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Measuring Sustainability in Economic Output in the Member States that Joined the European Union in 2004

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ABSTRACT

The 2004 enlargement of the European Union (EU) marked a significant shift, integrating ten new member states, most of which had experienced economic lag due to their historical background. This study assesses the progress of these countries in closing the gap with older EU members from 2011 to 2021, focusing on resource productivity as a key indicator of sustainable economic growth. Using panel regression and structural equation modeling, the analysis highlights persistent differences between the EU-27 and EU-10. Findings suggest that in EU-27 countries, resource productivity is driven primarily by circular economy measures, waste recycling, and renewable energy utilization. In contrast, EU-10 countries, still undergoing economic transformation, rely more on innovation, human capital development, and research and development (R&D) investments to enhance efficiency. Notably, while renewable energy positively impacts resource productivity in EU-27, it shows a paradoxical negative effect in EU-10, likely due to transitional inefficiencies. Fixed effects models confirm that institutional, political, and infrastructural differences shape resource productivity. The results underscore that while the EU-10 has significantly improved, gaps remain in areas such as higher education investment and circular material use. Importantly, research and development emerge as critical drivers of efficiency, especially in EU-10. The study concludes that while economic modernization fosters convergence, sustainability strategies must be tailored to regional contexts. Strengthening innovation systems and optimizing material efficiency are essential for long-term resource productivity gains.

1. Introduction

Sustainability has become a central issue in economic policymaking, particularly within the European Union (EU), where balancing economic growth with resource efficiency remains a significant challenge. The concept of sustainable development gained prominence with the Brundtland Report [15], emphasizing the need for policies that ensure long-term economic stability without compromising environmental integrity. In the EU, resource productivity—measured as the ratio of Gross Domestic Product (GDP) to Domestic Material Consumption (DMC)—has emerged as a key indicator of sustainability, reflecting a country's ability to decouple economic growth from resource use.

This study examines how sustainable economic growth can align with an environmentally conscious "green" approach. It explores options and methods to address this issue and identifies economic indicators that show progress. The study links growth factors (investments, material consumption, resource productivity, human capital, knowledge capital, research, and development) to sustainability efforts. Economic growth is typically measured by real GDP. While growth increases emissions and consumption, it also incurs environmental costs such as non-renewable resource use, pollution, global warming, and habitat damage [2]. However, increased real income allows for more environmental protection, and technological advancements can reduce pollution.

The interplay between environmental issues and economic development is central to the economics of sustainability. Various models describe that interplay. The classical production possibilities frontier

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(PPF) graphically represents that non-renewable resources are depleting in increasing measure as consumption is expanded [3]. The external costs of growth involve environmental degradation that is bad for future generations [14]. The environmental Kuznets hypothesis assumes that growth's adverse impacts will decline once a level of development is reached [48], though that hypothesis has faced skepticism [4]. Other more recent models propose that excessive environmental pollution will eventually hinder economic development. Ecologists argue that economic growth always puts a squeeze on the environment, whereas economists argue that can be alleviated with measures such as making alternative energy cheaper or implementing a carbon levy.

The 2004 enlargement of the EU was a pivotal moment, incorporating ten new member states (EU-10) that historically faced economic and structural challenges due to their socialist past. These countries - Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Slovakia, Slovenia, Cyprus, and Malta - entered the EU with the expectation that integration would accelerate economic modernization and convergence with older member states (EU-15). However, nearly two decades later, significant disparities persist, particularly in resource efficiency, technological adoption, and sustainability practices.

This research aims at analyzing the progress made by the EU-10 member states in closing the gap with the EU-27 in terms of resource productivity between 2011 and 2021. Using panel regression methods combined with Structural Equation Modeling (SEM), the study explains critical drivers that affect resource productivity, including innovation, human resources, renewable energy, and a circular economy. The innovation in this study lies in its empirical investigation between two distinct clusters in the EU, which highlights different trajectories on which resource productivity is achieved.

By examining structural differences, this research sheds light on the success of sustainability measures in the European Union as well as on measures that can enhance resources' utilization in transitional economies. The research contributes towards growing convergence economics as well as sustainability literature, which highlights the importance of tailored policy measures in promoting environmental sustainability as well as economy stability.

2. Theoretical background

2.1. Sustainability and its importance

An attitude survey in the 2020 Social Report by TÁRKI examined if Hungarians are willing to make financial sacrifices for sustainability through higher taxes, buying more expensive sustainable products, or reducing their standard of living. Comparing results to a 1993 survey, researchers found no increase in willingness to make such sacrifices over the past 30 years; in some cases, it has decreased. Despite over 50 % of respondents expressing concern for sustainability and the increasing commonality of environmental topics, environmental protection political activity in Hungary has not significantly changed in 30 years [39].

Relevant literature is categorized into global studies, starting with the 1987 Brundtland report which clarified conceptual foundations, and studies focusing on EU member states' sustainability goals post-2004 enlargement. This literature helps decide which data to include for answering research questions.

Meadows et al. [30] highlighted that infinite growth is impossible on a finite planet, predicting about a century of growth, half of which has passed. Economic growth has drawbacks like inflation due to rising wages, worsening balance of payments from increased consumption, and environmental degradation from non-renewable resource depletion. The relationship between GDP growth and environmental impact has been documented [20,43].

Sustainability is not new; traditional societies practiced it by only owning necessary goods made from natural materials, maintaining environmental balance. Modern society, however, is marked by consumerism and excessive use of disposable items. Although we attempt to live environmentally consciously today, true sustainability involves considering economic, environmental, and social aspects, which are often neglected in the current market system [31].

There are two directions for the implementation of environmental awareness:

[1] more efficient use of resources (an example is the energy-saving light bulb)
[2] reducing emissions (this is the purpose of the electric car)

Both strategies aim to boost production and consumption and establish a foundation for this. However, increased energy efficiency and lower emissions have led to greater consumption, which is unsustainable. This issue was highlighted by the Club of Rome fifty years ago [30], noting that by the early 1970s, humanity had reached Earth's carrying capacity. We now consume almost double the resources Earth can sustainably provide each year. The Ecological Footprint [46] illustrates this imbalance, with Earth Overshoot Day arriving earlier annually. Currently, 2 hectares of land per person are needed to meet global needs, but only 1.8 hectares/person are available.

Earth's carrying capacity is limited and difficult to measure precisely, especially as we share the planet with other species. Modern societal well-being does not equate to true well-being, as psychological disorders rise with material wealth. The current trajectory is unsustainable, particularly as wealthy economies exploit resources while millions live in poverty.

Global population growth and continuous economic expansion increase the demand for food, water, energy, and materials. Resource scarcity has prompted specific measures and political programs [36]. Major threats include physical depletion, rising extraction costs, and geopolitical issues due to unequal resource distribution or shared resources [36]. Understanding these reasons and effects requires a brief review of related historical contexts.

2.2. Material and energy consumption

Today we live in the age of Industry 4.0, marked by advanced technology, increased demand for rare earth metals, and rising energy consumption. Historical technical revolutions have always involved changes in energy use. Humans began using fire 400,000 years ago, animal power and irrigation 7000 years ago, coal in the late 18th century, and electricity and fossil fuels in the late 19th century. These transitions are incremental, adding new energy sources alongside old ones. Since the industrial revolution, our dependence on energy has grown due to high mechanization in agriculture and the food industry. Human or animal power is no longer sufficient. Today, civilization relies on energy more than ever, facing the dual challenges of reducing environmental impact and securing energy amidst conflicting interests. Additionally, since February 2022, increased defence spending has complicated matters, with military costs not necessarily aligning with energy efficiency. Király & Végvári [[26] p. 71] discussed this in detail:

> "…unfortunately, in the majority of cases…due to the apparent savings of pennies, the Hungarian Defence Forces acquires *technologies that are already decades out of date at the moment of planning."*

Improving energy efficiency is crucial for the defence economy, a concept that gained attention during the 1973 oil crisis. Efficient energy use is now integral to defence strategies, focusing on reducing facility energy consumption rather than weaponry. For example, the Hungarian Defence Forces, supported by the EU's Cohesion Fund and the Hungarian State, installed renewable energy systems, like solar collectors, at various sites. Enhancing operational energy efficiency also reduces the need for resupply, crucial for military operations. Hungary's energy efficiency strategy and the Hungarian Energy Efficiency Institute (MEHI) highlight this focus. International efforts include the ODYSSEE database and the TIAM model developed by French *IFP Energies nouvelles*

(IFPEN) to assess global energy system dynamics and resource use over 100 years. The TIAM model predicts significant material consumption by low-carbon technologies, necessitating sustainable mobility, energy prudence, and recycling solutions. The model also identifies criticality in metals like lithium and cobalt, essential for energy transitions but unevenly distributed globally. Resource use is expected to rise in developing countries, with industrialized nations having the greatest efficiency opportunities. The geopolitical implications of resource scarcity are significant, with Asia driving the energy transition, notably China, South Korea, and Taiwan.

Broader considerations reveal how resource security underpins seemingly unrelated events. The 2019 Bolivian coup, linked to lithium reserves crucial for green technologies, illustrates this. Tesla's Elon Musk hinted at supporting the coup to secure lithium, underscoring how resource scarcity influences economic and military actions. This scarcity can drive inflation, as noted by Isabel Schnabel, particularly in the context of the green transition.:

1) climate inflation – crop loss due to climate change (natural disasters, droughts, floods, heat waves), damage events, declining tourism, etc. resulting price increases; these will play an increasingly important role in making investment decisions [8],
2) fossil inflation – inflation due to the decreasing amount of fossil energy carriers, their more expensive extraction and the increasing environmental burden; which is further enhanced by the decreasing funding of projects based on such energy carriers, as well as the carbon tax,
3) green inflation – generated by a significant increase in the need for rare and irreplaceable materials essential in the green transition.

The issues are exacerbated by the impossibility of achieving the same productivity growth as a hundred years ago. Productivity growth slowed with the onset of the 2008 economic crisis. The recovery did not bring an increase in productivity, a paradox known as the productivity puzzle [32]. Stagnant productivity is problematic because economic growth relies on population, investment, and productivity. Although other sources are mentioned [1,11,16,35], these three are sufficient for this analysis. Global population growth does not equate to a proportional increase in skilled labor, prompting a rethink of the workforce-based productivity view [9]. Investments stem from savings, but their realization is influenced by more than just economic factors. Productivity, linked to economic growth, follows relation (1) in research [42,45].

$$\text{economic growth}\,(\%) = \text{research productivity}\,(\%) * \text{number of researchers} \tag{1}$$

Scientific productivity has declined significantly [10]. Comparing the growth of the USA's productivity (Total Factor Productivity - TFP) with the number of researchers required for a unit increase, it has been observed that over nearly a century, the number of researchers needed has increased twentyfold. This trend is evident in sectors like agriculture and the pharmaceutical industry. Countries prioritizing population, savings, and productivity could become future economic superpowers.

The Russian-Ukrainian conflict illustrates the impact of resource scarcity. Ukraine possesses coal, gas, oil, wheat, and crucial rare earth metals like lithium, essential for new energy technologies. About a third of Europe's lithium deposits are in Ukraine [29]. The conflict has placed a lucrative extraction opportunity under Russian control. Control over raw materials is a critical yet often unspoken goal of war. Economic experts and institutions like the European Parliament and the European Bank for Reconstruction and Development (EBRD) emphasize this [17,21,33,37,38]. The EU and the US aim to reduce Russia's export earnings through international trade sanctions. Russia is a significant exporter of palladium (45 %) and platinum (15 %) [27]. A January 2023 Newsweek article noted that the US and allies are seeking to leverage Ukraine's resources for advanced military technology, potentially creating a new titanium pipeline. If Ukraine prevails, the US and allies will benefit; if Russia secures these resources, it will enhance its global influence [12].

2.3. The need for action

In recent years, governments and international organizations have developed strategies for sustainable resource use. Examples include the OECD's Green Growth strategy, the EU's initiative for a resource-efficient Europe, and the FAO's Save and Grow guide. Many countries benefit from these programs, which are characterized by continuous monitoring. Local initiatives, such as those in Deventer, Netherlands, also contribute to sustainability efforts.

The primary challenge in maintaining our way of life involves raw materials, energy, and money, with raw materials being the bottleneck. Unlike money and energy, materials in products cannot be fully reused. The circular economy aims to recover materials from used products to make new ones, but finite materials limit long-term sustainability. Therefore, sustainability is linked to development, not growth.

Despite striving for sustainability, global warming, pollution, and other environmental issues persist, indicating that the history of technical civilizations may be finite. The Fermi paradox, questioning why we haven't encountered intelligent civilizations despite the universe's vastness, suggests a similar finite history for civilizations.

Addressing sustainability requires optimism and action, especially regarding CO_2 and methane emissions, which significantly contribute to global warming. The UN's 17 sustainable development goals highlight the importance of this issue, encompassing moral and measurable economic objectives. Hungary's sustainability strategy, while differing in focus, emphasizes resource preservation and has been publishing sustainability reports since 2007.

The relationship between the economy and natural resources is illustrated by domestic material consumption (DMC) and resource productivity (GDP/DMC ratio). This indicator shows how efficiently a country uses its resources. However, efficiency alone doesn't always lead to savings. Other factors, such as GDP and social conditions, also influence resource productivity.

A sustainable economy relies on adequate financing, with green finance playing a crucial role. Green finance includes state-funded programs and market-based solutions, aligning with ESG (Environmental, Social, and Governance) initiatives. The ESG approach aims to combine financial performance with sustainable development, reducing financial risks while promoting societal and environmental benefits.

3. Material and method

The largest expansion in terms of membership in the European Union occurred on 1 May 2004. Ten new member states with about 75 million citizens welcomed into membership on that date. The joining member states: the Visegrad Group (the Czech Republic, Hungary, Poland, Slovakia), Estonia, Latvia, Lithuania, Slovenia (all seven states from former Soviet/Eastern Bloc), Malta, and Cyprus. Seven out of 10 have a common historical context and no joining member state was a developed economy.

Given that the countries at the centre of the study are all EU member states, we used public databases available on Eurostat's website as a source. The Eurostat database also meets the research ethics conditions, as it is a publicly available (and of course anonymous) database, so a separate research ethics permit is not required for this investigation. As an additional advantage, it can be highlighted that the Eurostat sample contains national data that is assumed to be representative and has a sufficiently high number of elements. This ensures the same methodology, compliance with research ethics, and a representative and sufficiently high number of elements. The examined period is 2011–2021. When choosing the starting year, we took into account that the recovery from the 2008 crisis had already begun by 2011, so the effects of the crisis will hopefully not significantly affect the statistical indicators. The sample consists of two groups of EU member states: countries that joined in 2004 and all other member states. The list of databases used is provided at the end of the bibliography.

The variables from Eurostat data sources are as outlined below. The measure of resource productivity is Gross Domestic Product (GDP) over Domestic Material Consumption (DMC), GFCF is a ratio of investments over GDP. RAndD is a measure as a ratio over GDP also, employment knowledge is a ratio of at least high school level worker over all worker. The variables on recycle waste, circular material usage and on renewable energy are a ratio of recycle waste and recycle material over all waste and material usage, a ratio of renewable energy over energy mix in a country. Trains is a measure on railway network in thousand km, population density is a measure on people over a thousand squared km.

Table 1 is a summary of inferential statistical inferences from the data collected in the process of conducting our research.

The dataset is regarded as complete except in relation to variable TRAINS, which measures the length of a corresponding country's railway network. The variable does not have data in two countries, Malta and Cyprus, because these two do not have a railway transport network. The slight difference between means (Mean) and medians (Median) is a measure that reflects a distribution that is close to a form that is Gaussian. Normality in sample means in different countries was evaluated with the Shapiro-Wilk test. The outcome in one case, Denmark ($p < 0.001$), is a significant one. Denmark is excluded from the database in order to allow a non-parametrically more potent (see quotation above) series of tests. The quotation refers to a feature that makes these tests more effective in determining relationships between variables with more power in comparison with non-parametric tests. We also examined the normality of the country samples using the Shapiro-Wilk test [41]. Based on this result, we were forced to exclude the Danish data from the study in order to carry out the further studies with statistically more powerful parametric procedures. Denmark had no extreme values (outliers) and its trends do not differ significantly from the EU trends. Therefore, the weight of the other countries in the regression is much larger and the relationships do not change significantly with the removal of Denmark.

Since resource productivity is the quotient of GDP and material consumption (DMC), we examined the relationship of these three variables with a correlation study, followed by comparative studies. First, we compared the resource productivity performance of the ten member states that joined in 2004 examined in a separate group with those of the other member states of the Union. One of the questions of the research was to examine whether the resource productivity of the countries that joined in 2004 (EU10) lags behind that of the other member states. For answering, we performed a two-sample *t*-test [44], with the null hypothesis that the average of the two groups is the same. The conditions for performing the *t*-test are the already examined normality and homoscedasticity (the standard deviation of the two groups is the same). We examined this with Levene's test [28].

Subsequent to conducting the *t*-test, a panel regression analysis was conducted on available panel data. The intention is that in conducting this analysis, we will determine the level at which progress in terms of resource productivity is influenced by specified variables. A multicollinearity check before conducting the regression identified variables that are highly correlated. Due to these variables' relevance in our study, we did not drop them from our database; we combined them into a single composite innovation variable known as INNOV_COMB via a procedure known as a principal component analysis. The variable was later utilized in our research. The outcome from conducting a Hausman test confirmed that a Fixed Effects model is suitable, as it holds invariant effects over countries as well as assuming that independent variables are linked with each nation's peculiar attributes. In addition, a Fixed Effects model gives a better fit in terms of describing changes over time. Therefore, in presenting our findings, in this section, we will expound on the Fixed Effects model.

Then we looked for an answer to the extent to which resource productivity is influenced by the examined variables. We found the answer using a linear regression model. As the final step of the statistical data processing, a road model (Structural Equation Model - SEM) [6] to examine how the factors shaping resource productivity exert their effects in direct and indirect (interactions between each other) ways. The model was developed in a systematic manner. The independent variable, which is a direct consequence of both GDP growth and DMC, is assessed as a measure of resource productivity. The other variables are hypothesized to have a mediated impact on resource productivity either through either GDP or DMC. In model development, our strategy followed two guiding principles. The first emphasis was on maximizing overall model fit. The second emphasis was on simplifying both its explanation and interpretation. Consistent with these principles, we made systematic alterations in variable relationships.

4. Presentation of the results

4.1. Correlation study

The purpose of the correlation study was to examine the relationship between resource productivity and its components (Table 2).

Resource productivity is calculated using the following formula:

$$RP = GDP/DMC, \tag{2}$$

I.e. as a ratio of gross domestic product (GDP) to domestic material consumption (DMC).

The correlations that are noted are at a level that is statistical at $p < 0.01$, which means that the outcomes have statistical reliability. The differences between the EU27 and the EU10 are a demonstration that

Table 1
Descriptive statistics of sample.

Variable	N	Missing	Mean	Median	SD	IQR	Min	Max
TIME_PERIOD	11	0	Not interpre-table	Not interpre-table	Not interpre-table	Not interpre-table	2011	2021
RESOURCE_ PRODUCTIVITY	11	0	135.87	129.68	34.02	36.76	63.59	317.42
GDP_PerCap_PPS	11	0	100.91	91.00	43.15	48.00	46.00	283.00
DMC_per_Capita	11	0	17004.27	14987.00	7344.76	7844.75	7722.00	48605.00
Employment_rate	11	0	71.42	71.85	6.41	8.85	53.10	84.70
GFCF_GDP_ percentage	11	0	21.03	20.65	4.24	4.10	10.70	54.30
RAndD	11	0	1.65	1.38	0.87	1.34	0.38	3.62
EMPLOY_ KNOWLEDGE	11	0	44.16	44.15	7.23	11.23	24.90	60.00
WAST_REC	11	0	36.09	36.20	15.05	22.33	8.30	71.10
REN_EN	11	0	20.61	17.60	11.36	14.11	1.88	62.57
TRAINS	11	2	5.85	5.65	3.25	5.40	0.40	12.90
TERTIARY	11	0	63.84	64.11	6.52	9.71	42.33	80.08
RAW_IMP	11	0	9323.61	2856.95	16,441.78	9367.65	31.80	106,958.20
CIRC_MAT_USE	11	0	8.90	7.50	6.38	7.50	1.20	33.80

Note: Number of countries = 27, Number of EU10 countries = 10; There is no railway network in Cyprus and Malta.
Source: authors'own.

Table 2
Correlations between resource productivity and the indices that determine it (EU27 andEU10).

		RES_PROD	GDP	DMC
RES_PROD	Pearson's r EU27	—		
	Pearson's r EU10	—		
GDP	Pearson's r EU27	0.267***	—	
	Pearson's r EU10	0.274**	—	
DMC	Pearson's r EU27	0.404***	0.740***	—
	Pearson's r EU10	−0.245*	−0.286**	—

Notes:.
*** $=p < 0.001$.
** $=p < 0.05$.
* $=p < 0.1$
Source: own ed.

these areas are at different points in development in terms of sustainability as well as in terms of economic efficiency. In the EU-27 group, the correlation between material consumption (DMC) and resources' productivity is 0.404. The correlation is a weak to moderate positive correlation, meaning that a rise in material consumption does not necessarily lead to a marked boost in resources' efficiency. In a reverse manner, a high correlation is noted between resources' productivity and GDP (0.740), meaning that a boost in resources' productivity is generally followed by a boost in resources' efficiency. Therefore, in terms of the development in the EU27, resources' efficiency is more proximately related with economic growth (GDP) as compared to material consumption (DMC). The outcome is a demonstration that sustainability is becoming a more important consideration in terms of determining development in the EU. Resources are more efficiently utilized, hence a boost in GDP is not necessarily followed by a marked boost in material consumption.

The connection between resource productivity in the EU-10 countries is just as important as that between DMC and resource productivity. The two have a great impact on improving the level of resource efficiency. The correlation between DMC and that of resource productivity is inversely related with that of GDP, meaning that material consumption is followed by inefficiency that finally decreases the level of resource efficiency as well as not necessarily leading towards growth in GDP. In the case of EU-10 countries, growth in economics still means more material consumption that finally decreases the level of resource efficiency. That is a demonstration that material utilization is not optimized sufficiently.

In summarizing these observations, it is important to note that in the EU27, growth is more tied to innovation as well as to renewable resources, whereas in the EU10, high material intensity is predominant.

4.2. *The t-test*

The result of the *t*-test can be summarized as follows: the result of the Levene test is not significant (F1; 295 = 0.0147, p = 0.904), which means that the homoscedasticity condition is met, i.e. the *t*-test can be done. Based on the test results, the average value of the resource productivity of the countries that joined in 2004 is 137 (SD = 37.7), that of the other member states is 136 (SD = 28.3). However, the result is not significant (t(295) = −0.372; d = −0.0448, p = 0.71). This means that there is no significant difference between the two groups, i.e. the member states that joined in 2004 will perform in the same way as the other member states in terms of resource productivity in 2023.

4.3. *Panel regression*

The Fixed Effects model EU-27 general fit statistics ($F = 63.112$, p = 2.10e-110) are adequate. This means that the independent variables together affect the dependent variable. The explanatory power of the model (Adjusted R2) is 87.62 %, i.e. the independent variables explain 87.62 % of the changes in resource productivity. The Fixed Effects model EU-10 general fit statistics ($F = 63.567$, p = 5.16e-07) are also adequate. The explanatory power of the model is weaker (Adjusted R2) 56.86 %, i.e. the independent variables explain 56.86 % of the changes in resource productivity in the EU-10 countries (Table 3).

The intercept measure refers to the expected amount of resources at a situation in which all independent variables are at a level of zero. In models that employ fixed effects, its meaning in terms of interpretation is reduced because it excludes persistent country-specific factors. Therefore, it was not included in our estimation procedure in computing model estimates.

For the EU-27 countries, waste recycling and the use of renewable energy sources have a positive impact on productivity. The circular economy also has a significant positive impact on resource productivity. The effect of the share of people with higher education is negative. This is an unexpected result that requires further investigation. For the EU-10 countries, the combined innovation variable, which is formed from the share of highly skilled workers, investment and R&D expenditure, has the strongest effect (12,939). A 1-unit increase in this variable is associated with an increase in resource productivity of almost 13 units. This is followed by the proportion of people with higher education (2.201) and the waste recycled ratio (1.132). The impact of raw material imports and population density is significant, but negligible. It seems surprising that a 1 % increase in the share of renewable energy in the energy mix reduces resource productivity by almost 2 units (−1.728). The other variables have no significant effect.

Using the Fixed Effects model, we can also examine which countries' resource productivity values deviate significantly from the EU27 average. EU10 countries generally show higher resource productivity (Fig. 1).

Ireland and Spain have outstanding resource productivity, while Estonia and Sweden lag significantly behind the EU27 average.

4.4. *The results of the road models*

Based on the results of the correlation and regression tests, two path models (path model, Structural Equation Model – SEM) was also created, one model using data from the EU27 and the other from the EU10 countries (Figs. 2 and 3).

When creating the EU27 path model, the starting assumption was that resource productivity (RES_PROD) is directly influenced by the two factors included in its calculation formula (GDP and DMC), and the other factors act through them. However, there were several problems with the model based on this: the fitting statistics were not adequate, and GDP had a negative effect on the evolution of RES_PROD. However, the latter is not possible considering the calculation formula. The quasi-causal nature of the model helped when solving the question. This means that the arrows connecting the variables of the model indicate the direction of the effect, similar to a causal relationship. Therefore, reversing the arrow indicating a negative effect helped. Therefore, GDP does not affect the development of RES_PROD, but the performance of

Table 3
Variables in fixed effects model of EU-27 and EU-10 countries.

Variable	Coefficient (EU-27)	p value (EU-27)	Coefficient (EU-10)	p value (EU-10)
Intercept	183.46	6.78E-06	8.917	0.813
INNOV_COMB	1.53	0.557	12.939	0.030
WAST_REC	0.63	< 0.001	1.132	0.000
REN_EN	0.91	< 0.001	−1.728	0.000
TRAINS	−0.14	0.868	1.579	0.263
TERTIARY	−1.92	< 0.001	2.201	0.000
RAW_IMP	0.0001	0.74	0.003	0.024
CIRC_MAT_USE	1.48	0.001	−0.795	0.526
POP_DENS	0.02	0.524	−0.038	0.000

Source: authors' own.

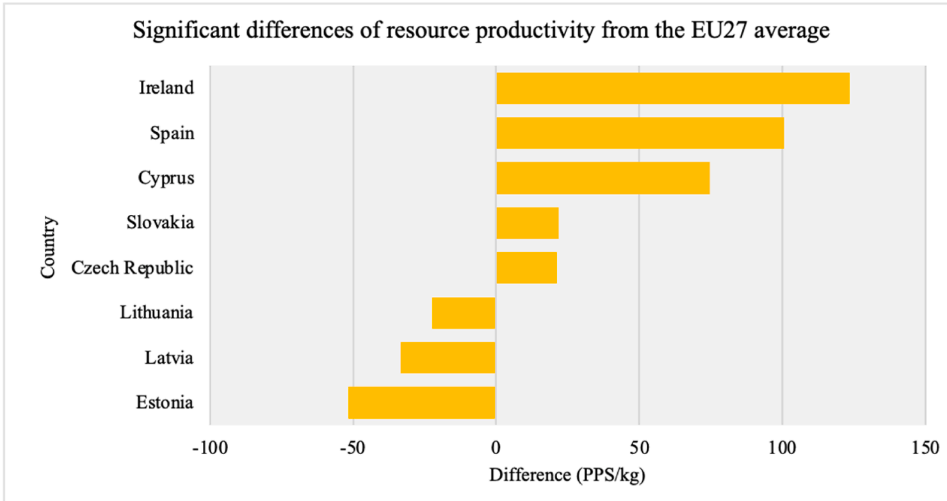

Fig. 1. Member States with resource productivity significantly different from the EU27 average.
Source: authors' own

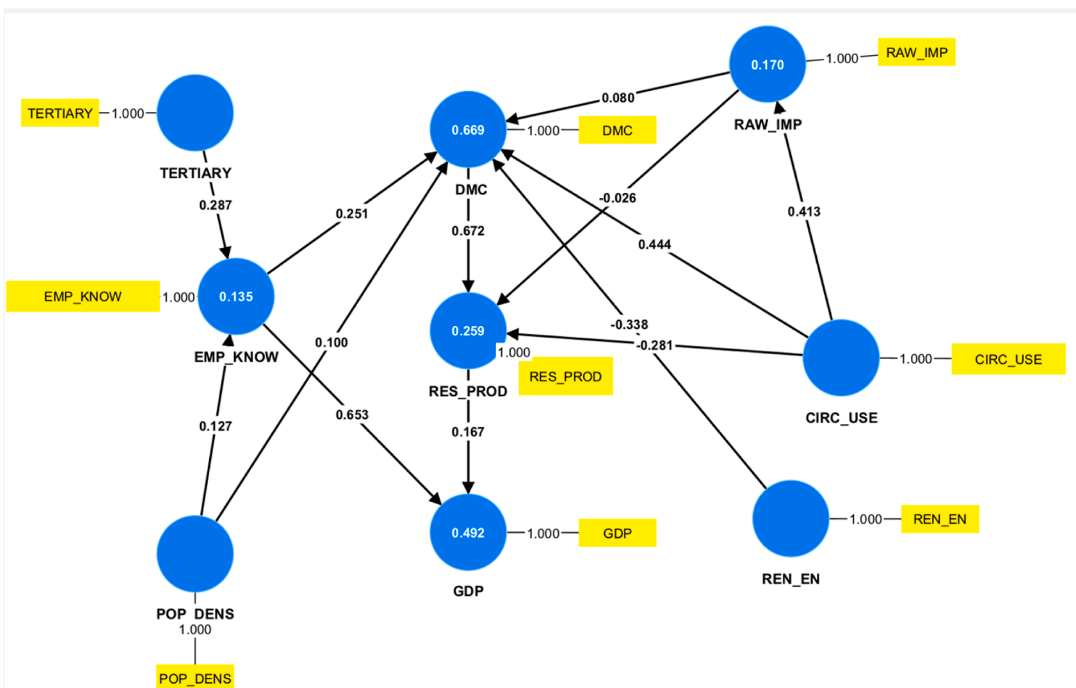

Fig. 2. Road model of the EU27 countries (source: own results).

RES_PROD contributes to the development of GDP.

The Fig. 2 shows this new model. The fit data are adequate (SRMR = 0.095 [below 0.1 is adequate [24]], NFI = 0.681 [value between 0–1, higher value is better], VIF = 1.0–1.3 [A value below 10 is appropriate]).

Several important new results are associated with the new model. One is the deviation of the actual logical connections from the assumed connections. Resource productivity is usually calculated using the GDP/DMC formula. Based on the model, however, resource productivity in the EU has a positive effect on the development of GDP. Although the purpose of the model was to examine the factors affecting resource productivity, in the end GDP became the explained variable. Of the examined variables, only resource productivity (RES_PROD) and the level of employee knowledge (EMP_KNOW) affect this, both effects are positive. The other variables exert their influence primarily through domestic material consumption (DMC) and resource productivity. Based on this, DMC can also be treated as an explained variable, although strictly speaking it is not. Simply put, the variable in the model is the explained variable in which the arrows pointing only to the given variable end - and DMC is not like that. Nevertheless, this is the variable explained to the highest extent (66.9 %) in the model.

The analysed variables explain almost 50 % (49.2 %) of the development of GDP, the explanation of resource productivity is 25.9 %. This suggests that the phenomenon is much more complex than simply being explained as the ratio of the GDP used to calculate it and the DMC. This finding is also supported by the observation that both reuse (CIRC_USE) and raw material import (RAW_IMP) have a direct impact on resource productivity in the model.

In the diagram of the model, the arrows indicate the strength of the direct effects. These are supplemented by indirect (direct) effects. The sum of the direct and indirect effect shows the overall effect of the given

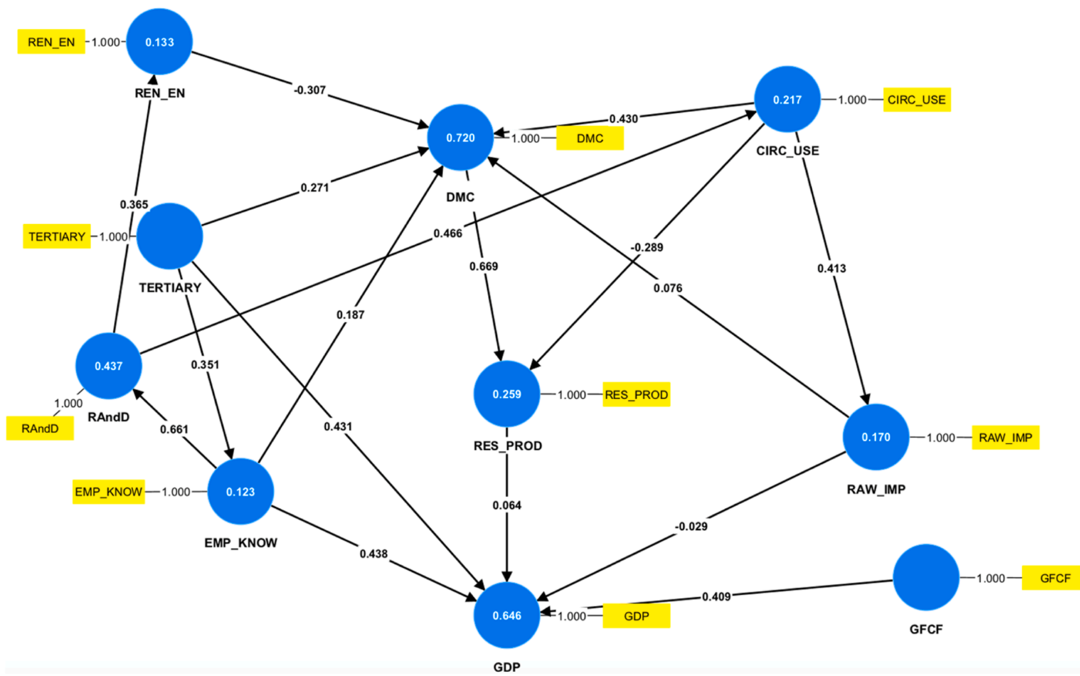

Fig. 3. Road model of the EU10 countries (source: own results).

independent variable on the explained variable (total effect).

The direct, indirect and total strengths are summarized in Among the direct effects of the model, we have three negative effects.

When analysing the SEM, we saw that the effect of DMC on resource productivity is much greater than the effect of GDP. The full effects of the SEM model confirm this result:

- DMC →RES_PROD = 0.672
- GDP →RES_PROD = −0.011 in the old model, now RES_PROD affects GDP

When creating the EU10 road model, a similar result was obtained as in the case of EU27. The model showed adequate fit (SRMR = 0.175, NFI = 0.613, VIF = 1.000–1.982) when GDP does not affect RES_PROD, but vice versa (Fig. 3), although the strength of this effect (0.064) is less, as half of what can be detected in the EU27 (0.167).

5. Discussion

The variances in the outcome of the panel regression can be largely attributed to the different economic structures, development levels, and transformation processes in each of the involved countries. The member states of the EU-27 have, in the majority, experienced a protracted engagement in implementing strategies on sustainable development, which have seen more developed operationalization of circular economy principles, waste recycling, as well as technologies on renewable energy, which can be a source of enhanced resource productivity. The above argument is supported by research from Pantcheva and Mengov [34], which finds that increased expenditures on research and development, improved resource productivity, increased GDP per capita, as well as imposition of a landfill prohibition, are essential drivers in attaining high rates of recycling. The countries forming the EU-10 are, on the other hand, in a stage of ongoing economic transition, with ongoing modernization, innovation in technologies, as well as human resources development, specifically through improved development in tertiary studies, as a key driver, hence a more evident impact of the innovation variable.

In the case of EU-10 countries, a greater emphasis on innovation and technical progress – as captured by the variable INNOV_COMB – can have a high impact on improving resource productivity [5,7]. This can mean that, in a dynamic economy, technical innovation, high schooling, as well as R&D expenditure are crucial in enhancing efficiency [13]. In contrast, whereas in the case of the EU-27, some other determinants (circular economy measures, for instance) are in play, in that of EU-10, research and development (R&D = 0.769) is a highly positive driver in relation to improving resource productivity, as compared with some other desirable variables like employment (EMP_RATE = 0.214).

A notable disparity is observed in terms of the impact of renewable energy on resource productivity in the EU-27, as compared with a negative correlation in the case of the EU-10. The observation is that either the transition towards renewable energy in member states in the case of the EU-10 is in its early developmental stage, or that transitional issues, marked by short-run declines in efficiency, have a negative impact on resource productivity in the short run. The apparently paradoxical situation is clarified by Jevons [25], who suggested that although energy efficiency improves over time, aggregate energy utilization tends to grow; that is because improved energy efficiency brings about cost savings, which in turn raises production levels and consequently pushes energy utilization up.

The essence of fixed effects models is that they control for country-specific, time-constant factors, so that the observed effects are partly a reflection of different institutional, political and infrastructural conditions. In the case of the EU-27 Member States, factors such as waste recycling and the circular economy dominate due to long-term stable, well-integrated systems. In particular, significant increases can be achieved through the professional recycling of industrial solid waste [47] and the management of municipal waste, which is a cyclically important factor in the reduction of total factor productivity (TFP) [22]. In the case of the EU-10, the positive impact of innovation and higher education is stronger due to the transforming economic structure, but the increase in tertiary education may be materially expensive in the short term, for example due to the development costs of university infrastructure (TERTIARY = −0.2124). In summary, the differences are likely to result from the different levels of development, economic structures and current transformation processes of the Member States. In the EU-27, the positive impact of long-term sustainability strategies and well-established circular systems prevails, while in the EU-10, economic modernization, innovation and human capital development are emphasized, but challenges still exist in certain areas (e.g. in the renewable energy transition). Among the factors influencing resource productivity, research and development and technological developments are the most significant in the EU-10, while in the EU-27, more advanced solutions in waste management and the circular economy dominate [18].

Based on the path models, the analysed variables in the case of the EU27 explain almost 50% (49.2%) of the GDP development, and in the model of the EU10 countries to a significantly higher extent, 64.6%. the resource productivity explained in both models is 25.9%. This suggests that the phenomenon is much more complex than simply being explained as the ratio of the GDP used to calculate it and the DMC. This finding is supported by previous studies, which also highlight the influence of various macroeconomic and institutional factors on sustainability and economic efficiency [19,23]. The result is also supported by the observation that reuse in the models (CIRC_USE) and raw material imports in the EU27 model (RAW_IMP) have a direct impact on resource productivity [18]. Over 50% of the GDP explained by the examined factors also indicates that resource productivity plays a significant role in economic growth. This is particularly evident in the example of Asian countries. Among the continent's three largest economies, Japan uses only 0.3 kg of material per dollar of its GDP, compared to 6 kg in China or 4 kg in India. The reason for this is that, in contrast to Japan's technical development, China and India prefer to use the "low-hanging fruits" of the economy, i.e. the easily available sources of growth, such as mass cheap labour [40].

Several important new results are associated with the EU27 and EU10 models. One is the deviation of the actual logical relationships from the assumed relationships. Resource productivity is usually calculated using the GDP/DMC formula. Based on the model, however, resource productivity in the EU has a positive effect on the development of GDP. This result corresponds to several observations in the literature [19,23].

Although the purpose of the model was to examine the factors affecting resource productivity, in the end GDP became the explained variable. Among the examined variables in the EU27, only resource productivity (RES_PROD) and the level of employee knowledge (EMP_KNOW) affect this, both effects are positive. The other variables exert their influence primarily through domestic material consumption (DMC) and resource productivity. Based on this, DMC can also be treated as an explained variable, although strictly speaking it is not. Simply put, the variable in the model is the explained variable in which the arrows pointing only to the given variable end – and DMC is not like that. Nevertheless, it is the highest explained variable in the models.

Comparing the two models, significant similarities and differences can be observed.

The first and perhaps most important similarity is that the explained variables are almost identical in both models (GDP is the only exception). This can be observed despite the fact that there is a different system of relationships between the variables in the two models, which also indicates that these explanations were not just the result of chance.

Resource productivity is explained equally by both models ($(R_{\text{RES\_PROD}})^2 = 0.259$. So, the examined factors explain roughly a quarter of the resource productivity. This clearly shows the complex nature of this indicator, that economic-social effects are more complex than the simplified relationships of a model. The high level of explanation of the DMC in the two models is also similar (66.9 % in the EU27 and 72 % in the EU10 the development of the DMC can be linked to the examined variables).

An interesting question is why, in both models, the increase in circular material consumption causes an increase in raw material imports to the same extent (0.413). A possible answer is that, thanks to the circular use of materials, the amount of products produced from a given material can be significantly increased without significantly increasing the DMC. However, in general, the production of a specific product does not require only this one material. Therefore, it may be that the expansion of production can only be achieved by increasing the import of other materials. The same mechanism may account for the equally explained (0.170) effect of raw material import (RAW_IMP) on DMC in the two models. The increase in RAW_IMP causes the increase in DMC to an almost equal extent (0.080 in EU27; 0.076 in EU10) in the two models.

The effect of circular material use (CIRC_USE) that weakens resource productivity (with a strength of −0.28 in both models) arises as a similar issue. Examining only the direct effects, the Jevons paradox probably prevails, i.e. cost reduction and more efficient use induce increased consumption. Examining the total effects, it can also be seen that circular material use has a very significant indirect effect on resource productivity in both models. The overall effect is thus positive in both cases (EU27: 0.005; EU10: 0.019).

Among the differences, it is certainly important that the EU27 model also includes two additional negative effects that require explanation. The negative effect of raw material imports (−0.026) on the RES_PROD variable means that national material consumption is not covered by own resources, and therefore the country's resource productivity decreases. At the same time, examining the total effects, we find that raw material imports also have a positive effect on resource productivity (0.027). This means that the import of raw materials is expensive, but it also has advantages: domestic raw materials do not run out, i.e. the DMC decreases. And based on the formula, this increases resource productivity, as shown by the positive overall effect.

The negative effect of the use of renewable energies (REN_EN) on the DMC (−0.338) can be explained in the simplest way: the increase in the use rate of renewable energies - precisely because of their renewable nature - does not lead to a real weight loss. This may be due to the material-intensive nature of renewable energy infrastructure, such as solar panels and wind turbines, which require significant amounts of critical raw materials [29,37].

Another significant difference is that in the EU27, research and development (R&D - R&D as a variable) did not appear in the model. In the EU10 countries, on the other hand, the developments significantly promote material-saving farming (0.466 strong effect on CIRC_USE variable) and the promotion of renewable energy sources (0.365 strong effect on REN_EN). These results are consistent with findings that emerging economies tend to rely more heavily on innovation-driven efficiency improvements to bridge the sustainability gap with more developed nations [7,13].

The EU27 model also includes four purely explanatory variables: tertiary education (TERTIARY), population density (POP_DENS), use of renewable energy sources (REN_EN) and the rate of circular use of materials (CIRC_USE). In the EU10 model, only higher education remains among these; population density is not included in the model, but the ratio of investments to GDP (GFCF) appears as a new explanatory variable. These results align with previous studies highlighting the role of capital investment in driving sustainability transitions in developing economies [11].

The explanation of GDP is also higher (64.6 %) in the EU10 group than in the EU27 (49.2 %)

In both models, tertiary education (TERTIARY) in the EU27 has an impact (0.278) on resource productivity through the knowledge of employees. In the EU10, however, this effect is stronger (0.351), moreover, the increase in the proportion of graduates has a positive effect on GDP (0.431) and DMC (0.271). The most important suggestion that can be made based on the results is the development of higher education, because it is the primary base of human knowledge capital. This is precisely one of the declared goals of the transformation of the structure of university education and the strengthening of industry-higher education cooperation - which processes are already underway. The concentration of knowledge capital and financial resources can also create a successful basis for raising the level of research, development and innovation, which is essential for the development and introduction of modern, material- and energy-saving processes. These processes are the most important foundations of sustainable development. These findings support prior research emphasizing the role of higher education and human capital development in enhancing economic resilience and sustainability [9,10].

Collectively, the outcomes imply that a mix of economic, technical, and policy-based factors impacts resource productivity, reflecting notable differences between the EU-27 and EU-10 regions. The EU-27 relies on established structures of sustainability and skilled material management methods, while the EU-10 relies on innovation, research activities, and human-capital development in order to enhance efficiency. The outcomes imply that tailored policy strategies that consider regional contexts of economics as well as development trajectories are necessary [33].

6. Conclusion

The present study intended to analyze the development trajectories of those countries that acceded to the European Union in 2004 with a special focus on resource productivity as a measure of sustainability. In spite of historical early setbacks in these economies, our study finds that these have largely followed the pattern of the EU-27 in terms of resource efficiency, though glaring gaps in their approach towards sustainability as well as innovation-based economy-led contemporary development persist.

Our results highlight several policy implications for improving sustainability and economic efficiency in both the EU-27 and EU-10:

- Enhancing Circular Economy Practice – The study finds that though increased application of circular material improves resource utilization over a longer time, short-term inefficacy is seen. Policymakers are suggested to adopt fiscal incentives (like taxation relief in case of utilization of recycle material) and rule-based regimes (like compulsory recycle target imposition) in order to accelerate transition towards circular economy practices [18].
- Focused Investment in Renewable Energy Infrastructure – In terms of the EU-10, the negative short-run impacts of the use of renewable energy on resource productivity reflect transitional inefficiencies. Governments have a mandate in improving energy storage technologies, upgrading grid infrastructure, as well as improving technical training schemes in order to boost technical efficiency in harnessing renewable energy [29].
- The notable impact on EU-10 resource productivity highlights the critical role that increased private as well as public expenditure on innovation, specifically in energy-efficient production, material sustainability, as well as waste management, can play [7,13]. In addition, innovation networks in the European Union have the ability to enhance transferability.
- The improvement in tertiary level resource productivity is considerably high, especially in the case of EU-10 member states. Therefore, policymakers are advised to expand measures concerning STEM educational curriculum, vocational training, as well as university-industry liaison activities in order to enhance labor competence in terms of green technologies [9,10].
- Equilibrated Strategies in Trade and Resources Security – The observed correlation between raw material importation and resources' productivity highlights the importance of diversified supply chain in addition to deliberate resources accummilation in order to counterbalance economic risks in terms of geopolitical uncertainty [37]. The European Union's Critical Raw Materials Act can be a key instrument in maintaining supply stability.

Although the research presents important insights, it is necessary to consider some limitations. The research relies on 2011–2021 data from Eurostat, which might not fully capture pandemic-led economic changes or the latest measures in terms of policymaking. Future research can be improved with more updated data series and qualitative appraisal in order to boost statistical outcomes. The EU-10 member states, with a shared timeline of integration, have diverse economics. Performing studies on a nation basis can lead to more in-depth understanding of specific policymaking challenges as well as best practices. The study presents high correlation; it does not establish definite cause-effect links. The employment of longitudinal studies or experimental studies on policymaking can enhance the legitimacy of inferences made.

Building on these findings, future research could explore sector-specific resource productivity trends – analyzing differences in sustainability performance across manufacturing, agriculture, and services could reveal more targeted policy solutions; investigating how AI, IoT, and smart grids impact circular economy and renewable energy transitions; and examining how similar sustainability strategies have been implemented in other economic blocs (e.g., ASEAN, NAFTA) could offer valuable lessons for the EU.

By leveraging innovation, education, and sustainable resource management, EU-10 countries can further close the gap with the EU-27, ensuring long-term economic resilience. However, achieving meaningful progress requires adaptive policy frameworks that integrate technological advancements, investment in human capital, and regulatory alignment with EU-wide sustainability goals.

CRediT authorship contribution statement

Botond Géza KÁLMÁN: Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Zoltán ZÉMAN:** Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Szilárd MALATYINSZKI:** Conceptualization, Methodology, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2025.100724.

Data availability

The data used comes from public databases, which are clearly referenced in the text of the article.

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