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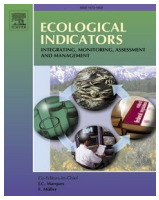

Original Articles

Upward convergence patterns in chosen environmental-related SDGs

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ABSTRACT

Sustainable development is a challenge facing humanity. EU countries not only strive to reach their specific objectives, but they also work collaboratively towards shared goals. There is a need to balance synergies and compromises to address these objectives effectively. When discussing countries' development and people's well-being, one often focuses on socio-economic development. However, it is crucial not to overlook the environmental repercussions and the need to care for the planet. Thus, our article pays attention to the sustainable development objectives of the "planets" group.

We analysed upward convergence in the scope of the "Planet" goals, i.e. the analysis of improving the results of Member States and, at the same time, reducing the differences between them. Convergence trends were examined individually for each variable and then for all variables combined (Planet). Our article fills a research gap because, to our knowledge, analyses of the trajectories of achieving individual goals in such a context have not been analysed so far. The results of our study indicate a favourable situation in the case of six out of eight examined variables. Areas in which intensification of activities is necessary for some EU countries are an increase in energy productivity and a reduction in net greenhouse gas emissions of land use. The second stage of the study concerned the development paths of individual countries. The most challenging situation concerns the variable sdg_07_20 (final energy consumption in households per capita). In this case, as many as 12 countries belong to the weak group.

1. Introduction

The 2030 Agenda is based on "leaving no one behind" to achieve sustainable development. Implementing the sustainable development goals (SDGs) is intended to foster balance and synergy between the social, environmental and economic areas (Furtado et al., 2023). For people and the planet, achieving the goals leads to peace and prosperity both now and in the future. Therefore, SDGs were set for the good of humanity, and all countries are monitoring their achievement. Of course, surveillance of the implementation of the SDGs is only possible with access to data (Nilashi et al., 2023).

Economic divergences between Member States can hinder achieving shared economic prosperity. Social divergences, however, undermine the project of European integration and progress towards improving living and working conditions within the single market. Therefore, the topic of convergence of EU countries in terms of sustainable development is essential and challenging. In our study, we used the concept of upward convergence defined by Eurofound (2018), which the authors initially used to measure convergence in employment, working and living conditions. Considering the efforts of EU Member States to implement the SDGs at the highest possible level, we hypothesise that "upward convergence" occurred in the years under consideration. In addition, the study aims to demonstrate what specific convergence pattern occurred for each country.

Our analysis covers 26 European Union Member States (excluding Great Britain) from 2004 to 2021. We focused on Sustainable Development Goals (SDGs) related to the "Planet" aspect (covering SDGs 6–7 and 13–15), which is one of five groups dividing the SDGs into

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Table 1
Variables included in the study.

Variable	Description
sdg_07_10	primary energy consumption
sdg_07_11*	final energy consumption
sdg_07_20	final energy consumption in households per capita
sdg_07_30	energy productivity
sdg_07_40*	share of renewable energy in gross final energy consumption by sector
sdg_07_50	energy import dependency
sdg_13_10	net greenhouse gas emissions
sdg_13_21*	net greenhouse gas emissions of the land use

*Not included in the composite indicator.
Source: Eurostat dedicated section on SDGs.

Table 2
Convergence/divergence types in the EU in 2004–2021.

Variable	$\nabla\mu_{EU}$	$\Delta_{t,t-1}\sigma^2$	Convergence/divergence type	Assessment
sdg_07_10*	−0.12	−0.04	Weak upward convergence	Positive
sdg_07_11*	−0.07	−0.02	Weak upward convergence	Positive
sdg_07_20*	−0.03	−0.15	Weak upward convergence	Positive
sdg_07_30	0.50	0.19	Weak upward divergence	Negative
sdg_07_40	0.99	−0.44	Weak upward convergence	Positive
sdg_07_50*	−0.03	−0.26	Weak upward convergence	Positive
sdg_13_10*	−0.24	−0.19	Weak upward convergence	Positive
sdg_13_21*	1.66	2.30	Weak upward divergence	Negative
CI	0.16	−2.94	Weak upward convergence	Positive

* Destimulants.
Source: Author's investigation

thematically similar sets, so-called 5P: people, planet, prosperity, peace and partnership (Agenda, 2015). After analysing the data in the Eurostat database, we chose SDG 7 and SDG 13 due to the availability of indicators related to goals in the "Planet" section. Moreover, this topic was raised due to the strong impact of the Planet goals on the implementation of other SDGs (Kuc-Czarnecka et al., 2023).

The analysis was carried out in two ways - first, we examined the convergence trends individually for each variable, and then a composite indicator was created from all the variables determining the degree of implementation of the sustainable development goals in terms of "planet".

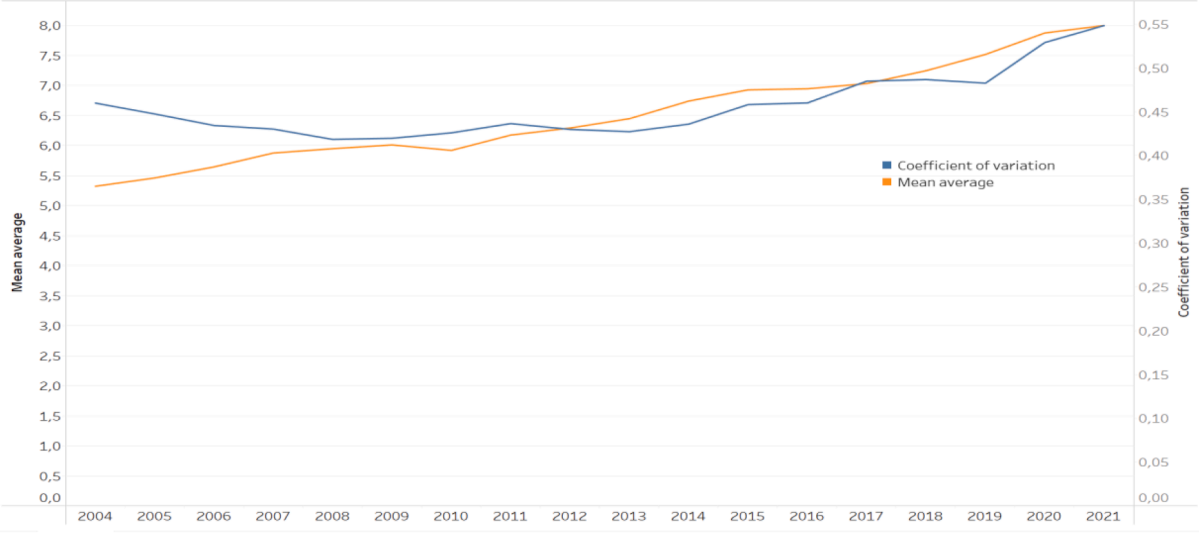
The formation of convergence/divergence trends was also tested for this second option. Our paper addresses a research gap, as to the best of our knowledge, analyses of the trajectories towards achieving specific goals in this context have not been undertaken so far. Our contribution to the literature is both methodological and empirical. From a methodological perspective, we propose an innovative approach to convergence estimation based on upward convergence. The proposed technique offers a dual advantage: it elucidates the convergence/divergence phenomenon among the analysed entities while also facilitating the description of the developmental trajectory for each country. From an empirical perspective, we examined the existence of convergence/divergence in EU countries regarding sustainable development concerning the Planet SDGs. This is an important area relating to the rational use of natural environmental resources and actions on climate change, which translates into achieving a better quality of life.

The article's structure is as follows: a literature review indicating the importance of convergence in achieving Sustainable Development Goals was performed. Then, upward convergence is described along with 12 corresponding scenarios. The following section presents the results of the empirical analysis. The article ends with conclusions.

2. Literature review

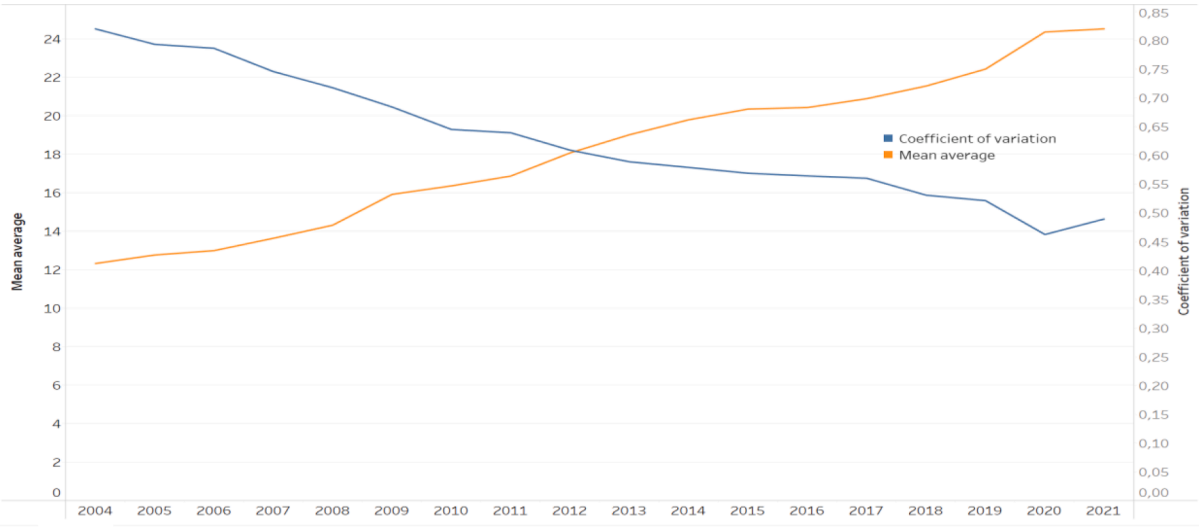
The consequence of the global financial and economic crisis that began in 2008 in the United States was the deterioration of living conditions of inhabitants of European Union countries, a reduction in the level of employment and the volume of gross domestic product. After fifteen years, the economies of EU countries have returned to more stable levels. Unfortunately, the COVID-19 pandemic and ongoing armed conflicts are not helping to maintain them. Moreover, the economic recovery is unevenly distributed across EU society and regions, and one of the adverse effects of the crisis is the widening differences in social and economic performance between Member States. Thus, one of the aims of the 1957 Treaty of Rome was to reduce the discrepancies between regions. Interest in the economic convergence of EU countries is related to the implementation of European cohesion policy. It has always been at the forefront of European political discourse, enjoying great interest. The term convergence has recently gained importance, with ample emphasis on studying economic and social convergence (Eurofound, 2018).

Given global population growth and rapid climate warming, it seems necessary to explore convergence concerning sustainable development



Source: Author's investigation

Fig. 1. Upward divergence on the example of the development of the sdg_07_30 variable. Source: Author's investigation.



Source: Author's investigation

Fig. 2. Upward convergence on the example of the development of the sdg_07_40 variable. Source: Author's investigation.

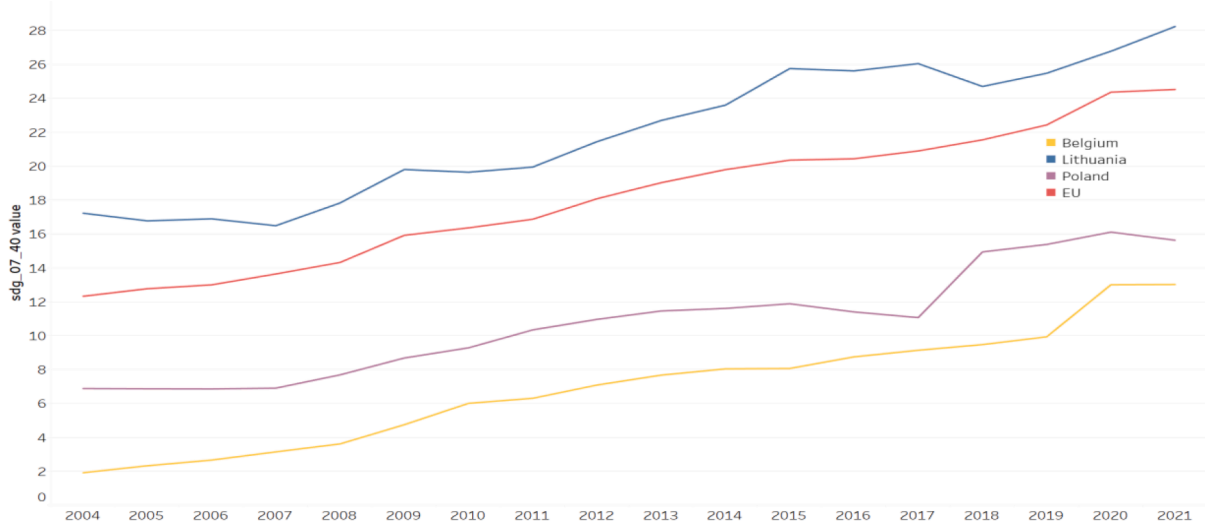
Table 3
Trajectories of change in individual EU countries.

Country	sdg_07_10*	sdg_07_11*	sdg_07_20*	sdg_07_30	sdg_07_40	sdg_07_50*	sdg_13_10*	sdg_13_21*	CI
Belgium	flattening	flattening	catching up	slower pace	catching up	catching up	catching up	catching up	flattening
Bulgaria	inversion	inversion	inversion	outperforming	flattening	catching up	inversion	catching up	catching up
Czechia	flattening	flattening	inversion	outperforming	catching up	inversion	flattening	catching up	inversion
Denmark	catching up	catching up	catching up	slower pace	catching up	catching up	catching up	catching up	catching up
Germany	catching up	flattening	catching up	slower pace	catching up	inversion	catching up	catching up	flattening
Estonia	catching up	flattening	inversion	outperforming	catching up	catching up	inversion	catching up	catching up
Ireland	flattening	flattening	catching up	outperforming	catching up	catching up	catching up	inversion	catching up
Greece	catching up	catching up	catching up	slower pace	catching up	inversion	catching up	inversion	inversion
Spain	catching up	catching up	catching up	slower pace	catching up	catching up	catching up	flattening	catching up
France	catching up	catching up	catching up	slower pace	catching up	catching up	catching up	catching up	catching up
Croatia	flattening	flattening	flattening	slower pace	flattening	inversion	flattening	flattening	catching up
Italy	catching up	catching up	flattening	slower pace	catching up	catching up	catching up	flattening	catching up
Cyprus	flattening	flattening	inversion	slower pace	catching up	catching up	catching up	inversion	inversion
Latvia	inversion	inversion	flattening	slower pace	flattening	catching up	inversion	catching up	catching up
Lithuania	catching up	inversion	inversion	outperforming	flattening	inversion	inversion	inversion	inversion
Luxembourg	flattening	catching up	catching up	outperforming	catching up	catching up	catching up	flattening	catching up
Hungary	inversion	inversion	inversion	slower pace	catching up	catching up	flattening	inversion	flattening
Malta	flattening	inversion	inversion	slower pace	catching up	flattening	catching up	catching up	inversion
Netherlands	catching up	catching up	catching up	slower pace	catching up	inversion	catching up	flattening	inversion
Austria	flattening	inversion	inversion	slower pace	flattening	catching up	flattening	catching up	catching up
Poland	inversion	inversion	inversion	outperforming	catching up	inversion	inversion	catching up	inversion
Portugal	catching up	catching up	catching up	slower pace	flattening	catching up	catching up	inversion	flattening
Romania	flattening	inversion	inversion	outperforming	flattening	inversion	catching up	inversion	catching up
Slovenia	flattening	flattening	catching up	outperforming	flattening	catching up	flattening	catching up	catching up
Slovakia	flattening	inversion	inversion	outperforming	catching up	catching up	flattening	flattening	catching up
Finland	catching up	flattening	inversion	slower pace	flattening	catching up	flattening	catching up	catching up
Sweden	catching up	catching up	catching up	outperforming	flattening	catching up	catching up	flattening	catching up

* Destimulants – interpretation was revered.
Source: Author's investigation

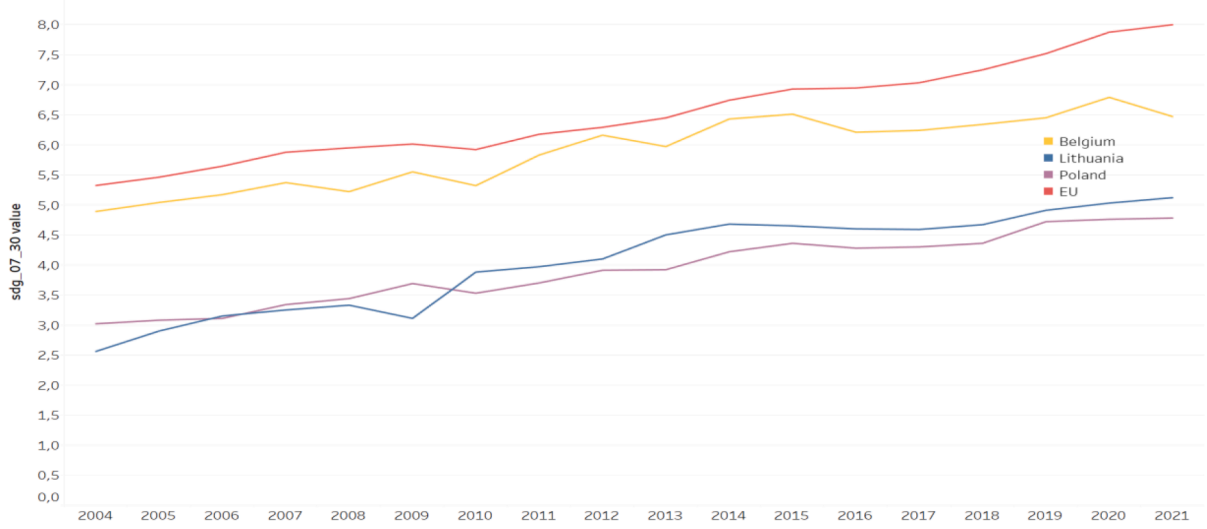
as reflected in the seventeen SDGs. While numerous publications have delved into economic convergence, there remains a need for more literature addressing the measurement and assessment of convergence concerning the realisation of SDGs. Upon the term "convergence" into the WoS search engine, an extensive body of over 460,000 results emerges. Focusing on *'economic convergence'* explicitly refines the search to around 14.5 thousand results. In contrast, the exploration of *'convergence and sustainability'* yields a more selective pool, with just over 1.5 thousand results and about 1.2 thousand articles from 2019 to 2023.

A vital aspect emphasised in the literature is the multifaceted nature of sustainable development, whose understanding depends on contextual frameworks. Turturean et al. (2022) also draw attention to works in the WoS database related to convergence and sustainable development, grouping them into four sections: Green Sustainable Science and Technology, Environmental Studies, Economics, and Development Studies. In their work, convergence in sustainable development is assessed using a composite sustainability index developed for the 27 EU countries and based on the values of the Index of Sustainable Development of EU Countries' Economies (ISDE-EU). Their study's primary objective is to test two hypotheses empirically: first, that there exists convergence in sustainability across the EU 27 countries, and second, that distinct trajectories of sustainability dynamics within the EU 27 nations can be categorised into homogeneous clusters. The



Source: Author's investigation

Fig. 3. Upward convergence scenario for variable sdg_07_40. Source: Author's investigation.



Source: Author's investigation

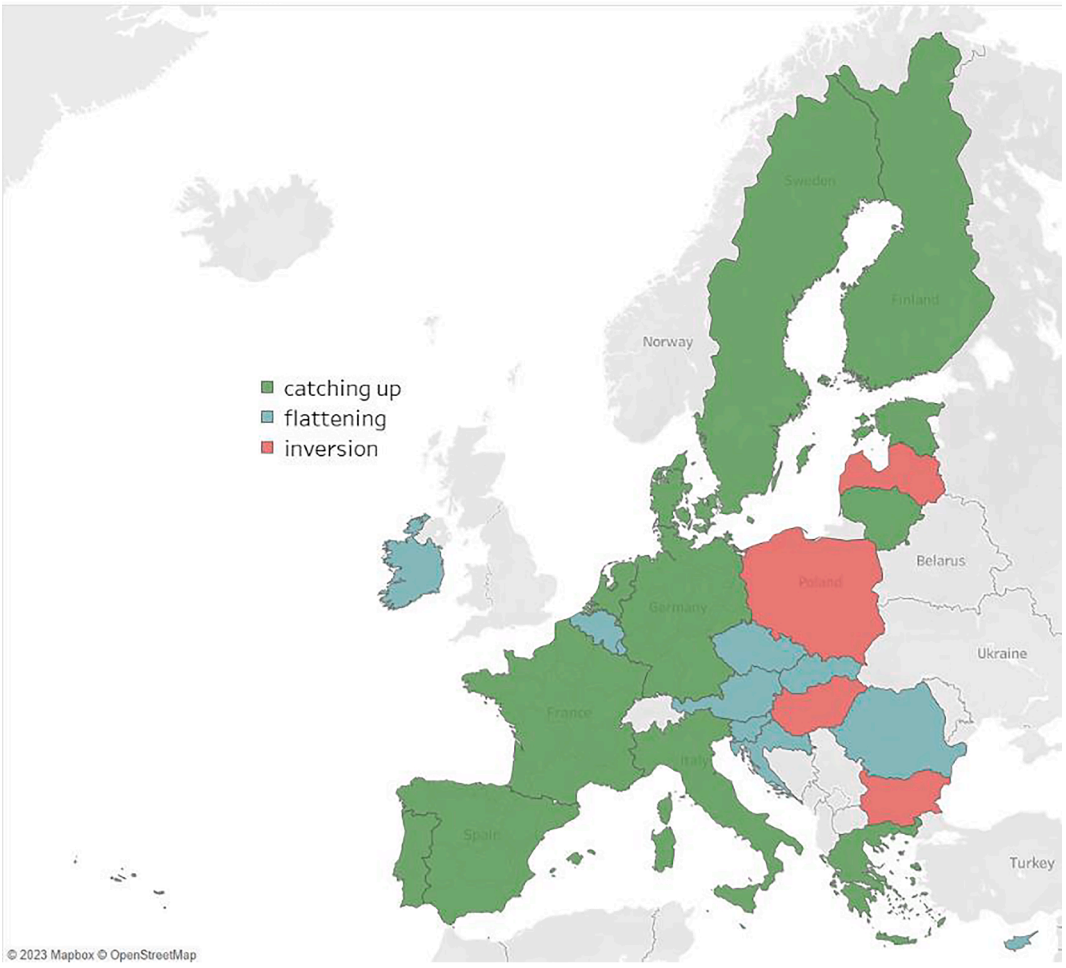
Fig. 4. Upward divergence scenario for variable sdg_07_30. Source: Author's investigation.

authors use the Hierarchical Cluster Method to achieve the goal and confirm the simultaneous existence of beta and sigma convergence in sustainable development.

Another example of assessing the convergence of variables consistent with the sustainable development goals of OECD countries is illustrated in the research of Megyesiova and Lieskovska (2018). The study's main aim was to understand the state and dynamics of variables related to the sustainable development goals of OECD countries. The work examined the countries' convergence, considering variables such as GDP per capita, per capita health expenditure and life expectancy at birth, which are part of the sustainable development goals. Several economic and health-related variables were also used, and five country classes were obtained.

The convergence of countries in terms of selected SDGs was investigated by Pereira et al. (2021). The authors proposed an approach to estimate convergence in performance assessments based on composite indicators. The study covered World Health Organization (WHO) member states to examine their convergence on SDG3 - Good Health and Well-being in 2016–2020. The study indicates partial beta convergence for two out of six WHO regions (Americas and the Eastern Mediterranean Regions) and no beta convergence for Southeast Asia and African Regions.

As mentioned earlier, in most cases, the convergence hypothesis was verified mainly through GDP per capita. However, over time, the issue of convergence was developed about other phenomena, including well-being, considering its four dimensions: economic, social, environmental and governance—an example of such a study paper by Boumahdi and Zaoujal (2023). The authors investigated the convergence of 389 regions in 36 countries based on the Synthetic Index of Well-Being data between 2000 and 2019. Beta convergence was assessed using the Environmental Synthetic Index (EnvSI). The findings revealed the absence of territorial convergence, observed solely within the domain of environmental indicators. Jianu et al. (2021) examined the convergence of EU countries regarding labour market inequalities, reflected in



Source: Author's investigation

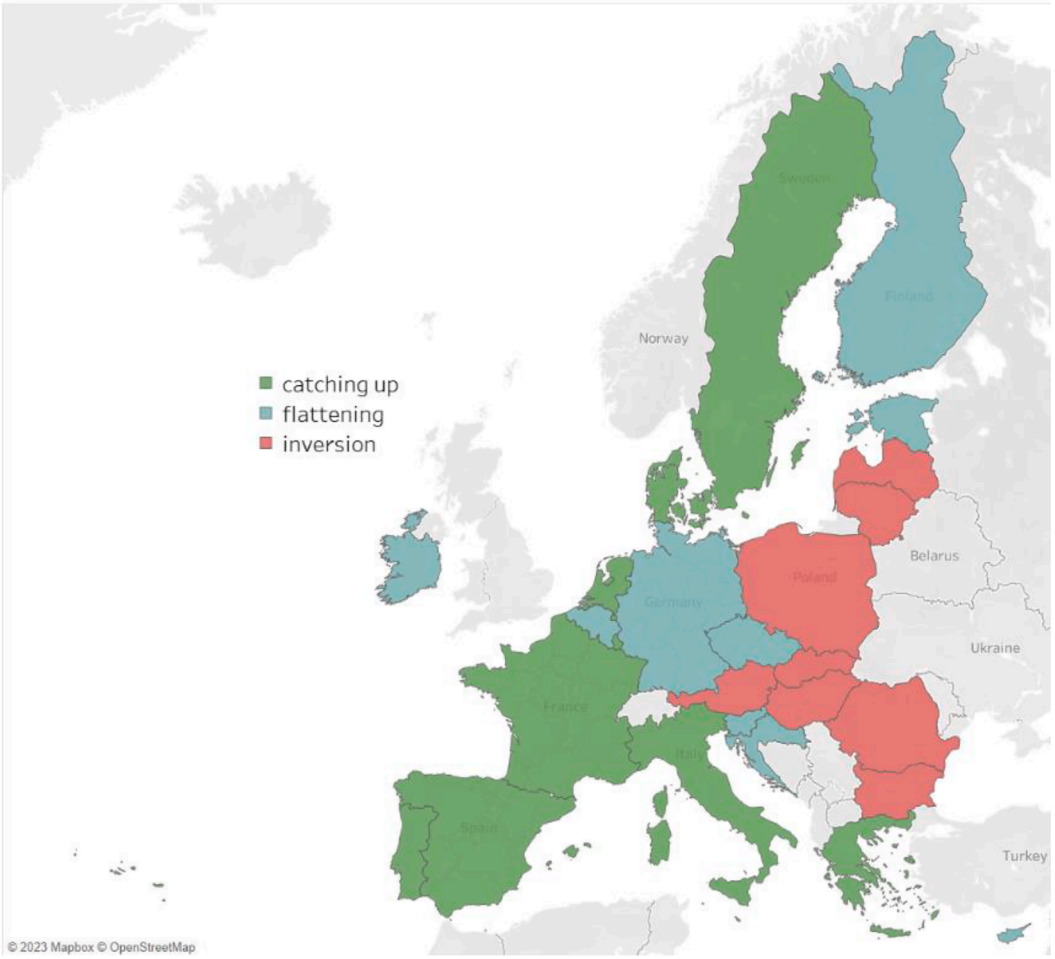
Fig. 5. Trajectories of changes for variable sdg_07_10. Source: Author's investigation.

specific indicators proposed for SDG8. Their analysis showed encouraging results from the perspective of convergence in the EU labour market but also revealed several variable effects that manifested themselves in regional inequalities.

In the study by Juknys et al. (2017), the general discussion on the sustainability of growth and convergence in different regions is focused on economic and environmental sustainability and the consequences of countries' convergence in different regions. The authors emphasise the need for a holistic approach to effectively analyse economic growth and sustainable development. The analysis, which uses the absolute β-convergence approach, enriches studying the economic convergence process in various regions in different periods, from the post-war period to the economic crisis. Three regions of developing countries were selected for the study: Southeast Asia, excluding Japan (13 countries), Latin America (17 countries), and Sub-Saharan Africa (27 countries). Countries are divided into two groups: developing countries and developed countries. Three approaches were used to assess the impact of economic convergence on the environment: decoupling process, intensity coefficients and catch-up rate. The results show that the direction and pace of economic convergence between countries in different regions largely depend on the stage of their development. Research also indicates that economic growth has been decoupling from environmental impact in the developed (EU-15) countries over the past few decades. Moreover, the authors point out that as the economy catches up, there is an upsurge in energy consumption and carbon dioxide emissions.

Recent research on convergence concerning energy and environmental economics mainly focuses on the effects and causes of energy poverty (Ballesteros-Arjona et al., 2022; Neacsa et al., 2020). Anastasiou and Zaroutieri (2023) examine the dynamic patterns of energy poverty across 27 EU member states between 2005 and 2020 using the log-t regression test and analyse the convergence of countries in terms of energy poverty based on the dataset from the EU Statistics on Income and Living Conditions (EU-SILC). The issue of convergence in energy intensity of GDP was highlighted in the article by Bello and Ch'ng (2022). Lee et al. (2023) analysed the convergence of carbon dioxide emissions per capita for 30 OECD countries from 1960 to 2018. Research by Bigerna et al. (2021) is another example of work that examines the convergence of renewable energy sources in countries worldwide.

The convergence of countries may be influenced by the interplay of digitalisation and sustainable development towards implementing the SDGs (Castro et al., 2021). Digitalisation, extensive data sets, and artificial intelligence (Bigerna et al., 2021) may affect the implementation of the 2030 Agenda. According to Castro et al. (2021), sustainable development and digitalisation are the main trends shaping the economy and society. The data-driven economy and knowledge society can accelerate sustainable development. The connection between both domains points to unique but untapped opportunities to support the transformation towards sustainable development (Osburg and Lohrmann, 2017).



Source: Author's investigation

Fig. 6. Trajectories of changes for variable sdg_07_11. Source: Author's investigation.

Many studies point to the SDGs' unequal implementation level and the different paces of their implementation (D'Adamo et al., 2021). In the work of Anselmi et al., 2023, the authors examined 27 EU countries in 2018–2020. Employing Multicriteria Decision Analysis (MCDA) with 58 indicators, the study discerned notable differentials in developmental levels and observed shifts in the rankings of countries throughout the period under study. Andrew-Nielsen (2023) emphasises that pursuing sustainability in infrastructure development is crucial because it can positively and negatively impact the environment.

3. Methods and data

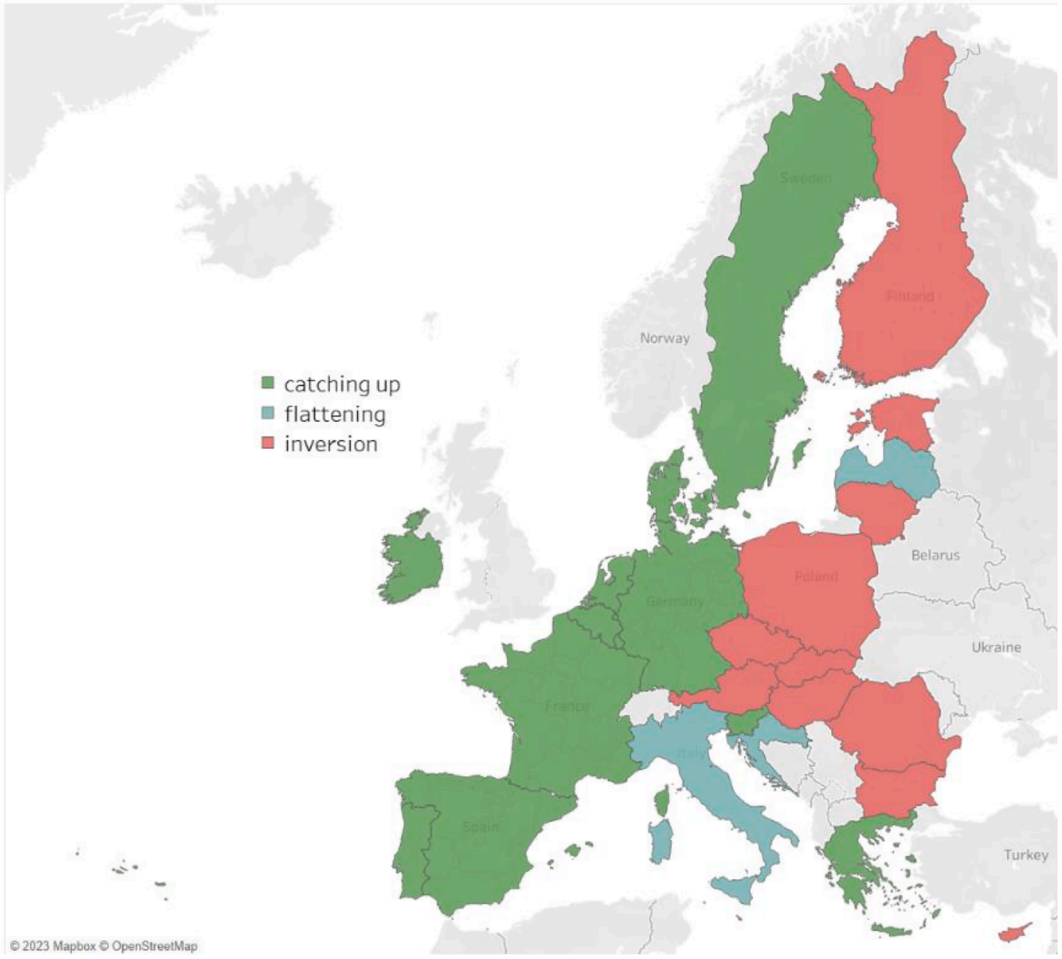
There is extensive literature on methods for measuring the convergence of various economic phenomena. The most common ones include conditional and unconditional beta (Solow, 1956) and sigma convergence (Sala-i-Martin, 1996). Gamma (Boyle and McCarthy, 1997), delta (Heichel et al., 2005) and club convergence (Galor, 1996) are used relatively less frequently. The concept of upward convergence proposed by Eurofound (2018) is even less prevalent in scholarly usage. The latter was employed in this research paper. We consider this methodology highly advantageous, as it not only elucidates the existence of convergence/divergence among analysed entities but also facilitates the description of the developmental trajectory for each country. Consequently, it provides an avenue for assessing the likelihood of future convergence. Additionally, this method enables the differentiation between convergence resulting from the progress of all nations (upward convergence) and the occurrence of convergence stemming from the deterioration of situations in those formerly progressing positively (downward convergence) — an undesirable outcome.

In Eurofound's (2018) study, we can read that *"Upward convergence means 'to move closer together upward', and it is the union of two concepts: growth, or improvement in performance and outcomes towards a policy target"*. So, as mentioned earlier, it is possible to assess the convergence of the analysed phenomenon and check whether there is visible progress in achieving it. Measurement and evaluation according to the proposed methodology (Eurofound, 2018) are based on a comparison of trends in the development of the average level of the phenomenon in the entire analysed group (in our case, the European Union) and trends in the development of the phenomenon in each of the studied countries, as well as trends in the degree of differentiation of the phenomenon (expressed as a coefficient of variation). The following situations can, therefore, be distinguished (Eurofound, 2018):

1. Upward convergence in the weak sense

$$\begin{cases} g(X_t) < g(X_{t-i}) \\ \mu(X(t)) \geq \mu(X(t-i)) \end{cases} \quad (1)$$

where: $g(X)$ – function of dispersion in period t and t-i, respectively; $\mu(X)$ – the average value of variable X in period t and t-i, respectively; $t = 1, \cdots, k$ – time, i – integer $0 \leq i \leq k$.



Source: Author's investigation

Fig. 7. Trajectories of changes for variable sdg_07_20. Source: Author's investigation.

2. Upward convergence in the strict sense

$$\begin{cases} g(X_t) < g(X_{t-i}) \\ X(t,j) \geq X(t-i,j)\,\forall j = 1,\cdots,n \end{cases} \quad (2)$$

where: $j = 1,\cdots,n$ – analysed entities.

3. Downward convergence in the weak sense

$$\begin{cases} g(X_t) < g(X_{t-i}) \\ \mu(X(t)) < \mu(X(t-i)) \end{cases} \quad (3)$$

4. Downward convergence in the strict sense

$$\begin{cases} g(X_t) < g(X_{t-i}) \\ X(t,j) < X(t-i,j)\,\forall j = 1,\cdots,n \end{cases} \quad (4)$$

5. Upward divergence in the weak sense

$$\begin{cases} g(X_t) \geq g(X_{t-i}) \\ \mu(X(t)) \geq \mu(X(t-i)) \end{cases} \quad (5)$$

6. Upward divergence in the strict sense

$$\begin{cases} g(X_t) \geq g(X_{t-i}) \\ X(t,j) \geq X(t-i,j)\,\forall j = 1,\cdots,n \end{cases} \quad (6)$$

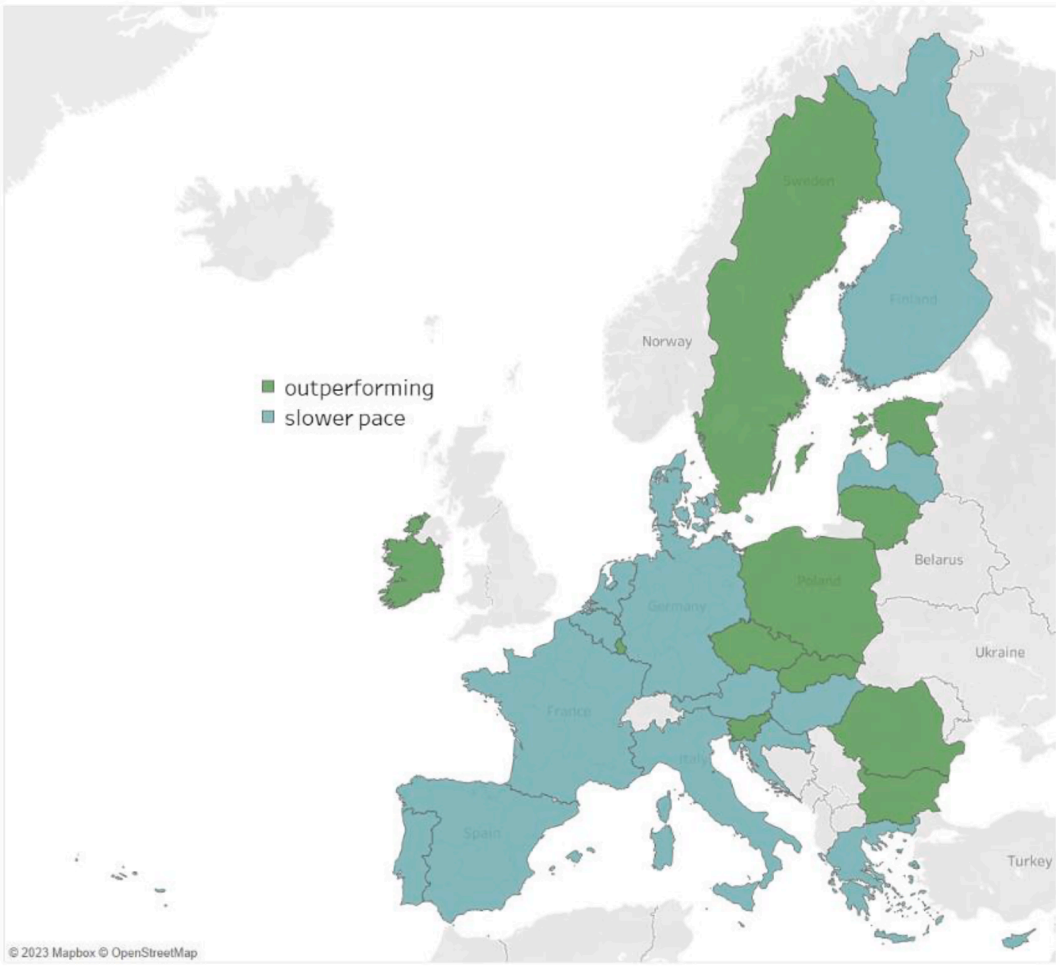
7. Downward divergence in the weak sense

$$\begin{cases} g(X_t) \geq g(X_{t-i}) \\ \mu(X(t)) < \mu(X(t-i)) \end{cases} \quad (7)$$

8. Downward divergence in the strict sense

$$\begin{cases} g(X_t) \geq g(X_{t-i}) \\ X(t,j) < X(t-i,j)\,\forall j = 1,\cdots,n \end{cases} \quad (8)$$

These scenarios relate to variables that act as stimulants, and for destimulants, their direction needs to be reversed (lowering the average is desired an perceived as upward change). A stimulant is a variable in which higher values are favourable concerning the analysed phenomenon (e.g., the proportion of energy from renewable sources), whereas a destimulant is a variable in which lower values are preferable regarding the analysed phenomenon (e.g., greenhouse gas emissions). Moreover, for each analysed object, one of twelve development trajectories can be



Source: Author's investigation

Fig. 8. Trajectories of changes for variable sdg_07_30. Source: Author's investigation.

determined (Eurofound, 2018):

- Catching up

$$\nabla\mu_{EU} > 0; \nabla\mu_{EU} < \nabla f_{MS}; \nabla f_{MS} > 0; \Delta_{t,t-1}\sigma^2 < 0 \quad (9)$$

where: $\nabla\mu_{EU}$ – the gradient of the EU average, ∇f_{MS} – the gradient of the trend of the Member State, $\Delta_{t,t-1}\sigma^2$ – change in the value of the differentiation measure between the analysed objects (in our case, coefficient of variation).

- Flattening

$$\nabla\mu_{EU} > 0; \nabla\mu_{EU} > \nabla f_{MS}; \nabla f_{MS} > 0; \Delta_{t,t-1}\sigma^2 < 0 \quad (10)$$

- Inversion

$$\nabla\mu_{EU} > 0; \nabla\mu_{EU} > \nabla f_{MS}; \nabla f_{MS} < 0; \Delta_{t,t-1}\sigma^2 < 0 \quad (11)$$

- Underperforming

$$\nabla\mu_{EU} < 0; \nabla\mu_{EU} > \nabla f_{MS}; \nabla f_{MS} < 0; \Delta_{t,t-1}\sigma^2 < 0 \quad (12)$$

- Recovering

$$\nabla\mu_{EU} < 0; \nabla\mu_{EU} < \nabla f_{MS}; \nabla f_{MS} > 0; \Delta_{t,t-1}\sigma^2 < 0 \quad (13)$$

- Reacting better

$$\nabla\mu_{EU} < 0; \nabla\mu_{EU} < \nabla f_{MS}; \nabla f_{MS} < 0; \Delta_{t,t-1}\sigma^2 < 0 \quad (14)$$

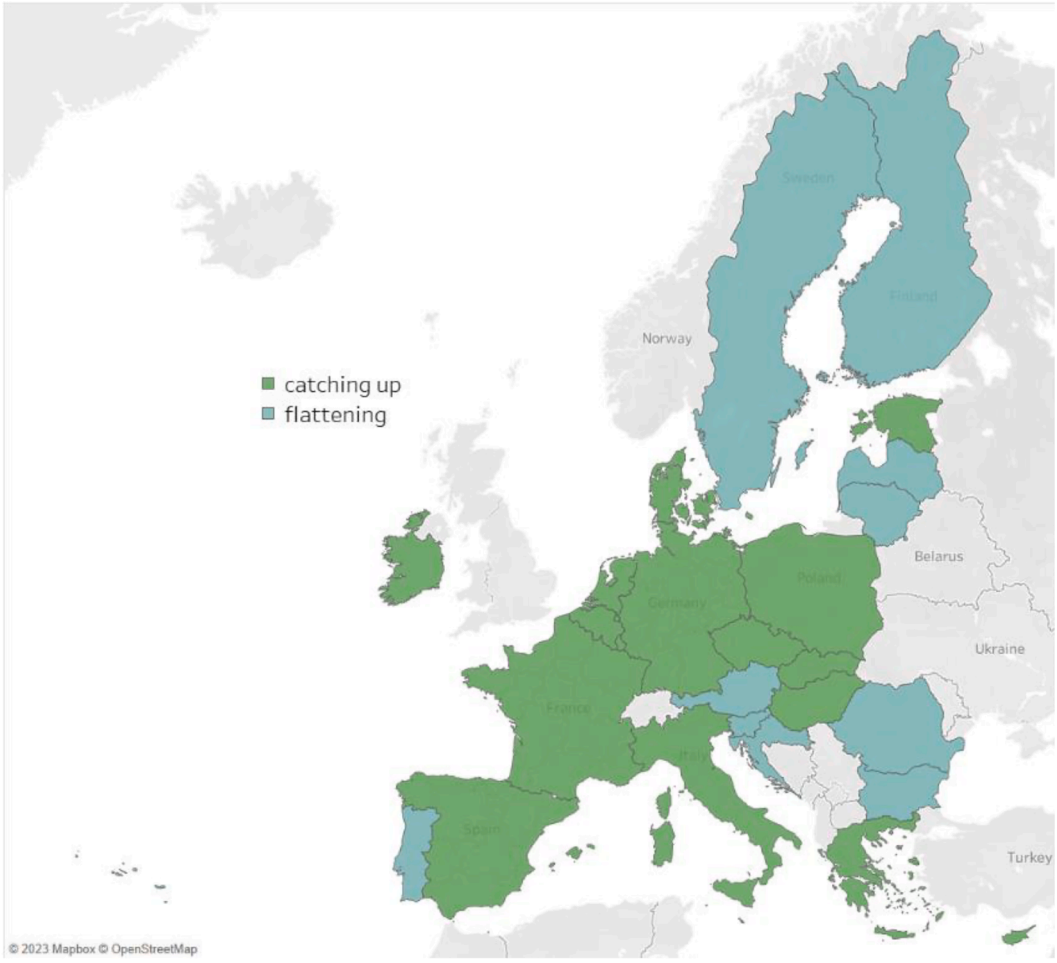
- Outperforming

$$\nabla\mu_{EU} > 0; \nabla\mu_{EU} < \nabla f_{MS}; \nabla f_{MS} > 0; \Delta_{t,t-1}\sigma^2 > 0 \quad (15)$$

- Slower pace

$$\nabla\mu_{EU} > 0; \nabla\mu_{EU} > \nabla f_{MS}; \nabla f_{MS} > 0; \Delta_{t,t-1}\sigma^2 > 0 \quad (16)$$

- Diving



Source: Author's investigation

Fig. 9. Trajectories of changes for variable sdg_07_40. Source: Author's investigation.

$$\nabla\mu_{EU} > 0; \nabla\mu_{EU} > \nabla f_{MS}; \nabla f_{MS} < 0; \Delta_{t,t-1}\sigma^2 > 0 \quad (17)$$

- Defending better

$$\nabla\mu_{EU} < 0; \nabla\mu_{EU} < \nabla f_{MS}; \nabla f_{MS} < 0; \Delta_{t,t-1}\sigma^2 > 0 \quad (18)$$

- Escaping

$$\nabla\mu_{EU} < 0; \nabla\mu_{EU} < \nabla f_{MS}; \nabla f_{MS} > 0; \Delta_{t,t-1}\sigma^2 > 0 \quad (19)$$

- Falling away

$$\nabla\mu_{EU} < 0; \nabla\mu_{EU} > \nabla f_{MS}; \nabla f_{MS} < 0; \Delta_{t,t-1}\sigma^2 > 0 \quad (20)$$

The analysis was conducted based on a composite indicator calculating following the procedure outlined, among others, in Kuc-Czarnecka et al. (2023) and estimated using compindexR package (Aydin et al., 2023). While detailed information about this process is available in the referenced sources, briefly, it entails the following steps:

1. Calculation of the first version of the composite indicator containing the whole set of diagnostic variables:

$$y_j = \sum_{i=1}^{d} w_i x_{ji}, \qquad j = 1, 2, \cdots, d; i = 1, 2, \cdots, n, \quad (21)$$

where: y_j – the value of the composite indicator for the j-th object, x_{ji}– the max–min normalised value of the i-th variable in the j-th object (Mazziotta & Pareto, 2021), w_i – the weight assigned by CI's creator to the i-th variable.

2. Evaluation of the compliance of the assigned weights with the actual significance of the variables using tools derived from sensitivity analysis:

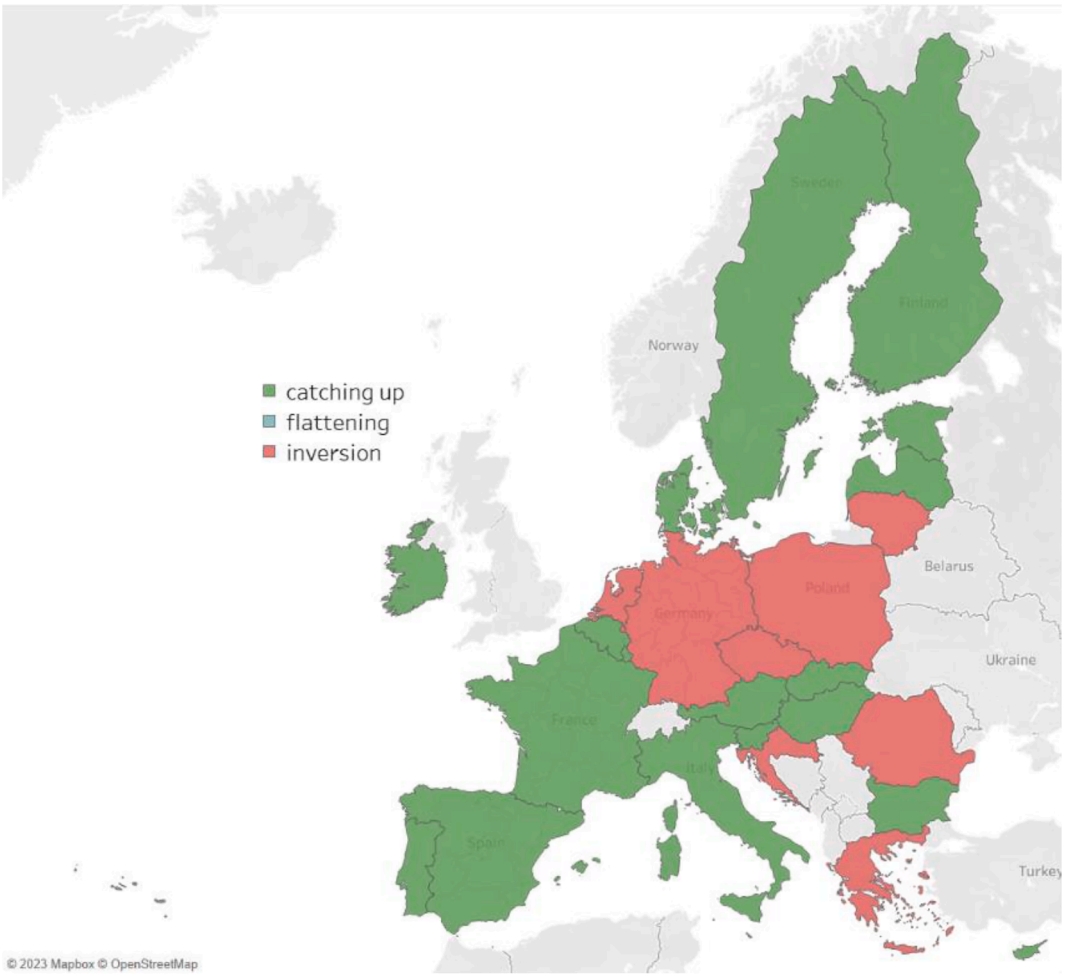
a. Computation of first-order sensitivity index (Saltelli et al., 2000; Saisana et al., 2005; Paruolo et al., 2013):

$$S_i \equiv \eta_i^2 = \frac{V_{x_i}(E_{x\ i}(y|x_i))}{V(y)} \quad (22)$$

where: S_i – first-order sensitivity measure, $S_i \in [0,1]$, $x_{\ i}$– vector containing all variables but x_i, $E_{x\ i}(y|x_i)$ – expected value of y at a given value of x_i with the expectation taken over $x_{\ i}$, $V(y)$ – unconditional variance of y.

b. Computation of uncorrelated contribution by performing the multivariate linear regression of x_i on $x_{\ i}$ and finding the residuals (Harezlak et al., 2018):

$$\widehat{z_i} = x_i - \widehat{x_i} = x_i - \left(\beta_0 + \sum_{l \neq i}^{d} \widehat{\beta}_l x_i\right) \quad (23)$$



Source: Author's investigation

Fig. 10. Trajectories of changes for variable sdg_07_50. Source: Author's investigation.

where: $\widehat{z}_i$ – residuals of a regression of x_i on $x_{\ i}$, β_0 – y-intercept from multivariate linear regression, β_l– coefficient from multivariate linear regression.

$$S_i^u = \frac{\sum_{j=1}^{n}\left(\widehat{y}_j^{(\ i)} - \underline{y}^{(\ i)}\right)^2}{\sum_{j=1}^{n}\left(y_j - \underline{y}\right)^2} \tag{24}$$

where: S_i^u – uncorrelated contribution. $\widehat{y}_j^{(\ i)}$ – non-linear regression fitted values, $\underline{y}^{(\ i)}$ – average value of $\widehat{y}_j^{(\ i)}$, y_j – composite indicator value in the j-th object, $\underline{y}$ – average value of y_j. S_i^u is the unique variability that can only be explained by x_i variable.

c. Computation of correlated contribution:

$$S_i^c = S_i - S_i^u \tag{25}$$

where: S_i^c – correlated contribution, i.e. the information load carried by x_i variable resulting from its correlation with other variables.

3 wt optimisation (Becker et al., 2017) using the Nelder–Mead simplex method (Nelder and Mead, 1965):

$$w_{opt} = argmin_w \sum_{i=1}^{d}\left(\widetilde{S}_i^* - \widetilde{S}_i(w)\right)^2 \tag{26}$$

where: $\widetilde{S}_i^*$– target normalised correlation ratio, w – set of initial weights assigned by CI creator, $w = \{w_i\}_{i=1}^d$, $\widetilde{S}_i$ – normalised correlation ratio of x_i.

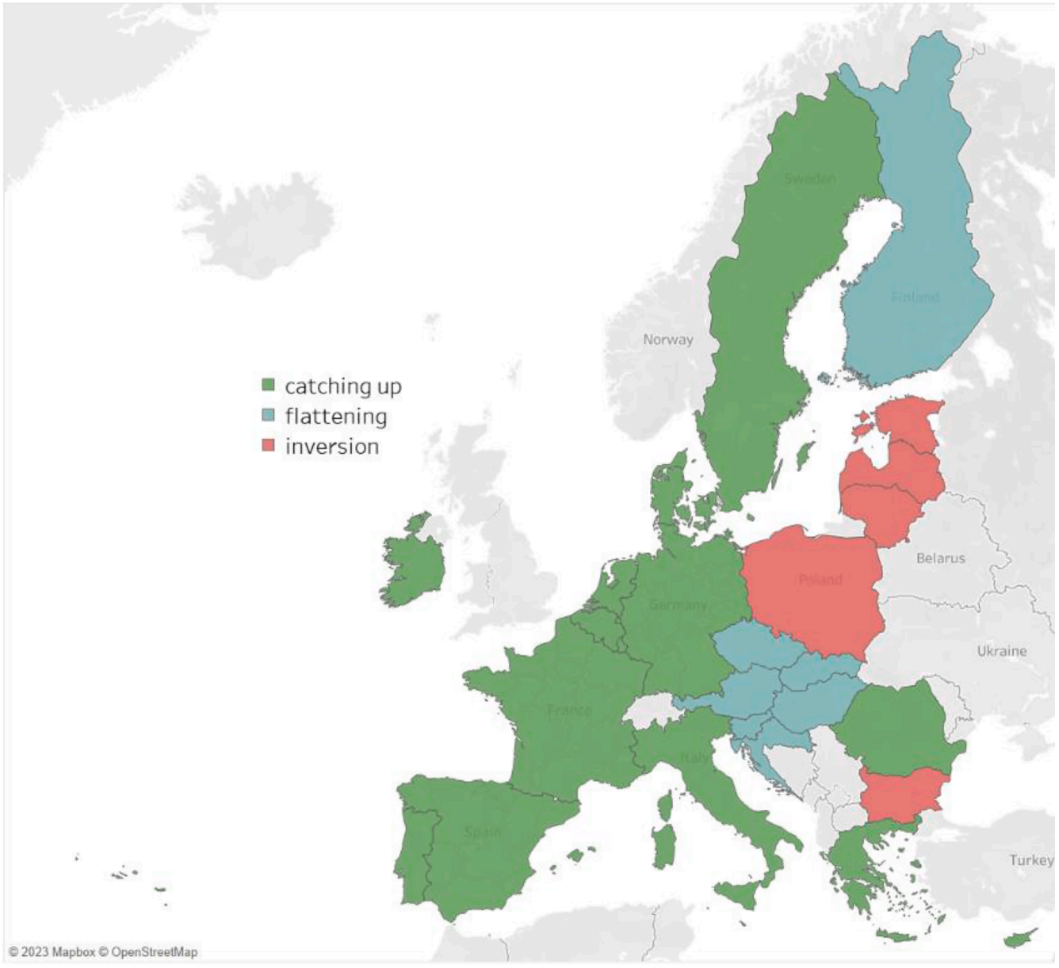
When correlations are excessively high, achieving the importance of variables consistent with the creators' assumptions becomes challenging. In such cases, we suggest utilising the Variance Inflation Factor (VIF to reduce the dataset by eliminating the most strongly correlated variable (Mansfield and Helms, 1982):

$$VIF_i = \frac{1}{1 - R_i^2} \tag{27}$$

Where: VIF_i – variance inflation factor for i-th variable, R_i^2 - the unadjusted coefficient of determination for regressing the i-th independent variable on the remaining ones.

Steps (21)-(28) are executed repeatedly until the assigned weights of all diagnostic variables are considered valid based on the variables' relative importance.

The formulas mentioned above (1–20) were used to assess the degree of convergence of the variables included in SDG 7 and SDG 13. Due to substantial data gaps, the analysis did not include the remaining goals in the planet area (6, 14, and 15). The complete set of diagnostic variables used in the study is presented in Table 1. These are also variables used in the initial stage of composite indicator creation. Following a sensitivity analysis, it was discerned that variables sdg_07_11, sdg_07_40, and sdg_13_21 were excluded from the construction of the CI. This exclusion was dictated by their noticeable correlation with other variables,



Source: Author's investigation

Fig. 11. Trajectories of changes for variable sdg_13_10. Source: Author's investigation.

thereby imparting an excessive redundancy level that disallowed the Composite Index (CI) optimisation. The main reason for eliminating the aforementioned variables was their large share of the correlated contribution (S_i^c) in the value of the first-order sensitivity index (S_i), resulting in a high VIF (formula 28). Variables were removed individually, starting with the one with the highest VIF value until a balanced composite indicator with equal importance was attributed to all included variables.

4. Results

Table 2 contains information on what type of convergence/divergence (1–8) occurred in the EU in 2004–2021 for each variable separately and for the composite indicator.

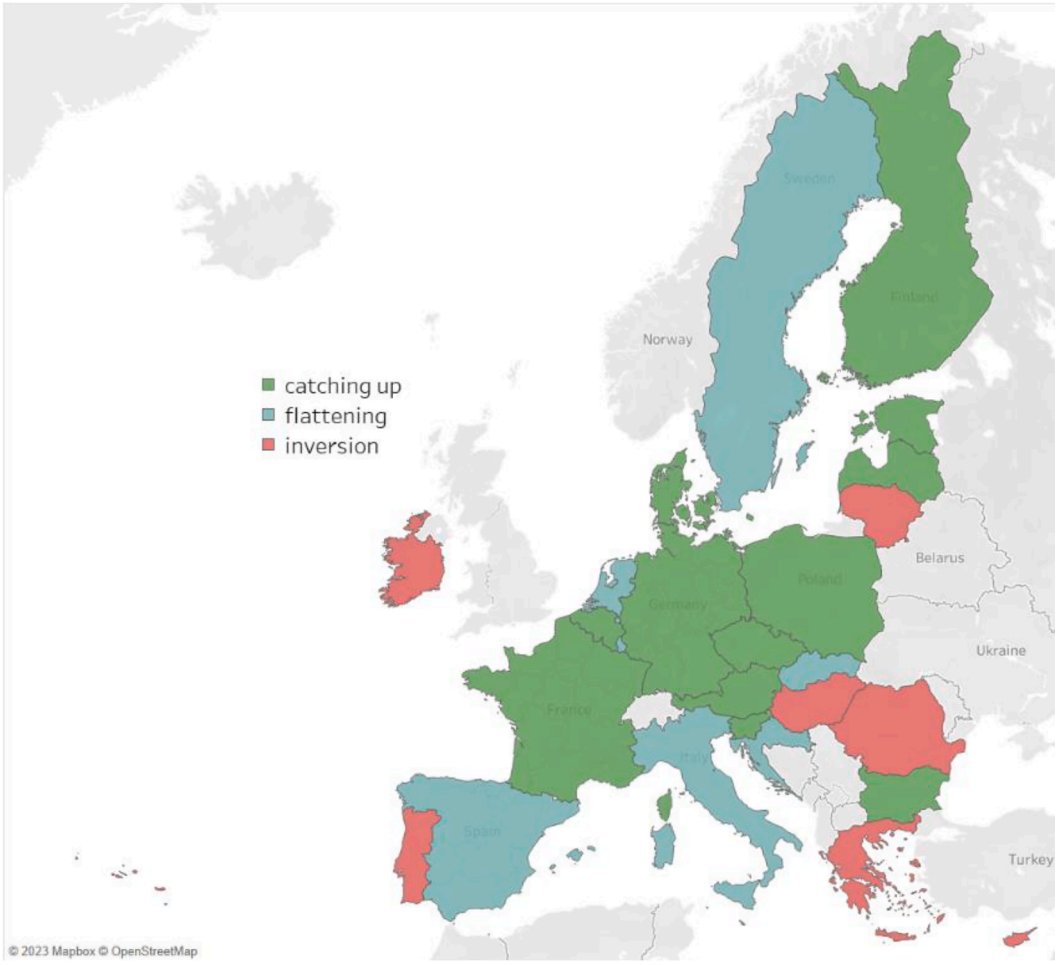
Analysing the data in Table 2, it can be seen that upward convergence and divergence occurred, but each in a weak sense. This means that the changes in the analysed countries did not proceed in the exact directions and that the values of the variables under consideration in some countries decreased/increased while the desired direction would be the opposite.

A visual presentation of individual scenarios is presented in Figs. 1-2. One variable was selected to represent each scenario. The orange curve determines the development of the average value of the analysed phenomenon in the European Union, while the blue curve determines the development of the coefficient of variation. Fig. 1 illustrates upward divergence on the instance of the variable sdg_07_30 (the average and diversity are growing). Fig. 2 is a graphical presentation of upward convergence (the average increases, the differentiation decreases) on the example of the variable sdg_07_40.

The variables sdg_07_10, sdg_07_11, sdg_07_20, sdg_07_50 and sdg_13_10 are destimulants, so the desired direction of change is to reduce their values and, at the same time, diminish differences among countries. According to the information in Table 2, this has been observed. Thus, upward convergence occurred. This upward convergence occurs in a weak sense, i.e. in the case of individual countries, a higher value was recorded in 2021 than in 2004. However, both the EU average and the degree of diversification in the final analysis period were lower than in the base year (2004). Upward convergence was also visible in composite indicator (CI) for implementing planetary sustainable development goals.

The variable sdg_07_40 is a stimulant, so in its case, it is desirable to increase the value while reducing differentiation, i.e., the upward convergence phenomenon. This situation, also in a narrow sense, was observed in 2004–2021 in the EU, which should be considered a positive phenomenon.

Situations opposite to the desired ones were observed in the case of the sdg_07_30 variable (energy productivity), which is a stimulus variable. Rising inequalities were observed, leading to an increase in the average level of the phenomenon. Undesirable trends were also observed for the variable sdg_13_21 (net greenhouse gas emissions of the



Source: Author's investigation

Fig. 12. Trajectories of changes for variable sdg_13_21. Source: Author's investigation.

land use), which also showed increased inequalities between member states.

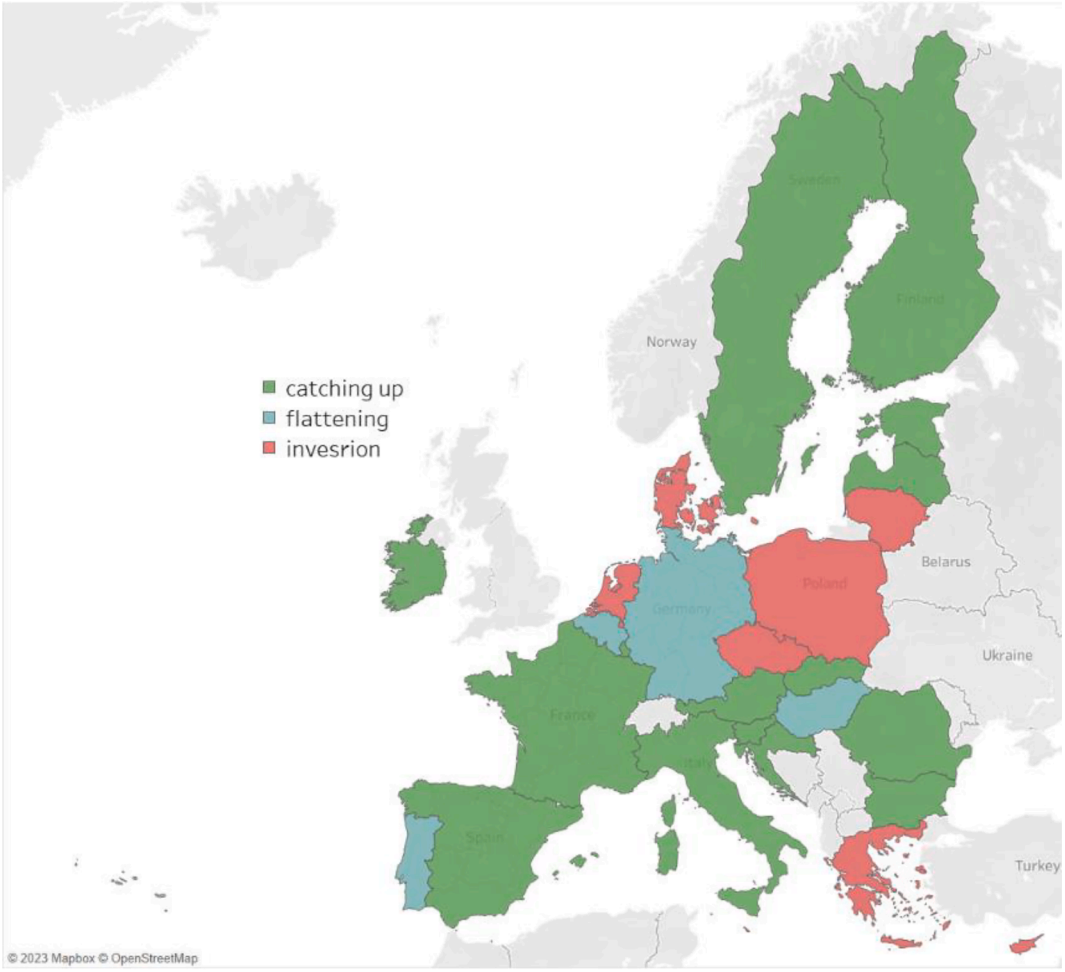
In the next step of the analysis, the development paths of each country were investigated. Table 3 contains the trajectory of changes for each member country following the characteristics included in formulas (9–20). In an upward convergence scenario, three options are possible: catching up, flattening or inversion (9–11). Countries that qualified for the catching-up group are those in which the pace of change was positive and faster than the EU average (see Table 2); those countries in which the pace of change was positive but slower than the EU average were included in the flattening group, and those that recorded a decrease in value over the analysed period were classified as inversion. In the case of the variable sdg_07_40, which represents an upward convergence scenario, Bulgaria, Croatia, Latvia, Lithuania, Austria, Portugal, Romania, Slovenia, Finland and Sweden were classified in the flattening group. The remaining countries were catching up. Inversion did not occur. The trends for selected countries for this variable are presented in Fig. 3—the red curve represents the EU average. The growth rate of the analysed variable in Lithuania (blue curve) was slower than the EU average, hence the country classification as flattening. In the case of Poland (purple curve) and Belgium (yellow curve), the average pace of change was faster than the EU average, hence their classification as catching up.

In the case of upward divergence, three scenarios were possible: outperforming, slower pace and diving (15–17). The variable sdg_07_30 represents this phenomenon, and the visualisation of individual paths is presented in Fig. 4. As in the case of the previous visualisation, the red curve here represents the EU average. Belgium (yellow curve) was defined as a slow pace because the change was slower than the EU average. However, Lithuania (blue curve) and Poland (purple curve) were defined as outperforming because their rate of change was much higher than the EU average. None of the countries was classified as diving, i.e. showing a decrease in the value of the analysed variable over time.

A graphical presentation of the results in Table 3 is provided in choropleth maps in Figs. 5–13. Consistent colour coding was adopted in all visualisations. Intense green colour means improvement in the value of the analysed variable at a much faster pace than the EU average; pale green colour means improvement in the value of the studied phenomenon at a slower pace than the EU average. The red indicates a decrease (increase) in the value of the analysed phenomenon as a stimulant (destimulant).

5. Discussion and conclusion

The literature review reveals that the study of convergence often focuses on assessing countries' economic convergence processes based on GDP per capita as an indicator of the level of economic development and prosperity. In most cases, beta convergence is used for this purpose (Manzi et al., 2023; Desli and Gkoulgkoutsika, 2020). Progressively, researchers are applying convergence analysis in other aspects, such as



Source: Author's investigation

Fig. 13. Trajectories of changes for composite indicator. Source: Author's investigation.

economy, information technology, energy poverty, sustainable development, tourism, and agriculture (Yuan et al., 2021). Convergence in education and training systems is also examined (Camanho et al., 2023; Kim and Lee, 2022). Convergence in tourism and divergence in agriculture are analysed by Zaplata and Hecker (2018). The authors underscore the significance of tourism in sustainable development and agriculture, proposing the preservation and enhancement of agricultural divergence as a means to attain more excellent spatial equilibrium. Thus, the concept of convergence extends to numerous facets of life. Lately, there has been a growing emphasis on sustainable development research, particularly in exploring convergence in pollution indicators, which entails assessing the convergence of different forms of environmental degradation (Tiwari et al., 2021; Lee et al., 2023). Moreover, various convergence methods (beta, sigma, gamma, stochastic, social, spatial, income, technological, sectoral or club convergence) are used in the study of such areas of sustainable development as ecological footprint (Salman et al., 2022), renewable energy sources (Bigerna et al., 2021) or climate change (Porada-Rochoń, 2021). Considering the factors mentioned above and the comprehensive literature review, we believe that our study addresses a significant gap in convergence research, particularly within sustainable development. Our proposition revolves around employing upward convergence in the analysis of Sustainable Development Goals and facilitates the description of each country's developmental trajectory.

The results of our study indicate a favourable situation in the case of six out of eight examined variables. However, for two variables, the differences between countries increased. This research result indicates areas where intensification of activities is necessary in some EU countries: increase of energy productivity and reduction in net greenhouse gas emissions in net greenhouse gas emissions of land use. The literature highlights that the growing global population and agricultural production per capita have increased emissions related to land use. However, our research has shown a positive trend in most EU countries. It is believed that future population and income growth will further increase food demand and complicate efforts to reduce land use emissions (Hong et al., 2021). Raya-Tapia et al. (2024) highlight the relationship between progress in implementing the SDGs and food waste.

The second stage of the study is the analysis of the development paths of individual countries. The countries were divided into groups. The negatively rated groups are "inversion" (decrease in the value of stimulants/increase in the value of destimulants), diving and falling away. The most challenging situation concerns the variable sdg_07_20 (final energy consumption in households per capita). In this case, as many as 12 countries belong to the weak group. The problem is, therefore, to motivate households to reduce energy consumption and replace devices with less energy-consuming ones. Studies in various countries have shown that energy consumption increases with the increase in household wealth (Piao and Managi, 2023). Chen et al. (2023) stress that numerous factors impact household energy consumption patterns, which can vary significantly from one country to another.

However, it turned out that there is no weak group for two variables - sdg_07_30 (energy productivity) and sdg_07_40 (share of renewable energy in gross final energy consumption by sector). Here, we observe the desired paths of development. Among the eight variables in the negative group of countries, Lithuania and Poland were most frequently found (6 times). The highest-rated activities were observed consistently in two countries in the positive group: Denmark and France. These are the leading countries in the EU in terms of caring for the planet. Numerous studies show that in more affluent countries, the choice of economy or ecology is losing importance (Meng et al., 2024), as they are treated equally.

Our research analysed upward convergence regarding the "Planet" goals. Following Eurofound (2018), we define the concept of upward convergence in the sustainable development goals regarding care for the planet as improving the performance of Member States and, at the same time, reducing the differences between them. We believe that the actions of EU countries are heading in the right direction. There is a need to raise awareness among households regarding electricity consumption and the impact of its production on the environment.

We posit that our research holds significant relevance for decision-makers in the EU. It becomes evident that, alongside initiatives targeting alleviating household energy poverty, there is a pressing need for educational campaigns concerning electricity consumption levels. Raising public awareness regarding energy consumption for space heating, water heating, lighting, and other electrical devices is paramount. Educational activities are necessary regarding the energy consumption of individual devices and their energy class. It is still necessary to heighten society's awareness regarding the implications of electricity consumption, extending beyond its financial costs to include its effects on the natural environment and climate change. Decision-makers must look for ways to influence both producers and consumers of electricity. Producers' activities are regulated by legal regulations and by raising awareness of sustainable development. However, awareness and appropriate actions among consumers can be achieved through education.

We want to continue to develop our research. First, we want to examine whether external factors (beyond the SDGs) influence the implementation of environmentally friendly goals. We also ask whether this impact is the same in individual EU countries. Our future research will focus on analysing convergence and divergence trends, also considering other areas of sustainable development and their interdependencies.

CRediT authorship contribution statement

Marta Kuc-Czarnecka: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Iwona Markowicz:** Writing – original draft, Data curation, Conceptualization. **Agnieszka Sompolska-Rzechuła:** Writing – original draft, Data curation, Conceptualization.

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.

Data availability

Data publicly available on the Eurostat website.

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