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Energy productivity as a part of the green growth agenda in European Union countries

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ABSTRACT: Green growth aims to achieve economic growth while preventing environmental degradation, biodiversity loss, and unsustainable use of natural resources. It decouples the effects of economic activities from environmental activities, thus seeking to make investing in the environment an engine of economic growth. Energy is one of the most critical inputs in all economic activities. It is an essential driver of economic development, and energy supply and efficiency of its use are crucial for green growth. Conventional sources of energy cause an increase in both greenhouse gas (GHG) emissions and regional air pollution. They also influence water quality and land use. There is a call for increased use of renewable energy sources to tackle climate change and energy security problems. Thus, countries worldwide should progress towards more energy-efficient technologies and provide consumers with more energy-efficient goods and services. This paper aims to assess the performance of EU countries in energy productivity using a synthetic measure (based on Hellwig's taxonomic measure of development) of the following indicators: energy productivity, energy intensity, total primary energy supply, renewable energy supply, and renewable electricity. The results show that although there has been progress in energy productivity in EU countries on average, there are still some disparities. Although the EU has adopted a common policy towards boosting energy efficiency by implementing the European Green Deal, some countries are still lagging behind. On average, western EU economies have a higher level of energy productivity; however, the rate of increase is higher in central and eastern EU countries, which may indicate a convergence process in EU economies.

KEY WORDS: Energy productivity · Renewable energy sources · EU countries · Green growth

1. INTRODUCTION

Green growth is the idea of pursuing economic growth and development while preventing environmental degradation, biodiversity loss, and unsustainable use of natural resources. This means decoupling economic performance from environmental performance and making investment in the environment a driving force for economic growth. It considers the rational use of natural capital, prevents and reduces pollution, and creates opportunities to improve social well-being by building green economies, enabling the achievement of the United Nations' sustainable development goals in the long term. Green growth provides an alternative concept to typical industrially intensive economic growth. A green economy improves the well-being of people and increases social fairness while reducing environmental risk and using natural resources. It includes sectors of the national economy that consider the principles of sustainable development, use local resources, and are environmentally friendly. A green economy also makes use of the experience of environmental economics and ensures proper relationships between the economy

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and ecosystems. This concept is a response to the global problems of environmental degradation caused by expansive economic, human activity. The challenges that green growth must meet include creating jobs that contribute significantly to preserving or restoring the quality of the environment, protecting the ecosystem and biodiversity, reducing energy, material, and water consumption through the use of highly effective strategies, and minimising or completely eliminating all types of waste and pollution. This paper focuses on a selected aspect of green growth, energy productivity, to see whether economic growth becomes greener with more efficient use of energy. Hence, the aim of this study is to assess the performance of EU countries in energy productivity. Different indicators are combined to formulate one synthetic complex measure of energy productivity. Thus, the study applies scientific tools to practically examine the current state of energy productivity across the EU economies and its development over the years. It brings new insights for scientists and policymakers seeking to determine whether any actions are required to improve the situation in particular regions.

2. LITERATURE REVIEW

The topic of energy productivity as part of the green growth agenda is vital in an academic debate. It is associated with many energy-related issues such as energy consumption (Grodzicki & Jankiewicz 2020, Brodny & Tutak 2022), energy security in the EU (Brodny & Tutak 2023, Gökgöz & Yalçın 2023), and economic and environmental performance including CO_2 emissions (Vavrek & Chovancová 2019, Grodzicki & Jankiewicz 2023).

Atalla & Bean (2017) analysed energy productivity in 39 selected countries from 1995 to 2009. They applied sectoral gross output and energy consumption data and used different methodologies, including the Fisher Ideal Index, the Logarithmic Mean Divisia Index (LMDI), the augmented Dickey–Fuller (ADF) test, the Phillips–Perron (PP) test, and the K-means clustering method. One of their findings was that countries with similar demographic and economic characteristics had similar energy productivity levels. Moreover, countries undergoing economic liberalisation showed the highest improvement rates — although they remained less energy-productive than developed countries.

Chang & Yu (2017) examined energy productivity in EU countries from 1995 to 2010. However, their particular territorial focus was the Baltic states, so they conducted analysis in 2 groups: in all EU countries (EU-27) and in the EU countries apart from the Baltic states (EU-19). They analysed energy productivity change, energy technical change, and energy efficiency change. In order to evaluate these changes, they applied the input-oriented Malmquist Data Envelopment Analysis (Malmquist-DEA) model. They used real gross domestic product (GDP) as the output factor, and real capital stock, labour employment, and energy consumption as the input factors. The results showed that both the energy productivity and energy technical change in the Baltic Sea countries had progressed. In contrast, the energy efficiency change in these countries was relatively weak due to environmental, economic, and historical concerns.

Finally, the topic of energy productivity convergence, meaning that countries with lower levels of energy productivity are catching up with those with initially higher levels, has appeared in several research papers (i.e. Markandya et al. 2006, Adhikari & Chen 2014, Han et al. 2018, Alataş et al. 2021, Liddle & Sadorsky 2021). Ağazade (2021), using the example of 11 Eastern European countries (EEC) from 1995 to 2018, looked for energy productivity convergence. He divided GDP (at 2015 prices in million USD) by the final energy consumption in thousand tonnes of oil equivalent (toe) as an indicator of energy productivity. The results indicated that although a β-convergence process occurred, its pace was relatively slow. There are several possible reasons for this slow catching-up process, e.g. difficulties of changing the production structure, different sectoral specialisation, market failures.

Another topical study presents energy productivity club convergence in 31 countries selected from all over the world from 1972 to 2012 (Apergis & Christou 2016). This research applied data on energy use, in kg of oil equivalent per capita, and gross value added (GVA) in constant 2005 USD. The empirical outcomes resulted in the rejection of full convergence among all considered countries. Nevertheless, there were several clubs in which convergence of energy productivity occurred. Therefore, these results imply that energy productivity should be analysed in a group of countries that have similar or even the same tools to shape energy policy in one direction.

Although these studies analysed energy productivity, they differ regarding the time range, territorial dimension, and method used. Hence, there is a need for updated studies on the performance of EU countries in energy productivity. The EU has many common environmental policies and action plans (such as the EU Green Deal, the Fit for 55 package, and the EU's Emissions Trading Scheme) aiming at better energy efficiency and, at the same time, lower or even zero carbon emissions (Frolova et al. 2019, Bäckstrand 2022, Belmans et al. 2022, Bonafé 2022, Bongardt & Torres 2022, European Parliament 2022, Oberthür & von Homeyer 2023), so it is vital to evaluate the performance of these countries.

3. METHODOLOGY AND DATA DESCRIPTION

The evaluation of one measure characterising a multidimensional phenomenon allows many factors to be considered. The difference between this approach and causality analysis is that the causality tests can be applied to the diagnostic variables separately. Moreover, when comparing the synthetic measure with cluster analysis, it should be noted that the clustering only shows similarity between objects (countries) without calculating the level of the phenomenon considered. Both causality analysis and cluster analysis can be applied to calculate the synthetic measure after assessment of the level of the presented phenomenon.

In this study, the taxonomic measure of development (TMD) proposed by Hellwig (1968) characterises the chosen aspect of green growth — energy productivity. This measure is built based on the several features influencing the analysed phenomenon and contains the following steps:

Step 1. Building a matrix containing potential diagnostic variables. The diagnostic variables characterising the considered phenomena (energy productivity) are presented in Table 1.

Step 2. Determining the final set of diagnostic variables based on formal, substantive, and statistical criteria. At this stage, quasi-constant variables and variables that are highly correlated with at least one of the remaining determinants are omitted.

Step 3. Determining the character of the influence of every variable on the considered process. The variables can be divided into those with a positive influence on the considered phenomenon (called stimulants) and those with a negative influence (called destimulants).

Step 4. Normalising variable values to enable comparability. In this study, the standardisation formula was used. Standardisation parameters (arithmetic average and standard deviation) were calculated based on data covering the entire period to enable the analysis of changes over time.

Step 5. Determining the development pattern — a vector of desirable values of diagnostic variables. The development pattern is the vector composed of the maximum values of chosen diagnostic variables. The maximum values are taken because all variables are characterised as stimulants.

Step 6. Calculating the value of the TMD measure using the following formula:

$$\mathrm{TMD}_i = 1 - \frac{d_{i0}}{d_0} \tag{1}$$

where d_{i0} is the distance between the i^{th} object and the pattern of development (calculated using Euclid-

Table 1. Diagnostic variables characterising energy productivity in the green growth agenda based on OECD (2024, p. 11–13). TES: total energy supply; toe: tonnes of oil equivalent; S: stimulant; PV: photovoltaic

Variable	Definition	Character
X1 – energy productivity	Energy productivity is calculated as GDP per unit of TES (USD toe^{-1}). It reflects, at least partly, efforts to improve energy efficiency and to reduce carbon and other atmospheric emissions. TES comprises production + imports – exports – international marine bunkers – international aviation bunkers ± stock changes. GDP is expressed at constant 2015 USD using purchasing power parity (PPP)	S
X2 – energy intensity	Energy intensity is calculated as TES per capita (toe person^{-1}). It reflects, at least partly, efforts to improve energy efficiency and to reduce carbon and other atmospheric emissions. Together with energy productivity, these indicators also reflect structural and climatic factors	S
X3 – total energy supply	TES is expressed in million toe. TES is also expressed as an index with values in 2000 normalised to equal 100	S
X4 – renewable energy supply	Renewable energy supply is calculated as a share of renewable sources in TES (expressed as percentage). Renewables include hydro, geothermal, solar (thermal and PV), wind and tide/wave/ocean energy, as well as combustible renewables (solid biomass, liquid biomass, biogas) and waste (renewable municipal waste)	S
X5 – renewable electricity	Renewable electricity is calculated as a share of renewables in electricity production (%)	S

ean distance), whereas d_0 is the norm of the distances d_{i0} expressed as its arithmetic average plus twice the standard deviation. Determining the distance between each country and the development pattern creates a single measure that evaluates the energy productivity level. In this analysis, the objects are countries and each country is a separate object.

The values of the synthetic measure allow evaluation of the spatio-temporal trend. This model shows directions of changes in the energy productivity level over time and space. The formula of this model is as follows (Schabenberger & Gotway 2005):

$$\mathrm{TMD}_{i,t} = \theta_{000} + \theta_{100} x_i + \theta_{010} y_i + \theta_{001} t + \varepsilon_{i,t} \quad (2)$$

where $\mathrm{TMD}_{i,t}$ denotes the value of the synthetic measure in the i^{th} country at time t, and x_i and y_i are the geographical coordinates of the i^{th} country (longitude and latitude, respectively). In turn, θ_{000}, θ_{100}, θ_{010}, and θ_{001} are model structural parameters, whereas $\varepsilon_{i,t}$ is a spatio-temporal bias.

Finally, the convergence process of energy productivity was considered. The convergence analysis is based on the β-convergence panel data model. The general form of the model is as follows:

$$\ln\left(\frac{\mathrm{TMD}_{i,t}}{\mathrm{TMD}_{i,t-1}}\right) = \alpha + \beta \ln(\mathrm{TMD}_{i,t-1}) + \gamma_1 \mathrm{CR1} + \gamma_2 \mathrm{CR2} + \varepsilon_{i,t} \quad (3)$$

where $\mathrm{TMD}_{i,t}$ and $\mathrm{TMD}_{i,t-1}$ are the energy productivity level at times t and $t-1$, respectively, α, β, γ_1 and γ_2 are the structural parameters of the model, and $\varepsilon_{i,t}$ denotes the random component. The parameter β signals whether a convergence process occurs. Negative estimates of β that are significantly different from 0 indicate that absolute convergence is favoured by the data. As there were 2 significant crises during the analysed period (the financial crisis and the COVID-19 pandemic), the model is enriched with 2 dummy variables CR1 and CR2. These variables are binaries and take on a value of 1 when the crisis occurred and 0 otherwise. Their task is to take into account possible negative structural brakes from the general tendency that could significantly influence the convergence process. Eq. (3) can be equivalently written as:

$$\ln(\mathrm{TMD}_{i,t}) = \alpha + (1+\beta)\ln(\mathrm{TMD}_{i,t-1}) + \gamma_1 \mathrm{CR1} + \gamma_2 \mathrm{CR2} + \varepsilon_{i,t} \quad (4)$$

In this case, convergence occurs if the estimate of $(1+\beta)$ is within the interval $(0,1)$ and is statistically significant. For the panel data model, the speed of convergence is evaluated using the following formula (Arbia 2006):

$$b = -\ln(1+\beta) \quad (5)$$

Speed of convergence (b) evidences the level of inequalities between units reduced in 1 yr. Based on the speed of convergence statistics, the half-life time statistic (h_{life}) can be evaluated. This measure indicates how much time is needed to reduce current inequalities by half and is calculated with the following formula (Arbia 2006):

$$h_{life} = \frac{\ln 2}{b} \quad (6)$$

Green growth is a multi-featured phenomenon, and therefore tools of multidimensional comparative analysis should be used. Green growth comprises 5 main categories: environmental and resource productivity, the natural asset base, the environmental dimension of quality of life, economic opportunities and policy responses, and socio-economic context. This study focuses on 1 factor — energy productivity. This is included in the environmental and resource productivity, which is subdivided into the following factors:

- CO_2 productivity
- Energy productivity
  - Energy productivity, GDP per unit of total energy supply (TES)
  - Energy intensity per capita
  - Total energy supply
  - Renewable energy supply
  - Renewable electricity generation
  - Energy consumption
  - Renewable energy supply (excluding solid biofuels)
- Non-energy material productivity
- Environmentally adjusted multifactor productivity

The energy productivity aspect of green growth is characterised by the 7 crucial indicators listed above. This study only takes 5 of these into account since 2 of them cannot be adopted into the synthetic measure. Thus, 'renewable energy supply' was selected instead of 'renewable energy supply (excluding solid biofuels)' since it contains more information — it is a broader indicator. 'Energy consumption' could not be included since it is presented in the form of a share of energy consumption by each sector of an economy, e.g. agriculture, industry, etc., and not in absolute form. Table 1 presents the defined variables and their character. All of the used processes positively influence green growth, so they are defined as stimulants (marked as S). Data were obtained from the Organisation for Economic Co-operation and Development (OECD) database (https://stats.oecd.org/; accessed 17 May 2023). The analysis concerns energy productivity levels between 1995 and 2020 across 27 EU countries.

4. EMPIRICAL RESULTS

Firstly, the TMD was evaluated. Table 2 presents the synthetic indicator for level of energy productivity in the years 1995 and 2020, and the rankings based on these values are also shown. Countries were sorted in decreasing order based on the TMD values for 1995. Sweden was at the top of the ranking in 1995, where energy productivity demonstrated the highest level, slightly higher than in Austria. The first place for Sweden was largely due to the massive level of renewable electricity. In turn, the energy productivity level (variable X1) lead to the high level of TMD in Austria. These 2 states significantly exceeded the third, Luxembourg, and the next — Latvia and Denmark. Ireland and Cyprus were at the bottom of the ranking in 1995 due to having the lowest levels of renewable energy supply and renewable electricity.

Significant differences were visible when comparing rankings for 1995 and 2020. Ireland and Lithuania showed the largest improvements in energy productivity conditions. This resulted in a strong positive correction of ranking places — from 27th to 3rd and from 22nd to 8th, respectively. In Ireland, values of variables X1 (energy productivity) and X4 (renewable energy supply) showed a considerable increase in 2020 compared to 1995. In turn, improving the diagnostic variables concerning renewable energy (X4 and X5) caused a significant jump in ranking in 2020. A fall in order in 2020, despite an increase in TMD level, was noted for Italy and France. This was a drop in ranking of 14 and 16 places, respectively. Development in all diagnostic variables in these countries was relatively weak, and the energy productivity conditions did not improve significantly.

Table 2. Values of the synthetic measure of energy productivity as part of the green growth agenda and country rankings in the years 1995 and 2020. TMD: level of taxonomic measure of development that shows the energy productivity level; EU27: EU average; **bold:** biggest changes in rankings between 1995 and 2020

Country	TMD_1995	TMD_2020	Rank 1995	Rank 2020
Sweden	0.2682	0.3360	1	5
Austria	0.2635	0.3962	2	2
Luxembourg	0.2075	0.4359	3	1
Latvia	0.1873	0.3408	4	4
Denmark	0.1812	0.3213	5	6
Finland	0.1721	0.3058	6	7
Italy	**0.1549**	**0.1967**	**7**	**21**
Croatia	0.1505	0.2610	8	9
France	**0.1390**	**0.1738**	**9**	**25**
Portugal	0.1323	0.2276	10	14
Germany	0.1314	0.2226	11	18
EU27	0.1285	0.2243	12	15
Netherlands	0.1170	0.2227	13	17
Romania	0.1142	0.2152	14	19
Slovenia	0.1025	0.2328	15	12
Malta	0.0985	0.2606	16	10
Estonia	0.0946	0.2531	17	11
Belgium	0.0870	0.1735	18	26
Czechia	0.0840	0.1797	19	23
Spain	0.0811	0.2240	20	16
Greece	0.0680	0.1048	21	28
Lithuania	**0.0657**	**0.2960**	**22**	**8**
Slovakia	0.0623	0.1751	23	24
Hungary	0.0622	0.1954	24	22
Bulgaria	0.0618	0.1236	25	27
Poland	0.0594	0.2304	26	13
Ireland	**0.0366**	**0.3740**	**27**	**3**
Cyprus	0.0287	0.2101	28	20

Generally, in the EU, energy productivity improved in the period from 1995 to 2020. All countries showed higher levels of TMD in the last year of the research than at the beginning of the analysed period. The fact that in the last year, more countries (14) exceeded the EU average level than in 1995 (11) also indicates better energy productivity conditions.

Significant changes in rankings suggest the occurrence of the gamma-convergence process. Countries that were lower in the ranking in 1995 skipped countries with better conditions of energy productivity and were placed higher in 2020.

The improvement in energy productivity between 1995 and 2020 can be seen in Fig. 1. This figure presents the average values of the TMD measure across EU countries in the analysed period. In the general upward trend, 2 significant crashes are visible. The first was in 2009, and the second in 2020. This is when 2 major crises took place — the financial crisis and the COVID-19 pandemic. In recent years, energy productivity has fallen. These structural brakes were taken as dummy variables in the convergence model to reduce the impact of disruptions.

Fig. 2 shows the spatial differentiation of TMD values in the years 1995 (Fig. 2a) and 2020 (Fig. 2b). The first group (with the lowest values) ranges from the minimum values of the measure to the median value lowered by the quartile deviation. The next interval is between the median value lowered by the quartile deviation and the median value. The median enlarged by the quartile deviation is the upper limit of the third interval. The countries characterised with a level of energy productivity that is above the median enlarged by the quartile deviation constitute the last group. Generally, in both years, the southeastern part of the EU was dominated by countries from groups with TMD values below the median. Moreover, Scandinavian countries and Latvia, located in the northern

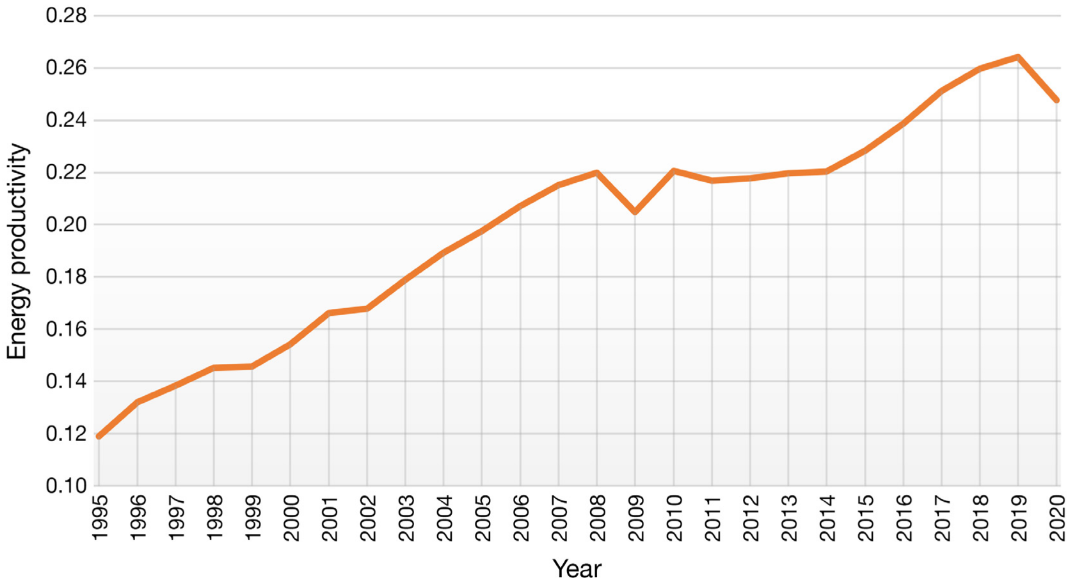

Fig. 1. Average values of the energy productivity level in the period from 1995 to 2020

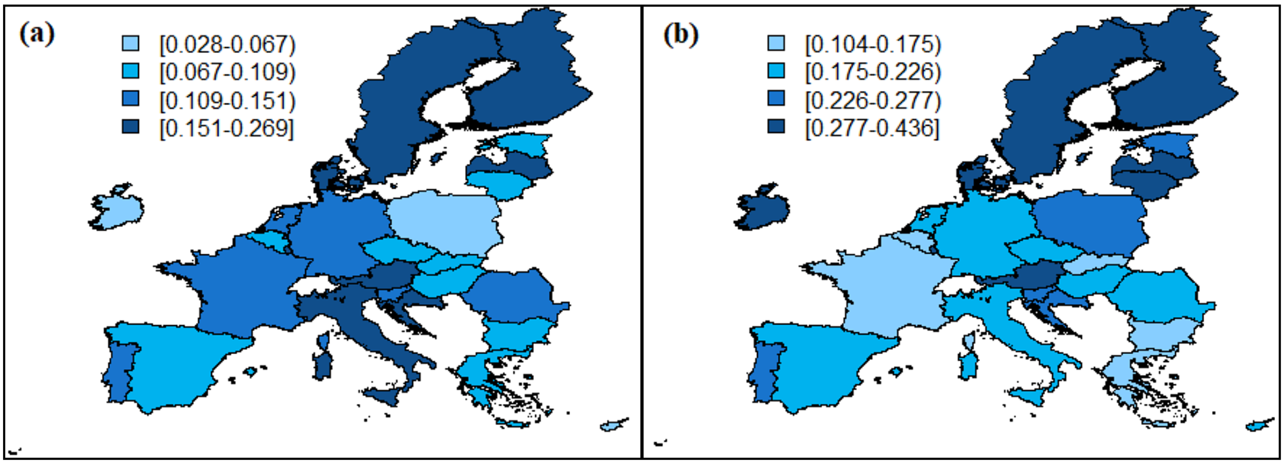

Fig. 2. Spatial differentiation of the synthetic measure of development in (a) 1995 and (b) 2020

part of the EU, were in the group with the highest energy productivity. The central part of the considered area was more diversified in the extreme years of the research.

Table 3 presents the results of estimating and verifying the spatio-temporal trend model for energy productivity in the EU. The positive and statistically significant parameter θ_{001} indicates an increase in the TMD values over time. Therefore, a general improvement of the energetic aspect of energy productivity in the EU was noted. In turn, estimates of parameters θ_{100} and θ_{010} (negative and positive, respectively) showed rising values of TMD in the north and west.

Table 3. The results of estimation and verification of the spatio-temporal trend model. The Student's *t*-test was used to test for significance

Parameter	Estimate	SE	*t*	p-value
θ_{000}	−0.0321	0.0169	−1.8960	0.0583
θ_{100}	−0.0020	0.0002	−8.5970	<0.0001
θ_{010}	0.0039	0.0003	11.6070	<0.0001
θ_{001}	0.0053	0.0003	16.3990	<0.0001

From the map presented in Fig. 3, it can be seen that most of the countries located in the eastern part of the EU showed the highest growth rates of the synthetic measure. This group also contained Ireland and Spain.

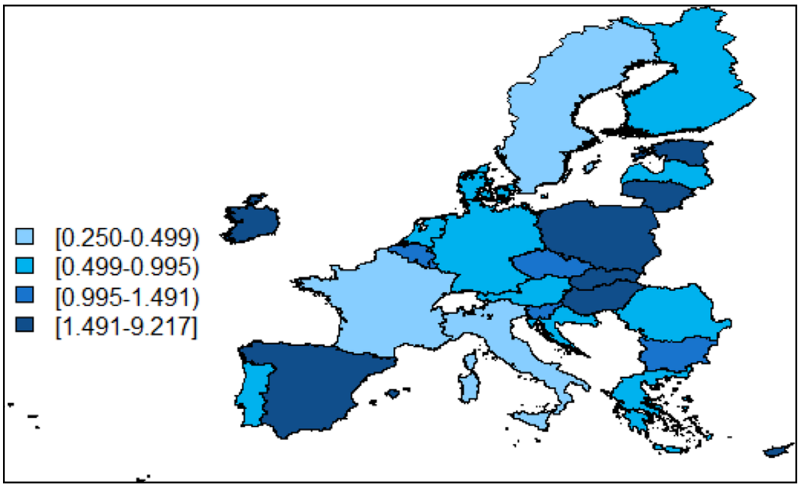

Fig. 3. Spatial distribution of the growth rate of TMD in the period from 1995 to 2020

On the other hand, a growth rate below the median was observed in Scandinavian countries and Italy, for example. Comparing Fig. 3 with Fig. 2a reveals a certain tendency: Countries with a lower level of TMD in 1995 generally showed the highest growth rates of this measure from 1995 to 2020. Therefore, convergence of energy productivity across the EU can be presumed.

Table 4 contains the results of the estimation and verification of the panel data β-convergence model in the period from 1995 to 2020. The value of parameter (1+b) was less than 1, and it was statistically significant. This indicates energy productivity convergence between EU countries from 1995 to 2020. The h_{life} statistic shows that the time needed to reduce current inequalities by half is over 8 yr. This results from the calculated speed of convergence, which indicated that 8.16% of inequalities between units were reduced in 1 yr. Negative estimations of parameters γ_1 and γ_2 confirm a decrease in energy productivity in the EU countries in the years 2009 and 2020, respectively.

Table 4. Results of estimation and verification of the β-convergence model for energy productivity in the green growth context. The Student's *t*-test was used to test for significance

Parameter	Estimate	SE	t	p-value
1+β	0.9216	0.0178	51.8044	<0.0001
α	−0.0929	0.0300	−3.0992	0.0019
γ_1	−0.1081	0.0191	−5.6634	<0.0001
γ_2	−0.0865	0.0157	−5.5237	<0.0001
β		8.1600%		
h_{life}		8.4924		

5. DISCUSSION AND CONCLUSION

This paper has significantly contributed to the debate on green growth and, in particular, the energy productivity issue in the EU. It complements the current literature on this topic as it confirms that there are countries lagging behind in terms of energy productivity level. Hence, it provides clear evidence of the performance of the EU countries, showing significant disparities in energy productivity across the EU.

Green growth in EU countries should be analysed not only because these are neighbouring countries but also because they have common tools and policies such as the EU Green Deal, in particular, that enhance energy changes. This study examined energy productivity in the EU from 1995 to 2020. The results show that EU countries were converging in terms of energy productivity at a speed of 8% annually. This means that the countries that were initially the least energy efficient caught up over time with those that were the most energy productive. Moreover, the level of energy productivity across EU economies increased over time. The values of energy productivity increased on average towards the north but decreased towards the eastern part of the EU. This all provides impetus to the debate on energy productivity and green growth strategies tailored for EU economies: more renewables, more affordable energy, energy communities, etc. Further research on this topic could include a comparison of energy productivity convergence results with economic growth (values of GDP per capita) and a more detailed focus on different territorial dimensions, i.e. more countries in addition to the EU or the EU regional dimension, e.g. NUTS2 level.

This research highlights some of the issues that need to be tackled by different stakeholders from academia, business, and policymakers: (1) Inclusive growth and cohesion in the EU region. If all these also relate to energy productivity, are there any actions (action-plans), monitoring programmes, etc.? (2) Country-specific and tailor-made policy. Each country is different regarding energy demand and supply, infrastructure, energy consumption, etc. What can be done in this matter to foster the energy productivity growth of the countries lagging behind?

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