficiency, including increasing renewable energy sources, implementing waste reduction strategies, and developing green technologies. These measures not only reduce environmental impacts but also contribute to ensuring the sustainability of economic growth.

The cluster analysis results highlight the regional economic differences within the European Union. Western and northern European countries typically have higher GDP and RMC efficiency, whereas eastern and southern European countries have lower economic performance and efficiency. This result confirms the existence of regional distribution within the EU based on RMC efficiency.

The very high Pearson correlation coefficients between GDP and RMC for France, Estonia, Croatia, Poland, and Greece indicate a strong correlation between these variables. These results suggest that the production of GDP in these countries strongly depends on RMCs. The results of the divergence indicator further shed the picture, showing that individual member countries use RMCs with different efficiencies for their economic growth. For example, Germany, France, and Italy use raw materials efficiently, whereas Bulgaria, Slovakia, and Croatia have the lowest efficiency. These results underline the importance of optimizing resource use for sustainable economic growth in the EU and globally.

In the following sentences, the study formulates some policy recommendations. The EU should provide financial and technological support to Eastern and Southern European countries, especially those with low material efficiency, such as Bulgaria, Slovakia, and Croatia. This could help them modernize their economies by introducing material-efficient technologies and practices. For example, EU funds could finance research and development programs or industry innovations to increase the efficiency of raw material use. The EU should encourage knowledge transfer between Member States with high RMC efficiency and those with low efficiency. This could include workshops, technological collaborations, or international partnerships. Finally, it could be proposed that the EU set ambitious but achievable targets for improving RMC efficiency for each Member State. The guidelines could consider the current economic and technological situation of each EU Member State, ensuring gradual adaptation. In addition to country-specific targets, implementing a circular economy should be encouraged to reduce raw material dependency and boost sustainable economic growth.

7. Study limitations and future research directions

As with all studies, this study has several limitations. One limitation is that it examines one economic region: the 27 member states of the EU. The analysis could be extended to OECD countries, BRICS countries, etc. Another limitation is that resource efficiency could also be examined with other macroeconomic variables. Such variables could include, for example, the rule of law index, government efficiency, regulatory quality index, etc. In an investigation to demonstrate differences in the productivity of raw material use, sector-level data of the EU member states would be needed, such as the raw material use of industry, agriculture, and services, as well as the ratio of their contribution to GDP. In addition, member countries' innovation and technological development, workforce productivity, and added value in individual sectors should also be considered. In this study, it is impossible to formulate specific proposals for the EU because the individual member states' economic structure, technological development, and raw material consumption patterns differ significantly. Increasing the efficiency level of raw material use requires individual measures considering the EU member state's financial conditions, industrial structure, and environmental objectives. The tasks formulated in the previous sentences would require independent research, which is impossible in this study (primarily due to scope reasons). However, answering these questions would be an exciting research task.

Based on the results of this study, future research can focus on how to increase the effectiveness of RMC in Eastern and Southern European countries, such as Bulgaria, Slovakia, and Croatia, where the lowest effectiveness was shown. In the case of countries with a high correlation between RMCs and GDP, such as France, Estonia, Croatia, Poland, and Greece, the correlation between material consumption and economic growth deserves special attention. Further research is needed to analyze and adapt the material efficiency models of the Western and Northern European countries of the EU (such as Germany, France, and Italy). Based on the phenomenon of "decoupling," it would be relevant to study how GDP growth could be achieved with even less material consumption throughout the EU.

The results of the present study may influence the debates in the EU's environmental economics, especially regarding territorial inequalities in the efficiency of raw material use. The cluster analysis highlighted the high RMC efficiency of Western and Northern European countries (such as Germany and France). In contrast, Eastern and Southern countries show lower efficiency, which urges introducing region-specific measures. The strong correlation between GDP and RMCs in Estonia and Croatia suggests that the economic growth of these countries is closely related to raw material consumption, which may lead to fundamental questions regarding the sustainability of material consumption. These findings can help inform the EU's policy guidelines for sustainable development, particularly in encouraging material efficiency and economic growth decoupling.

Acknowledgments: This research was supported by the "University of Debrecen Program for Scientific Publication".

Conflict of interest: The author declares no conflict of interest.

References

Almodóvar-González, M. Fernández-Portillo, A. & Díaz-Casero, J.C. (2020). Entrepreneurial activity and economic growth. A multi-country analysis, European Research on Management and Business Economics, Vol. 26. Núm. 1., DOI: 10.1016/j.iedeen.2019.12.004

Ashby, F. Michael (2012). Materials for low-carbon power. Materials and the Environment, (Second Edition), 349–413. https://doi.org/10.1016/B978-0-12-385971-6.00012-9

Bánhidi, Z.& Dobos, I. (2023). Measurement of digital development with partial orders, Tiered DEA, and cluster analysis for the European Union, Int. Rev. Appl. Sci. Eng, Volume 14: Issue 3, https://doi.org/10.1556/1848.2023.00612

Bányai, O. (2013). The European Union regulation concerning the energy consumption of buildings — an ecological point of view, Int. Rev. Appl. Sci. Eng, Volume 4: Issue 2, https://doi.org/10.1556/irase.4.2013.2.3

Bithas, K. & Kalimeris, P. (2018). Unmasking decoupling: Redefining the Resource Intensity of the Economy, Science of The Total Environment, Volumes 619–620, Pages 338-351., https://doi.org/10.1016/j.scitotenv.2017.11.061

Bolboacâ, S.D. & Jäntschi, L. (2006). Pearson versus Spearman, Kendall's Tau Correlation Analysis on

Bringezu, S. (2015). Possible Target Corridor for Sustainable Use of Global Material Resources. Resources, 4, 25–54., https://doi.org/10.3390/resources4010025

Cautisanu, C. & Hatmanu, M. (2023). A Study of the Decoupling of Economic Growth from CO2 and HFCs Emissions in the EU27 Countries. Energies 2023, 5546. https://doi.org/10.3390/en16145546

Chen, L., Yang X., Li L. et al. (2021). The Natural and Socioeconomic Influences on Land-Use Intensity: Evidence from China. Land, 10, 1254. https://doi.org/10.3390/land10111254

Destek, M.A., Ulucak, R. & Dogan, E. (2018). Analyzing the environmental Kuznets curve for the EU countries: the role of ecological footprint. Environ Sci Pollut Res 25, 29387–29396. https://doi.org/10.1007/s11356-018-2911-4

Dogan, E. & Shah S. F. (2022). Analyzing the Role of Renewable Energy and Energy Intensity in the Ecological Footprint of the United Arab Emirates. Sustainability, 14, 227. https://doi.org/10.3390/su14010227

Domaracka, L., Matuskova S. Tausova, M., et al. (2022). Efficient Use of Critical Raw Materials for Optimal Resource Management in EU Countries. Sustainability, 14, 6554. https://doi.org/10.3390/su14116554

Du, J., Zhang J. & Li X. (2020). What Is the Mechanism of Resource Dependence and High-Quality Economic Development? An Empirical Test from China. Sustainability, 12, 8144. https://doi.org/10.3390/su12198144

Dziechciarz, M. (2024). Panel Data Analysis of Subjective Well-Being in European Countries in the Years 2013–2022. Sustainability, 16, 2124. https://doi.org/10.3390/su16052124

Eurostat (2024a). GDP and main components (output, expenditure and income), Current prices, million euro, (2014-2023), Available online: https://ec.europa.eu/eurostat/databrowser/view/nama_10_gdp/default/table?lang=en (accessed 15 Sept 2024)

Eurostat (2024b). Material flow accounts, Available online: https://ec.europa.eu/eurostat/databrowser/view/env_ac_mfa/default/table?lang=%3Cfont%20style%3D%22vertical-align:%20inherit;%22%3E%3Cfont%20style%3D%22vertical-align:%20inherit;%22%3Ehu%3C%2Ffont%3E%3C%2Ffont%3E, (accessed 15 Sept 2024).

Forchini, G. & Peng, B. (2012). A Conditional Approach to Panel Data Models with Common Shocks. Econometrics, 4, 4. https://doi.org/10.3390/econometrics4010004

Ghita, S. I., Saseanu, A. S., Gogonea, R. -M., & Huidumac-Petrescu, C. -E. (2018). Perspectives of Ecological Footprint in European Context under the Impact of Information Society and Sustainable Development. Sustainability, 10(9), 3224. https://doi.org/10.3390/su10093224

Glawe, L. & Wagner, H. (2021). Divergence Tendencies in the European Integration Process: A Danger for the Sustainability of the E(M)U? J. Risk Financial Manag., 14, 104. https://doi.org/10.3390/jrfm14030104

Golam, K. (2023). Ecological footprint in Bangladesh: Identifying the intensity of economic complexity and natural resources, Heliyon, Volume 9, Issue 4, E14747, https://doi.org/10.1016/j.heliyon.2023.e14747

Haberl, H., Wiedenhofer, D., Virág, D. et al. (2020). A systematic review of the evidence on decoupling of GDP, resource use, and GHG emissions, part II: Synthesizing the insights. Environ. Res. Lett., 15, 065003., DOI 10.1088/1748-9326/ab842a

Herman, E., Zsido K-E. & Fenyves, V. (2022). Cluster Analysis with K-Mean versus K-Medoid in Financial Performance, Evaluation. Appl. Sci., 12, 7985. https://doi.org/10.3390/app12167985

Huong, T-T., Dong, L. & Shah, I-H. (2021). Exploring the Sustainability of Resource Flow and Productivity Transition in Vietnam from 1978 to 2017: MFA and DEA-Based Malmquist Productivity Index Approach. Sustainability, 13, 11761. https://doi.org/10.3390/su132111761

Ikerd, J. (2024). Business Management for Sustainability. Sustainability, 16(9), 3714. https://doi.org/10.3390/su16093714

Kalantaripor, M. & Najafi A-H. (2020). Spatial Effects of Energy Consumption and Green GDP in Regional Agreements. Sustainability, 13(18), 10078. https://doi.org/10.3390/su131810078

Kassouri, Y., Alola, A-A. & Savaş S. (2021). The dynamics of material consumption in phases of the economic cycle for selected emerging countries. Resources Policy, 70, 101918. https://doi.org/10.1016/j.resourpol.2020.101918

Kazemzadeh, E., Fuinhas J-A, Shirazi, M. et al., (2023). Does economic complexity increase energy intensity? Energy Efficiency, 16, 29, https://doi.org/10.1007/s12053-023-10104-w

Kinnaman, T-C. (2023). A New Perspective on the Natural Resource Curse. World, 4, 670–683. https://doi.org/10.3390/world4040042

Koskela, S., Mattila, T., Antikainen, R. & Mäenpää, I. (2013). Identifying Key Sectors and Measures for a Transition toward a Low Resource Economy. Resources, 2, 151-166. https://doi.org/10.3390/resources2030151

Kuemmerle, T., Erb, K., Meyfroidt, P. et al., (2013). Challenges and opportunities in mapping land use intensity globally. Current Opinion in Environmental Sustainability, 5(5), 484-493. https://doi.org/10.1016/j.cosust.2013.06.002

Kuziboev, B., Saidmamatov, O., Khodjaniyazov, E. et al. (2024) .CO2 Emissions, Remittances, Energy Intensity and Economic Development: The Evidence from Central Asia. Economies, 12, 95. https://doi.org/10.3390/economies12040095

Li, Z., Lu Z., Xu L. et al. (2023). Examining the Decoupling of Economic Growth with Land Expansion and Carbon Emissions in Zhejiang Province, China. Land, 12, 1618. https://doi.org/10.3390/land12081618

Liang, S., Song, Y., Li X. et al. (2023). The Impact of Resource Endowment on Provincial Green Development: An Empirical Analysis from China. Energies, 16, 4661. https://doi.org/10.3390/en16124661

Mahmood, A., Farooq, A., Akbar, H. et al. (2023). An Integrated Approach to Analyze the Progress of Developing Economies in Asia toward the Sustainable Development Goals. Sustainability, 15, 13645. https://doi.org/10.3390/su151813645

Mahmood, H. (2023). The Determinants of Carbon Intensities of Different Sources of Carbon Emissions in Saudi Arabia: The Asymmetric Role of Natural Resource Rent. Economies, 11, 276. https://doi.org/10.3390/economies11110276

Malatesta, T. & Breadsell, J. K. (2022). Identifying Home System of Practices for Energy Use with K-Means Clustering Techniques. Sustainability, 14, 9017. https://doi.org/10.3390/su14159017

Martins, F. F., Castro, H., Smitková, M. et al. (2024). Energy and Circular Economy: Nexus beyond Concepts. Sustainability, 16, 1728., https://doi.org/10.3390/su16051728

Min, X., Wang Y. & Chen, J. (2022). Resource Carrying Capacity Evaluation Based on Fuzzy Evaluation: Validation Using Karst Landscape Region in Southwest China. Sustainability, 14, 16548. https://doi.org/10.3390/su142416548

Mostert, C. & Bringezu, S. (2019). Measuring Product Material Footprint as New Life Cycle Impact Assessment Method: Indicators and Abiotic Characterization Factors. Resources, 8, 61. https://doi.org/10.3390/resources8020061

Pepłowska, M. & Olczak, P. (2024). Review of Research on the Impact of Changes Resulting from the Hard Coal Mining Sector in Poland on the GDP Value. Energies 17, 1477. https://doi.org/10.3390/en17061477

Platon, V., Pavelescu, F. Surugiu, M. et al. (2023). Influence of Eco-Innovation and Recycling on Raw Material Consumption; Econometric Approach in the Case of the European Union. Sustainability, 15, 3996. https://doi.org/10.3390/su15053996,

Rybak, A., Rybak A., Joostberens, J. & Kolev, S. D. (2022). Cluster Analysis of the EU-27 Countries in Light of the Guiding Principles of the European Green Deal, with Particular Emphasis on Poland. Energies, 15, 5082. https://doi.org/10.3390/en15145082

Salas-Velasco, M. (2023). Panel Data Models for School Evaluation: The Case of High Schools' Results in University Entrance Examinations. Stats, 6, 312-321. https://doi.org/10.3390/stats6010019

Stoenoiu, C. E., & Jäntschi, L. (2024). Connecting the Computer Skills with General Performance of Companies—An Eastern European Study. Sustainability, 16(22), 10024. https://doi.org/10.3390/su162210024

Structure-Activity Relationships of Biologic Active Compounds, Leonardo Journal of Sciences, Available online: http://ljs.academicdirect.org/A09/179_200.pdf, (accessed 26 November 2024)

Suad, A., Maalee, A., Ghassan, A. et al. (2024). Statistical Inference of Normal Distribution Based on Several Divergence Measures: A Comparative Study. Symmetry, 16, 212. https://doi.org/10.3390/sym16020212

Szustak, G., Dąbrowski, P., Gradoń, W. & Szewczyk, Ł. (2022). The Relationship between Energy Production and GDP: Evidence from Selected European Economies. Energies, 15, 50. https://doi.org/10.3390/en15010050

Taguchi, H. & Ganbayar, J. (2022). Natural Resource Funds: Their Objectives and Effectiveness. Sustainability, 14, 10986. https://doi.org/10.3390/su141710986

Taušová, M., Čulková, K., Tauš, P. (2021). Evaluation of the Effective Material Use from the View of EU Environmental Policy Goals. Energies, 14, 4759. https://doi.org/10.3390/en14164759

Török, L. (2022). The importance of digitalization and robotization in vehicle production in the European Union, Int. Rev. Appl. Sci. Eng., Volume 14: Issue 1, https://doi.org/10.1556/1848.2022.00481

Török, L. (2023). Ambivalent changes in the correlation of energy consumption and economic growth in the member states of the European Union (2010–2019), Heliyon, Volume 9, Issue 3, E14550, https://doi.org/10.3390/en16145546

Török, L. (2024). The Trend in Environmental Load in the European Union during the Period of 2012–2022. Energies, 17, 3473. https://doi.org/10.3390/en17143473

UNEP. (2013). Recent Trends in Material Flows and Resources Productivity in Asia and the Pacific DEW/1579/BA United Nations Environment Programme Regional Office for Asia and the Pacific: Bangkok, Thailand. Available online: https://www.unep.org/resources/report/recent-trends-material-flows-and-resource-productivity-asia-and-pacific. (accessed 1 Nov 2024).

Wackernagel, M., Monfreda, C., Schulz, N. B. et al., (2004). Calculating national and global ecological footprint time series: resolving conceptual challenges, Land Use Policy, Volume 21, Issue 3, Pages 271-278, https://doi.org/10.1016/j.landusepol.2003.10.006

Wandebori, H. & Murtyastanto. (2023). The Implication of Steel-Intensity-of-Use on Economic Development. Sustainability, 15, 12297. https://doi.org/10.3390/su151612297

Wang, Y., Qamruzzaman, Md. & Kor, S. (2022). Greening the Future: Harnessing ICT, Innovation, Eco-Taxes, and Clean Energy for Sustainable Ecology—Insights from Dynamic Seemingly Unrelated Regression, Continuously Updated Fully Modified, and Continuously Updated Bias-Corrected Models. Sustainability, 15(23), 16417. https://doi.org/10.3390/su152316417

Wiedenhofer, D., Virág, D., Kalt, G. et al., (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: Bibliometric and conceptual mapping. Environ. Res. Lett., 15, DOI 10.1088/1748-9326/ab8429

Xu, Y., Xu X., & Tang, Q. (2016). Human activity intensity of land surface: Concept, methods and application in China. J. Geogr. Sci., 26, 1349–1361. https://doi.org/10.1007/s11442-016-1331-y

Yoder Clark, A., Blumenfeld, N., Lal, E. et al., (2021). Using K-Means Cluster Analysis and Decision Trees to Highlight Significant Factors Leading to Homelessness. Mathematics, 9, 2045. https://doi.org/10.3390/math9172045

Zhang, X., Shi, X., Khan, Y., et al. (2023). The Impact of Energy Intensity, Energy Productivity and Natural Resource Rents on Carbon Emissions in Morocco. Sustainability, 15, 6720. https://doi.org/10.3390/su15086720

Zhang, Z., Xue, B., Pang, J. & Chen, X. (2016). The Decoupling of Resource Consumption and Environmental Impact from Economic Growth in China: Spatial Pattern and Temporal Trend. Sustainability, 8, 222. https://doi.org/10.3390/su8030222

Ziolo, M., Jednak, S., Savić, G.& Kragulj, D. (2020). Link between Energy Efficiency and Sustainable Economic and Financial Development in OECD Countries. Energies, 13, 5898. https://doi.org/10.3390/en13225898

Zschieschang, E., Denz, N., Lambrecht, H. &Viere, T. (2013). Resource Efficiency-oriented Optimization of Material Flow Networks in Chemical Process Engineering. Procedia CIRP, 2013, 15, 373-378. https://doi.org/10.1016/j.procir.2014.06.066

Appendix

The European Union (EU) consists of 27 countries: Sweden (SE), Spain (ES), Slovenia (SI), Slovakia (SK), Romania (RO), Portugal (PT), Poland (PL), the Netherlands (NL), Malta (MT), Luxemburg (LU), Lithuania (LT), Latvia (LV), Italy (IT), Ireland (IE), Hungary (HU), Greece (EL), Germany (DE), France (FR), Finland (FI), Estonia (EE), Denmark (DK), the Czech Republic (CZ), Cyprus (CY), Croatia (HR), Bulgaria (BG), Belgium (BE), and Austria (AU).