ISSN 1822-8038 (online)
INTELEKTINĖ EKONOMIKA
INTELLECTUAL ECONOMICS
2025, No. 19(2), p. 11–45

GREEN GROWTH IN THE EU: INNOVATION, INVESTMENT, AND THE PATH TO SUSTAINABILITY

Elvira Böcskei
Department of Finance, Faculty of Economic and Social Sciences, Budapest University of Technology and Economics, Hungary
bocskei.elvira@gtk.bme.hu
https://orcid.org/0000-0002-8312-3908

Adrienn Veit[1]
Department of Finance, Faculty of Economic and Social Sciences, Budapest University of Technology and Economics, Hungary
veit.adrienn@gtk.bme.hu
https://orcid.org/0000-0002-1282-6948

Márk Gyula Tóth
Department of Finance, Faculty of Economic and Social Sciences, Budapest University of Technology and Economics, Hungary
toth.markgyula@gtk.bme.hu
https://orcid.org/0009-0003-0442-3879

DOI:10.13165/IE-25-19-2-01

Abstract

Purpose. The study examines interactions among economic growth, innovation, and environmental sustainability across the EU-27 countries from 2015 to 2022. It aims to evaluate advancement toward United Nations' Sustainable Development Goals.

Design/Methodology/Approach. Using Eurostat data, the analysis employs Pearson correlation coefficients to explore relationships between key economic and environmental variables and applies cluster analysis to EU Member States based on their performance and sustainability profiles.

1 Adrienn Veit (corresponding author)

Findings. Pearson correlations show strong positive links between economic growth and greenhouse gas emissions (0.950 in 2015, declining to 0.945 in 2022), economic growth and energy consumption (0.990 to 0.981), and economic growth and investment in fixed assets (0.996-0.997). Gross domestic expenditure on research and development correlates negatively with emissions (0.909 to 0.886), while energy-greenhouse gas ties remain stable (0.976-0.979).

Cluster analysis identified six heterogeneous groups, ranging from Germany's high research growth and emission reductions to EU Member States in sustainable energy transition to reduce fossil fuel and achieve energy independence.

Originality. The study provides integrated empirical analysis that combines post2015 Eurostat data, Pearson correlations, and Gaussian mixture model cluster analysis to systematically investigate interdependencies between GDP, greenhouse gas emissions, energy consumption, fixed capital formation, and research and development expenditure across all EU27 countries, thereby advancing Environmental Kuznets Curve and green innovation research through contemporary, countrylevel evidence on emerging decoupling patterns and six distinct transition pathways that directly inform differentiated policy actions under the European Green Deal.

Practical implications. Policy recommendations include targeted research incentives and renewable energy transitions for underperforming states.

Keywords: green innovation, sustainable development goals (sdg), cluster analysis, environmental kuznets curve, european union, pearson correlation

JEL CODES: Q01; Q55; Q56; C38; O52; O44

1. Introduction

The global environment is facing unprecedented challenges, including climate change and geopolitical conflicts, posing threats to achieve the 2030 Sustainable Development Goals (SDGs) imposed by the United Nations. These goals represent an internationally recognized framework to address economic, social, and environmental sustainability in an integrated manner. The European Union (EU) emphasizes sustainability via the European Green Deal, indicating innovation as a key driver toward climate neutrality by 2050. Decoupling economic growth from greenhouse gas emissions (GHG) remains a persistent challenge.

Prior research has extensively examined the complex nexus between economic development and environmental impact. Foundational studies on the Environmental Kuznets Curve (EKC) suggest an inverted U-shape relationship between income and environmental degradation, where emissions initially rise with economic growth but eventually decline once a certain income threshold is attained. Key reviews by Dinda (2004) and Kaika and Zervas (2013) have corroborated this phenomenon whilst drawing the attention to its sensitivity on context and methodology. More recent empirical evidence highlights the pivotal role of green innovation, such as works by Rennings (2000) and Horbach et al. (2012) demonstrating how research and development (R&D) investments can simultaneously promote economic growth and emissions reduction. Several prior studies precede the EU's post-2015 innovation and policy developments, limiting analysis of their effects on sustainable development.

Building upon these afore-mentioned foundations, this study addresses the urgent need to empirically understand how economic growth, innovation, and environmental sustainability interact across EU Member States. Leveraging on comprehensive Eurostat data from 2015 to 2022, this research investigates correlations among economic growth using gross domestic product (GDP) as an indicator, greenhouse gas (GHG) emissions, the contribution of investment in fixed assets to economic growth using investment in fixed capital formation (GFCF) as an indicator, and gross domestic expenditure on research and development (GERD). Cluster analysis reveals variation in sustainability progress across EU Member States, exemplified by Germany's 36.8% GERD increase during the period under analysis compared to Member States with limited innovation growth. Unlike prior studies that rely on aggregated global or sectoral data, this paper provides granular insights critical for tailoring EU Green Deal policies to diverse national contexts.

This paper's novelty lies in its integrated methodological approach that combines Pearson correlation and cluster analyses to empirically test hypotheses derived from the EKC theory within a contemporary EU framework shaped by dynamic innovation patterns and renewable energy transitions. The findings propose new evidence on the weakening but persistent link between economic growth and emissions, emphasizing innovation's mitigating role. These insights have direct implications for policy setting aimed at achieving a sustainable, competitive, and climate-neutral European economy.

2. Literature review

2.1. *SDGs – Research trends*

Energy security and climate change influence policymaking and economic planning. According to a cross-sectional analysis, attention to concepts related to energy and climate change in the scientific literature shows a steadily increasing trend after 1985, which became significantly more consolidated after 2010. The appearance of conceptual associations related to the energy transition and climate intensified in the scholarly literature after 2015, reaching its highest frequency in 2022 (Georgescu *et al.*, 2025).

Current academic research on the SDGs can generally be divided into two main streams (Huang, 2023). One approach qualitatively analyses the trade-offs and synergies among the different targets of the SDGs (Fuso Nerini *et al.*, 2018; Soergel *et al.*, 2021). These analyses examine SDG interlinkages and propose integrated governance solutions to enhance progress across targets. Among these optimizations, the role and potential of blockchain technology in advancing the SDGs, such as supporting gender equality, were examined. (Di Vaio *et al.*, 2023). Another recent study deals with the assessment of sustainability impacts in the pre-seed and seed phases of start-ups, which play a key role in promoting innovative activities (Di Vaio *et al.*, 2022). This research provides practical guidance for achieving the SDGs, helping to develop more effective sustainability strategies.

The other strand creates sustainability assessment frameworks by collecting data on various SDG indicators and then quantitatively analysing the state of sustainability and development in different regions. This allows governments to concisely and clearly assess how close or far they are from their sustainability goals (Xu *et al.*, 2020; Zhang *et al.*, 2022). These studies construct composite sustainability indices using indicators from multiple dimensions. Such approaches are gaining increasing importance and are seen as effective and practical tools for decision-making and to inform the public. Such indices facilitate assessment of national performance across social, economic, environmental, and technological domains (Lamichhane *et al.*, 2021).

Researchers as well as international organizations have developed sustainability indicators to track and analyse progress and changes in sustainability in different regions. These assessments provide governments with a scientific basis for formulating sustainable development policies (Huang, 2023). Comprehensive analyses and targeted solutions support SDG implementation and advance global sustainability. These studies show that progress towards the SDGs is uneven across countries and dimensions, and that economic performance and innovation capacity are central determinants of sustainability outcomes.

Huang (2023) categorises SDG research into qualitative trade-off analyses and quantitative indices; however, this global overview does not address EU-specific dynamics, including the weakening GDP-GHG correlation (0.95 to 0.945) in Eurostat data, which constrains its applicability to European Green Deal policies. Fuso Nerini et al. (2018) and Soergel et al. (2021) identify SDG interlinkages through scenario modelling but lack empirical validation against post-2015 EU heterogeneity; the present cluster analysis differentiates high performers such as Germany from lower performers such as Slovakia. Quantitative indices by Xu et al. (2020) and others serve as benchmarking tools but underemphasize innovation drivers such as GERD; the present Pearson correlations (r=0.886-0.909) address this by associating research and development growth with emission decoupling.

Against this background, the next subsection focuses on how green innovation and economic growth interact in shaping sustainable development, with particular attention to the EU context.

2.2. *The role of green innovation in achieving sustainable development*

Among the three pillars of the sustainability framework, the economic factor plays a prominent role in advancing the SDGs. Green innovation supports both environmental sustainability and economic performance (Rennings, 2000; Horbach *et al.* 2012). Nevertheless, the potential of green innovation in promoting sustainable practices remains a relatively under-researched area (Horbach, 2008).

Urban and Hametner (2022) emphasized in their research that increasing GDP per capita is associated with increased material consumption and environmental pressures, especially in the agricultural sector, which have adverse effects on terrestrial ecosystems. Therefore, they drew attention to the need to integrate ecological and economic SDGs to minimize environmental damage while achieving economic growth.

Burdiuzha et al. (2020) analyse environmental social responsibility's role in sustainable development, examining GDP, population, and pollution correlations in Europe, and proposes enhancing responsible consumption and reducing agriculture's environmental impact.

Lamei *et al.* (2023) examined progress in achieving the SDGs, revealing complex relationships between SDG achievement, revenues from natural resources, climate technology innovation, and the efficiency of environmental systems.

Research by Thore and Tarverdyan (2022) has shown that economic growth can help achieve the SDGs, but prudent economic management is needed to ensure balanced progress. In contrast, Gazi *et al.* (2024) found a negative relationship between GDP growth and SDG achievement, suggesting that unregulated economic growth may hinder progress on the SDGs.

Wu *et al.* (2023) examined the trade-offs between socio-economic development and environmental sustainability. According to their findings, development often comes at the expense of the environment, climate, resources and social equality. The research shows that growth in GDP per capita is associated with environmental degradation and rising inequality, suggesting that economic growth needs to be carefully managed to avoid compromising environmental and social goals.

Empirical studies indicate varied effects of economic growth on sustainable development. While economic investment is essential to achieve some SDGs, unregulated growth can create environmental and social challenges (Del-Aguila-Arcentales *et al.*, 2022; Islam, 2025; Amin *et al.,* 2023; Younas *et al.,* 2023; Ravn Boess and González Del Campo, 2023).

Countries prioritizing sustainability in economic strategies exhibit stronger outcomes. Sustainable development requires integrating economic, environmental, and social dimensions through international cooperation. The key question for the coming years and decades is how European nations can reconcile their economic interests with the requirements of environmental sustainability (Basheer *et al.*, 2022)

It is therefore essential to develop a balanced approach that considers the complex interrelationships between economic growth and sustainability goals, ensuring that economic development does not compromise environmental and social sustainability. Innovative solutions, political commitment and social participation together play a key role in making sustainability goals a reality (Meadowcroft, 2007; Reed, 2008).

Khan *et al.* (2025) examined the effects of natural resources and technological innovation on the achievement of the SDGs in OECD countries, paying particular attention to the role of democracy and globalization. Their results suggest that there is a positive relationship between natural resources, technological innovation, democracy, and globalization in achieving the SDGs. At the same time, they also pointed out that the relationship between natural resources and democracy can have a negative effect, since the slow decision-making of democratic systems and political interests often hinder the success of sustainability efforts. In contrast, globalization plays a positive moderating role, accelerating the introduction of sustainability practices and innovations.

Islam (2025) examined the interrelationships of economic, social and environmental factors in achieving the SDGs through the example of the G7 countries, emphasizing the moderating role of technological progress and green innovation. According to his research, technological progress has a positive impact on achieving the SDGs, while green innovation can paradoxically hinder them in some cases, especially if the economic structure is unable to properly apply innovations. Previous research also supports that to achieve sustainable development, it is essential for countries to develop effective policy measures that consider green innovations, the use of renewable energy sources, and economic development. Regulations and policies of the EU, such as the European Green Deal, clearly set the goal of achieving climate neutrality by 2050, which provides guidance for the Member States (Tomassi *et al.*, 2024; Talenti, 2025; Koundouri *et al.,* 2024; Wolf *et al.*, 2021; Ottomano Palmisano *et al*., 2025).

Taken together, this evidence indicates that while economic growth remains indispensable for achieving several SDGs, its environmental and social consequences crucially depend on the scale and direction of green innovation and policy frameworks, especially within the European Green Deal. Green innovations also appear in the corporate sector, where they can create new jobs, and it has been shown that through strategic partnerships and technological adaptation, green enterprises have contributed to an average annual reduction of 60,000 tons of CO_2 emissions. The impact of green enterprises extends beyond environmental benefits, as they also generate significant social development within local communities (Prokopenko et al., 2024).

Rennings (2000) and Horbach et al. (2012) establish green innovation's dual role in growth and emissions reduction, but their pre-SDG data predates the EU's 2015-2022 innovation surge, underestimating GERD's mitigating effect (r=0.955 with GDP). Contradictory findings — Thore and Tarverdyan (2022) on managed growth aiding SDGs versus Gazi et al. (2024) on unregulated GDP hindering them — highlight a key limitation: absence of Member State clustering, which is revealed by the result of cluster analysis of this study. Urban and Hametner (2022) emphasize GDP-driven economic pressures but fail to quantify renewable energy shares' weakening role, positioning our hypotheses as an empirical advancement.

This motivates a closer look at the Environmental Kuznets Curve as a benchmark for assessing whether, and under what conditions, growth can be decoupled from environmental pressures in EU Member States.

2.3. *Environmental Kuznets Curve and Sustainable Development*

During the economic growth of recent decades, the study of the Environmental Kuznets-Curve (Kuznets, S., 1995), which models the relationship between economic development and environmental pressure, has received increasing attention. According to the EKC theory, environmental pressures initially increase until a certain level of economic development is reached, but then begin to decrease as economic growth continues (Dinda, 2004; Kaika and Zervas, 2013; Leal and Marques, 2022; Zuniga and Pincheira, 2020). In the EU, where economic development and environmental protection are both high priorities, the study of the Kuznets curve is particularly relevant, as it offers an opportunity to reveal the stages of development of individual Member States and to point the way for policy measures to promote sustainable development.

Several researchers have analysed the relationship between economic and environmental factors, examining whether there can be economic development without changing or even reducing environmental pressures (Kaika and Zervas, 2013, Leal and Marques, 2022; Stern, 2018).

In their analysis, You and Lv (2018) examined the data of 83 countries from 1985 to 2013.Their research supports the EKC hypothesis, which states that GDP growth initially increases CO_2 emissions and then decreases them after a certain level of development.

Yang *et al.* (2021) examined the impact of economic globalization and social aging on long-term carbon emissions in OECD countries. Their results showed that economic globalization reduces CO_2 emissions in the long run by supporting technological development, energy-efficient production processes, and the spread of green innovation.

Liu *et al.* (2020) analysed the G7 countries and found that globalization initially increases CO_2 emissions, but after a certain level reduces it, owing to the transfer of technologies and knowledge, as well as international environmental protection measures. The impact of economic growth on CO_2 emissions is mixed, as growth generally increases emissions, but renewable energy consumption significantly reduces them.

Alnafrah (2025) assessed the environmental efficiency of 42 countries for the period 2000–2020, emphasising the role of green innovations and the use of renewable energy. The results of the study show that the efficiency of green innovations follows a U-shaped curve, initially showing efficiency gaps, but with significant improvements in the longer term. The study also emphasizes that green innovation alone is not sufficient to achieve the sustainability goals. Effective environmental policies, the use of green taxes, and the widespread use of renewable energy sources are essential to achieve success.

Gilli *et al.* (2013) examined the economic, environmental and innovation performance of the EU at sectoral level, highlighting that the effective integration of environmental innovations into the economic structure and competitive sectors is key to achieving sustainable economic growth. Germany and Sweden are examples of how the success of environmental innovations can significantly contribute to economic performance, while the example of Italy warns that weak environmental innovation capacity and low economic productivity can be serious obstacles to the green economic transition. Environmental innovation can also be used in Ukraine to support the post-war recovery of the Ukrainian economy and its integration into the European energy system (Koval *et al.*, 2022).

The EKC literature, combined with research on green innovation and EU climate policy, suggests that the relationship between GDP, investment, innovation and environmental outcomes is complex but potentially compatible with sustainable development.

Core EKC reviews (Dinda 2004; Kaika and Zervas 2013; Stern 2018) affirm an inverted-U pattern but question its universality due to specification sensitivity, a critique validated by our EU-27 data showing GDP-GHG links weakening without full reversal. You and Lv (2018) support EKC via global panels, yet their 1985-2013 scope misses recent EU policy shifts like the Green Deal, where GERD (r=0.886-0.909) and renewable energy (23.58% share by 2022) drive decoupling. Gilli et al. (2013) excels in sectoral EU insights but predates SDGs; our country-level clusters extend this. Table 1 anchors these streams but reveals a critical gap: most studies use pre-2022 or non-EU data, neglecting the role of innovation and renewable energy in recent decoupling trends. This literature's mixed EKC evidence and innovation contradictions motivate our EU-27 focus—extending global works (e.g., Khan et al. 2025) by quantifying correlations. Our perspective is, that while prior research maps tensions, it underemphasizes policy-tailored heterogeneity, which our analysis resolves for actionable Green Deal insights.

Table 1: Summary of anchor studies, critiqued for pre-2022 data and limited EU granularity, motivating our innovation-focused hypotheses

Authors, year	Region/ sample period	Focus/ question	Indicators and methods	Main findings	Limitations/ research gap	Relevance for this study
SDG Measurement and Research Trends						
Huang (2023)	Global overview	Synthesis of SDG research streams	Review of SDG indicators, indices, governance approaches	Identifies two main streams: qualitative SDG trade-offs and quantitative indicator-based assessments for policy tracking.	Conceptual; limited EU-specific growth-emission dynamics.	Structures SDG literature and justifies quantitative indicator approach for EU-27.

Authors, year	Region/ sample period	Focus/ question	Indicators and methods	Main findings	Limitations/ research gap	Relevance for this study
Fuso Nerini et al. (2018); Soergel et al. (2021)	Global/ multi-country	SDG trade-offs and synergies	Scenario analysis; systems modelling; SDG indicators	Reveal complex interlinkages where policy choices create synergies or trade-offs across economic/ environmental SDGs.	Global focus; less macro-economic indicator detail.	Motivates joint analysis of GDP, GHG, energy for EU sustainability.
Xu et al. (2020); Zhang et al. (2022); Lamichhane et al. (2021)	Cross-country; recent panel data	Quantitative SDG progress assessment	SDG indicators; composite index construction; statistical analysis	Show uneven cross-country SDG performance; indices effective for policy benchmarking and public communication.	Limited focus on growth-innovation drivers of SDG scores.	Supports using GDP/ GHG/ GERD indicators and EU-27 comparative analysis.
Georgescu et al. (2025)	1985–2022	Legal and policy nexus between energy–security–climate change	Google Ngram Viewer, cross-sectional analysis, Pearson correlation	Increasing attention since 1985; consolidation after 2010. Strong correlation between the concepts	Dominance of the English language in digitised literature	Outlines trends
Green Innovation, Growth and SDGs						
Rennings (2000); Horbach et al. (2008, 2012)	OECD/ European contexts	Determinants of green/environmental innovation	Innovation surveys; theoretical/ empirical analysis	Green innovation reconciles growth and environment; driven by regulation, R&D investment.	Earlier data; pre-SDG/ Green Deal frameworks.	Theoretical basis for GERD as decoupling channel in H1.

Authors, year	Region/ sample period	Focus/ question	Indicators and methods	Main findings	Limitations/ research gap	Relevance for this study
Urban & Hametner (2022); Burdiuzha et al. (2020); Lamei et al. (2023)	EU/ European countries; recent years	GDP, environmental pressures, SDG progress	GDP, material/ pollution indicators, SDG scores; correlations/ regressions	GDP growth raises pressures, but responsibility measures/ innovation can mitigate; complex resource-innovation-SDG links.	Limited energy structure or EU-27 specificity.	Shows EU growth-emission tensions motivating H1/H2 tests.
Thore & Tarverdyan (2022); Gazi et al. (2024)	Cross-country	Economic growth vs. SDG achievement	GDP growth, SDG indices; quantitative analysis	Managed growth supports SDGs; unregulated growth can hinder via environmental/social costs.	Less focus on innovation/energy moderators.	Contrasting evidence justifies testing EU innovation conditions.
Khan et al. (2025); Islam (2025)	OECD/ G7 countries	Innovation, resources, globalization and SDGs	SDG scores, innovation proxies, GDP; panel econometrics	Tech innovation/ globalization boost SDGs; green innovation impact conditional on economic structure.	Broader than EU-27; indirect GHG modelling.	Supports GERD/ energy roles in weakening GDP-GHG link (H1/ H2).
Prokopenko et al. (2024)	global	Green entrepreneurship models; social impact on sustainable development	literature review, data analysis	Creativity and partnerships are key. An average of 15,000 new jobs per region. Annual reduction of 60,000 tons of CO_2	Need for supportive policies; development of financing mechanisms	Provides guidance for green business models
EKC and Growth–Emissions Nexus						

Authors, year	Region/ sample period	Focus/ question	Indicators and methods	Main findings	Limitations/ research gap	Relevance for this study
Dinda (2004); Kaika & Zervas (2013); Stern (2018)	Various countries/ regions	EKC: income-environment relationship	GDP per capita, emissions; EKC regressions/ reviews	Inverted-U pattern possible but sensitive to specification; questions universality.	Mixed evidence; limited recent EU tests.	Core framework for testing weakening EU GDP-GHG correlations.
You & Lv (2018); Liu et al. (2020); Yang et al. (2021)	83 countries/G7/ OECD; 1985-2013+	EKC, globalization, energy and CO_2	GDP, CO_2, globalization/ renewables; panel EKC models	EKC confirmed; globalization/ renewables eventually reduce emissions post-growth peak.	Global/G7 focus; less EU policy detail.	Suggests advanced economies decouple; motivates EU-27 2015-2022 analysis.
Leal & Marques (2022); Zuniga & Pincheira (2020); Alnafrah (2025)	EU/multi-country; recent periods	EKC, efficiency, green innovation	GDP, emissions, innovation/ renewables; panel/ efficiency analysis	EKC varies by region/pollutant; green innovation U-shaped, needs policy support.	Not EU-27 exclusive; efficiency vs. correlation focus.	Justifies EU-specific correlations/ clusters with GERD emphasis.
Gilli et al. (2013)	EU sectors	EU environmental innovation performance	Sectoral innovation/ environmental indicators; EU data analysis	Competitive sectors with strong green innovation (e.g. Germany) achieve sustainable growth.	Sectoral/ pre-SDG; not country-level clusters.	Prefigures this study's EU-27 cluster findings on innovation.

Building on these insights, the present study tests the following hypotheses for EU27 countries over the period 2015–2022:

H1: GDP shows a strong positive correlation with the growth of GFCF and the increase in GHG emissions. If the growth rate of research and development investments exceeds the growth rate of GDP, then a negative correlation between GDP and GHG emissions is expected.

H2: GDP growth is in line with the growth of energy consumption and is positively correlated with the rise of GHG emissions. However, as the share of renewable energy sources in total energy consumption increases, this relationship is expected to weaken or disappear, indicating improvements in energy efficiency and sustainability.

3. Methods

This study examines trends in energy consumption, GHG emissions, GDP, GFCF, and GERD for EU-27 Member States from 2015 to 2022.

The variables selected for the analysis reflect key aspects of innovation, economic performance and environmental sustainability, allowing for the examination of the complex interrelationships between these dimensions in the context of the EU Member States. The variables examined in the analysis were:

- GDP (million euros) as a primary measure of economic performance, indicating economic growth (Eurostat, 2025b).
- GHG emissions (tonnes) as a key indicator of environmental pressure and impact on climate change (Eurostat, 2024).
- Gross fixed capital formation that shows investments that form the basis for economic capacity expansion and future production (2025c).
- Gross domestic research and development expenditure as a percentage of GDP (GERD) as a key indicator of innovation activity and commitment to technological development (2025d).
- Final energy consumption (tons of oil equivalent) as it reflects the energy demand and energy efficiency of the economy (2025a).

Multivariate statistical methods were applied using Eurostat data and Pearson's correlation coefficient was applied to test the hypotheses.

Cluster analysis for the EU Member States was conducted based on economic indicators, which proved to be an appropriate method for identifying economic similarities and differences between the Member States of the EU. Before the cluster analysis was conducted, all data sets were standardized[2] so that scale differences between variables do not distort the results of the analysis.

For cluster analysis, we applied Gaussian Mixture Models (GMM), using the sklearn.mixture.GaussianMixture class. Normal mixture models are being increasingly used to model the distributions of a wide variety of random phenomena and to cluster sets of continuous multivariate data. GMM operate on the principle that the observed data arises from a combination of multiple Gaussian distributions, with each cluster represented by a distinct Gaussian component. In contrast to the K-Means algorithm, which strictly allocates data points to specific clusters, GMM calculates the probability of each data point belonging to a cluster, facilitating "soft" clustering (Peel et al., 2020; Paramarta et al., 2025).

GMM is particularly effective for scenarios involving overlapping clusters, where soft

2 Using sklearn.preprocessing

boundaries between groups are essential and it is also beneficial where data points may belong to multiple clusters simultaneously. However, one of the main challenges with GMM is its sensitivity to the initialization of parameters, which can lead to convergence on suboptimal solutions (McLachlan and Peel, 2000).

To select the optimal number of clusters in GMM, we computed the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) for models with varying numbers of components. Both criteria balance model fit: lower values indicate a better trade-off between the likelihood of the data given the model and the number of parameters. AIC tends to favour models with more components, as it penalises model complexity less strongly. BIC imposes a stricter penalty for additional parameters and is therefore more conservative, often selecting a simpler model that still explains the data well.

In our analysis, we primarily rely on BIC to determine the optimal cluster number, since it generally avoids overfitting while capturing the main structure in the data. The resulting BIC curve shows a clear minimum at the chosen number of clusters, indicating the point beyond which additional components do not substantially improve model fit.

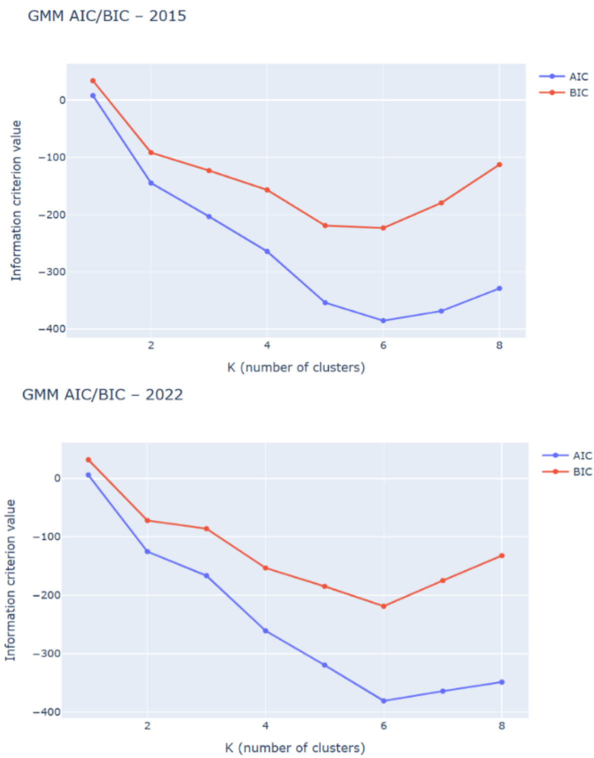

Figure 1: GMM – AIC/BIC, selection of the optimal number of clusters

4. Results

4.1. *Economic trends and sustainability challenges in the EU*

In response to sustainability challenges, the European economy is supporting the implementation of innovative, environmentally friendly investments. The development of investments is a key indicator of the economy, as it directly influences GDP growth, innovation, and the economy's competitiveness.

Trends across EU Member States show that a strong relationship between GFCF and GDP can be observed, showing a positive correlation (0.996-0.997). GFCF increased, which contributed to the growth of GDP. To increase the efficiency of investments, it is necessary to expand the scope of government support in the future and stabilize the economic environment. During the period under review, investments fell for a short time due to COVID-19, and the Russian-Ukrainian war also resulted in a minor shock.

The correlation coefficient between GHG emission and GDP is high, but the relationship is weakening (0.95-0.945). GHG emissions typically increase with GDP growth, but after a while this growth stagnates, or a slight decrease can be observed. In case of EU Member States, the impact of steps taken towards sustainability, including the transition to renewable energy sources, is noticeable, which explains the slightly decreasing trend.

On the basis of these findings, it can be concluded that hypothesis H1—which posits a close correlation between GDP, growth of GFCF, and the increase in GHG emissions—is supported. The observed correlations are both strong and positive, aligning with the hypothesized relationships.

For hypothesis H2 the relationship between GERD, energy consumption and GDP was examined. A strong relationship can also be observed between GERD and GDP, but at the same time the correlation coefficient decreased slightly (0.958-0.955). Investments in research and development play a key role in economic growth. Although the correlation has weakened slightly, it remains strong, indicating that investment in research and development contributes to GDP growth. Strengthening research and development investment, especially in innovative and technology-oriented industries, is strategically essential. The shift towards digital technologies is essential for dynamic development.

A very strong positive relationship can be observed between energy consumption and GDP, which indicates that the energy demand of Europe's economy is high. As economic performance increases, energy consumption typically increases as well. However, the correlation decreased between 2015 and 2022 (from 0.990 to 0.981), indicating that economic growth has resulted in relatively lower energy consumption. In addition, a strong positive relationship can be observed between energy consumption and GHG emissions. The value of the correlation coefficient (from 0.976 to 0.979) indicates stability. Increasing energy efficiency and transitioning to renewable energy sources are key to achieve sustainable development.

Hypothesis H2 is also supported, as the relationship between energy consumption and GDP growth remained robust. However, the observed decline in correlation suggests that economic growth is becoming increasingly decoupled from energy consumption, indicating the effectiveness of sustainability measures. Moreover, the growing share of renewable energy sources represents a positive trend for future economic and environmental development.

Table 2: Correlation of economic and energy indicators of the EU-27 Member States in 2015

Correlations 2015						
		Energy consumption (ton)	**GHG emission (ton)**	**GDP (m€)**	**GFCF (m€)**	**GERD (m€)**
Energy consumption (ton)	Pearson Correlation	1	0.976**	0.990**	0.985**	0.938**
	Sig. (2-tailed)		<0.001	<0.001	<0.001	<0.001
	N	27	27	27	27	27
GHG emission (ton)	Pearson Correlation	0.976**	1	0.950**	0.943**	0.909**
	Sig. (2-tailed)	<0.001		<0.001	<0.001	<0.001
	N	27	27	27	27	27
GDP (m€)	Pearson Correlation	0.990**	0.950**	1	0.996**	0.958**
	Sig. (2-tailed)	<0.001	<0.001		<0.001	<0.001
	N	27	27	27	27	27
GFCF (m€)	Pearson Correlation	0.985**	0.943**	0.996**	1	0.969**
	Sig. (2-tailed)	<0.001	<0.001	<0.001		<0.001
	N	27	27	27	27	27
GERD (m€)	Pearson Correlation	0.938**	0.909**	0.958**	0.969**	1
	Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	
	N	27	27	27	27	27

Source: Calculation based on Eurostat database (Eurostat, 2025a; 2025b;2025c;2025d;2024)

Table 3: Correlation of economic and energy indicators of the EU-27 Member States in 2022

Correlations 2022							
		Energy consumption (ton)	**GHG emission (ton)**	**GDP (m€)**	**GFCF (m€)**	**GERD (m€)**
Energy consumption (ton)	Pearson Correlation	1	0.979**	0.981**	0.974**	0.921**
	Sig. (2-tailed)		<0.001	<0.001	<0.001	<0.001
	N	27	27	27	27	27
GHG emission (ton)	Pearson Correlation	0.979**	1	0.945**	0.926**	0.886**
	Sig. (2-tailed)	<0.001		<0.001	<0.001	<0.001
	N	27	27	27	27	27
GDP (m€)	Pearson Correlation	0.981**	0.945**	1	0.997**	0.955**
	Sig. (2-tailed)	<0.001	<0.001		<0.001	<0.001
	N	27	27	27	27	27
GFCF (m€)	Pearson Correlation	0.974**	0.926**	0.997**	1	0.955**
	Sig. (2-tailed)	<0.001	<0.001	<0.001		<0.001
	N	27	27	27	27	27
GERD (m€)	Pearson Correlation	0.921**	0.886**	0.955**	0.955**	1
	Sig. (2-tailed)	<0.001	<0.001	<0.001	<0.001	
	N	27	27	27	27	27

Source: Calculation based on Eurostat database (Eurostat, 2025a; 2025b;2025c;2025d;2024)

Our analysis reveals a persistent and strong positive correlation between GDP growth and GHG emissions across EU member states, evidenced by Pearson coefficients of 0.950 (2015) and 0.945 (2022). Although this marginal decline signals an initial, albeit modest, step towards decoupling, a full separation of economic growth from increased GHG output has not been achieved. This modest deceleration in the strength of the positive relationship can be partially attributed to the increasing deployment of renewable energy sources and the mitigating influence of heightened research and development investments, as supported by the analysis of Hypotheses H1 and H2. This highlights the ongoing challenge and the necessity for further intensified sustainability policies and innovation to accelerate decoupling.

EU covered 23.58% of its gross final energy consumption from renewable energy sources in 2022, which was 5.76 percentage points higher than in 2015 (17.82%). At the same time, to reach the 2030 target value - according to which the share of energy from renewable energy sources in the gross final energy consumption must be increased to 45% - additional measures on the part of the Member States are still necessary (Directive (EU) 2023/2413) considering that there has been a slight decrease in research and development investment, indicating the need for further sustainability related measures.

4.2. *Cluster analysis*

In our study, cluster analysis on five indicators was conducted – GDP, GHG emissions, GFCF, GERD and energy consumption. 2015 was chosen as the base year, as in 2015 the UN General Assembly adopted the 2030 Agenda for Sustainable Development. The SDGs are intended to promote the sustainability of social, economic and environmental development and form the basis for global strategic planning.

In the years under study – 2015 and 2022 – six clusters can be distinguished:

1. The largest economy of the EU – Economic performance of Germany
2. Growth burdened by crises - France and Italy's options to solve the energy crisis
3. Innovation as a focus point - Energy transition of Spain and Poland
4. Challenges and opportunities in the energy transition for sustainable development – Austria, Belgium, The Netherlands, Sweden
5. Diverse economy for common goals - Cyprus, Estonia, Croatia, Latvia, Lithuania, Luxembourg, Malta, Slovakia, Slovenia and Bulgaria
6. Sustainable energy transition – reducing fossil energy sources, challenges to energy dependency - Czech Republic, Denmark, Finland, Greece, Ireland, Hungary, Portugal, Romania

The indicators are linked to all SDGs. Progress in one SDG is linked to progress in another SDG, meaning that there is a strong link between each SDG.

4.2.1. *The largest economy of the EU – Economic performance of Germany*

Among the member states of the EU, Germany stands out, forming an independent cluster as the largest economy in the EU (GDP value of 3,953.85 billion euros), thus playing a significant role in the implementation of the SDGs (Eurostat, 2025b).

Table 4: Change in Germany's economic performance (2015 and 2022)

Country	Energy consumption Change (%)	GHG emissions Change (%)	GDP Change (%)	GFCF Change (%)	GERD Change (%)
Germany	(-) 4,9	(-) 16,7	28,1	40,8	36,8

Source: Calculation based on Eurostat database (Eurostat, 2025a; 2025b;2025c;2025d;2024)

Germany has shown stable economic growth in the period under review – 2015-2022. GDP grew by more than 28%, partly because of the strategic investments supporting sustainable development. Investments have helped to preserve jobs (SDG8). Germany has made significant strides in promoting innovation (Horne *et al*., 2020). Investments require technological innovation (SDG 9) and new energy sources (SDG 10), which reduce GHG emissions, contributing to climate protection goals (SDG13). Germany has the highest gross investment value (EUR 858.253 billion), which increased by more than 40% in the period under review (Eurostat, 2025d). Germany exhibits the highest GERD growth in the EU, enabling reductions in energy consumption and GHG emissions despite high economic activity.

The structural transformation of the German economy remains key in creating a sustainable economy, with a focus on increasing the share of renewable energy (Pata *et al*., 2023).

Table 5: Germany's share of renewable energy sources in gross energy consumption

Share of energy from renewable sources (%)	2015	2022
European Union - 27 countries (from 2020)	17.82	23.058
Germany	14.90	20.814

Source: Calculation based on Eurostat database (Eurostat, 2025a)

Germany is a major player in the European renewable energy market due to its significant contribution to renewable energy production (Hassan *et al*., 2024b). As part of its energy transition strategy called "Energiewende", it aims to achieve carbon neutrality by 2045 by relying heavily on renewable energy in its energy supply (Pata *et al*., 2023).

4.2.2. *Growth burdened by crises – France and Italy's options for solving the energy crisis*

After Germany, the two most dynamically developing countries in Europe are France and Italy. Both countries have a dominant economy in Europe, with the largest GDP after Germany (Eurostat, 2025b). They have achieved economic growth by reducing both energy consumption and GHG emissions, i.e. the Environmental Kuznets Curve (EKC) is applicable.

In France, nuclear technology and renewable energy sources play a significant role in this. It obtains more than 70% of its electricity from nuclear energy through its extensive network of 56 reactors (Hassan *et al.*, 2024a).

Nuclear energy reduces pollution and GHG emissions. It also meets the growing energy demand by reducing energy dependence on imports. However, it shall be emphasized that economic growth and the improvement of social and environmental conditions require the acceptance of nuclear technology by society (Ridwan *et al.*, 2023). Especially considering that reducing energy consumption can be a constraint on economic growth in the long term (Ahmad *et al.*, 2019). Renewable energy is needed to replace fossil fuels in order to ensure dynamic economic growth, but also to meet climate goals (Ma *et al.*, 2021).

France is among the three largest hydrogen producers in Europe – alongside Germany and the Netherlands – due to its extensive industrial base and progressive energy policy. It currently accounts for less than 2% of global hydrogen production, indicating a huge untapped potential. By serving as a clean energy carrier that can be produced without CO_2 emissions, green hydrogen offers a sustainable alternative to fossil fuels in several sectors, including transport, industry and heating (Hassan *et al.*, 2024a).

Table 6: Change in the economic performance of France and Italy (2015 and 2022)

Country	Energy consumption Change (%)	GHG emissions Change (%)	GDP Change (%)	GFCF (Change (%)	GERD Change (%)
France	(-) 7.0	(-) 11.7	20.6	38.8	20.4
Italy	(-) 3.8	(-) 6.8	20.1	53.6	23.1

Source: Calculation based on Eurostat database (Eurostat, 2025a; 2025b;2025c;2025d;2024)

Italy has the third largest GDP in Europe after Germany and France. Despite all this, the country faces serious challenges, as it has low productivity and high debt. It has the second highest public debt-to-GDP ratio in the EU, after Greece. Following the global financial crisis of 2007–2008, COVID–19 and then rising energy prices had a negative impact on the Italian economy. (Canelli *et al.*, 2024).

Italy does not have sufficient domestic energy resources to meet its national energy needs, so the shift towards renewable energy sources has become a fundamental strategic issue. In recent years, significant steps have been taken to reduce energy dependence and reduce GHG emissions. Hydropower is one of the main sources of electricity generation in Italy's energy mix, with solar power, wind power and bioenergy also playing an increasingly important role (Esposito and Romagnoli, 2023).

In addition to solar energy generation, the installed capacity of wind energy has undergone significant development. In order to ensure the sustainable development of wind energy in the country, it is important to preserve the social and environmental sustainability of wind farms. To this end, potential conflicts related to land use must be addressed, and it is of utmost importance to ensure the intermittent nature of wind energy generation so that it remains a sustainable, reliable energy source in the long term (Esposito and Romagnoli, 2023).

Although electrification dominates the current energy transition, the utilization of carbon-neutral biomass remains of significant importance due to its low cost and compatibility with traditional fossil fuel systems. Bioenergy has emerged as a promising renewable energy source in Italy. Bioenergy is the only renewable energy source that can cover the country's energy needs in multiple forms, be it electricity, heating or transport fuels. Bioenergy and geothermal energy capacity have also increased, although their growth has been limited by environmental concerns and technical challenges (Scarlat *et al.*, 2013; Esposito and Romagnoli, 2023).

Italy's geographical location allows it to achieve energy self-sufficiency by developing and improving its energy infrastructure and introducing power plant conversion processes. Although significant progress has been made in the development of renewable energy sources in recent years - with investments worth billions of euros - growth has been slow and uneven. One of the main reasons for this is the difficulty of financing, as building new energy infrastructure is extremely expensive (Esposito and Romagnoli, 2023).

Table 7: Share of renewable energy sources in France's and Italy's gross energy consumption

Share of energy from renewable sources (%)	2015	2022
European Union - 27 countries (from 2020)	17.82	23.058
France	14.80	20.445
Italy	17.53	19.131

Source: Calculation based on Eurostat database (Eurostat, 2025a)

It is essential for the Italian government to continue to increase its research and development spending, supporting the rapid deployment of innovative, low-emission technologies. This is essential not only for environmental sustainability but also for the country's economic competitiveness (Esposito and Romagnoli, 2023).

4.2.3. *Innovation as a focus point – Energy transition of Spain and Poland*

Spain's energy consumption increased very slightly during the period under review. In addition to its economic growth (26.4%), GHG emissions developed favourably (decreased by 11.3%), which is due to the favourable utilization of renewable energy sources. Investments increased by 40.9%, and research and development expenditures by 46.7%, indicating that the country prioritizes innovation and the development of sustainable technologies. (Eurostat, 2025a; 2024;2025d).

Table 8: Change in the economic performance of Spain and Poland (2015 and 2022)

Country	Energy consumption Change (%)	GHG emissions Change (%)	GDP Change (%)	GFCF Change (%)	GERD Change (%)
Spain	1.1	(-) 11.3	26.4	40.9	46.7
Poland	16.4	2.5	53.0	24.2	121.0

Source: Calculation based on Eurostat database (Eurostat, 2025a; 2025b;2025c;2025d;2024)

Spain plans to primarily utilize solar and wind energy – considering its natural resources – which are expected to improve energy efficiency by 2030. Spain has a long-term decarbonisation strategy until 2050, which aims to address the climate crisis while seizing the opportunities of modernising the economy and competing globally. However, Spain's overall energy mix remains largely dominated by fossil fuels, despite significant progress in decarbonisation and increasing the share of renewable energy in the energy sector. (IEA, 2021).

From the Central and Eastern European countries, Poland was placed in the same cluster with Spain.

Among the member states of the EU, Poland's situation is special, as its energy consumption is high (it is the fifth largest energy consumer in the EU after Germany, France, Italy and Spain) and traditional industrial sectors, such as manufacturing and agriculture, are dominant in the country's economy (Kaczmarek *et al.,* 2022).

Poland has significant coal resources and remains highly dependent on hard coal and lignite for electricity generation (almost 70% of electricity and heat generation was generated using coal) (Kaczmarek *et al.*, 2022). All this results in high GHG emissions, making the energy transition one of the biggest challenges for Poland. Even though coal still represents a large share in Poland's energy mix, compliance with EU requirements has a decisive influence on the country's energy policy (Kaczmarek *et al.*, 2022), thus measures are in place to gradually reduce the share of coal (the share of energy generated by coal consumption was reduced from 96% to 68% over ten years) (Kaczmarek *et al.*, 2022). Poland has increased its GDP by more than 50% in the past decade and has doubled its research and development expenditure, but for further development will need to attract resources (Eurostat, 2025b). Although Poland has taken significant steps towards achieving sustainability goals, the energy transition is not yet complete and further innovative investments are necessary.

Table 9: Share of renewable energy sources in Spain's and Poland's gross energy consumption

Share of energy from renewable sources (%)	2015	2022
European Union - 27 countries (from 2020)	17.82	23.058
Spain	16.22	21.896
Poland	11.88	16.629

Source: Calculation based on Eurostat database (Eurostat, 2025a)

Spain's primary objective is to achieve energy security, flexibility, energy savings and promote the energy transition by reaching a 42% share of renewable energy, mainly solar and wind energy. It aims to cover 74% of electricity demand from renewable sources by 2030. Renewable hydrogen plays a key role in achieving decarbonization (Dessi *et al.*, 2024).

Patents are an effective and potential option to achieve the country's new goals for the deployment of renewable energy sources and energy efficiency in transportation, industry, and construction (Oyebanji *et al.*, 2022).

Poland's energy policy aligns with Spain's strategic objectives; however, the relative emphasis on particular energy sources differs. For Poland, the development of a diversified energy mix based on renewable energy sources is essential to achieving a transition away from fossil fuels. Critical aspects of the renewable energy sector include the efficient utilization of solar power, the expansion of wind and hydropower generation, the promotion of biomass for energy production, and the exploitation of geothermal resources. These elements are particularly significant for the Polish economy in light of the ongoing war in Ukraine, as they contribute to strengthening national energy security through renewable energy (Igliński et al., 2022). Furthermore, Poland possesses substantial waste biomass potential owing to its strong agricultural tradition (Zyadin et al., 2018). The country's geographical location, especially along the Baltic Sea coast, also provides favorable conditions for the development of wind farms (Igliński et al., 2022).

The energy transition itself—both in Poland and globally—must occur in such a way that it ultimately achieves an optimal energy mix that relies to the greatest possible extent on renewable energy sources (Erat et al., 2021).

4.2.4. *Challenges and opportunities in the energy transition for sustainable development – Austria, Belgium, The Netherlands, Sweden*

Table 10: Changes in the economic performance of Austria, Belgium, The Netherlands and Sweden (2015 and 2022)

Country	Energy consumption Change (%)	GHG emissions Change (%)	GDP Change (%)	GFCF Change (%)	GERD Change (%)
Austria	(-) 3.1	(-) 0.3	31.0	45.7	35.6
Belgium	(-) 7.5	(-) 12.0	35.6	39.7	83.4
The Netherlands	(-) 10.6	(-) 19.2	42.1	33.4	46.0
Sweden	(-) 3.2	(-) 14.0	22.0	34.1	30.7

Source: Calculation based on Eurostat database (Eurostat, 2025a; 2025b;2025c;2025d;2024)

Austria has made significant strides in energy efficiency and renewable energy use, especially in the development of hydropower and wind power. The country's economy is stable, and its budget is heavily invested in innovative, sustainable technologies. Research and development are strongly supported, thereby reducing dependence on imported energy, especially oil and gas (Hassan *et al.,* 2024a).

Belgium is gradually phasing out its nuclear power plants, while reducing energy consumption and increasing the share of renewable energy. The country plans significant investments in expanding wave and wind energy capacity, while looking for innovative solutions in research and development to increase energy efficiency and reduce energy imports (Asiaban *et al.,* 2021).

In the Netherlands, increasing the share of renewable energy sources and encouraging technological innovations is a high priority. The country's specific geographical conditions allow for the construction of efficient hydropower and wind farms. The Netherlands is among the European leaders in wind energy, with a significant offshore wind farm. Over the past thirty years, offshore wind energy has grown from an immature market niche into a major industry and market, with the aim of facilitating the energy transition from fossil fuel sources to renewable energy (Van der Loos *et al*., 2021). In addition to making domestic energy consumption sustainable, wind farms can play a significant role in energy exports.

Sweden's gross final energy consumption was covered by renewable sources, accounting for 66% of the country's total. It used hydropower, bioenergy and wind power capacity to produce electricity and heat (Hassan *et al*., 2024a)

Table 11: Share of renewable energy sources in gross energy consumption of Austria, Belgium, The Netherlands and Sweden

Share of energy from renewable sources (%)	2015	2022
European Union - 27 countries (from 2020)	17.82	23.058
Austria	33.497	34.075
Belgium	8.06	13.816
The Netherlands	*5.714*	15.134
Sweden	52.22	66.287

Source: Calculation based on Eurostat database (Eurostat, 2025a)

4.2.5. *Diverse economy for common goals*

The countries in the fifth cluster have different industrial structures that significantly influence their energy consumption patterns. Although all of them have seen positive GDP growth over the past decade, they face different challenges in terms of energy transition and sustainable development due to their different economic structures and levels of development.

Table 12: Change in the economic performance of "Diverse economy for common goals" cluster (2015 and 2022)

Country	Energy consumption Change (%)	GHG emissions Change (%)	GDP Change (%)	GFCF Change (%)	GERD Change (%)
Cyprus	5.9	6.3	63.9	154.1	142.7
Estonia	-	(-) 21.7	73.4	85.9	111.9
Croatia	4.5	(-) 1.2	48.6	68.2	156.0
Latvia	2.6	(-) 7.2	52.1	56.9	92.6
Lithuania	10.2	11.0	80.2	106.7	82.3
Luxembourg	(-) 7.5	(-) 9.4	43.2	44.9	20.6
Malta	16.7	60.7	78.7	82.8	47.4
Slovakia	3.1	(-) 9.3	37.0	10.3	15.9
Slovenia	-	(-) 6.4	47.8	71.3	40.1
Bulgaria	4.2	(-) 3.1	88.0	53.2	48.8

Source: Calculation based on Eurostat database (Eurostat, 2025a; 2025b;2025c;2025d;2024)

Energy consumption and CO_2 emissions vary, but they all share a consistent reduction in GHG emissions, reflected in the increasing share of renewable energy sources. This is important as these countries are gradually diversifying their energy mix, with a focus on renewable energy sources, especially solar and wind power. On a national scale, countries employ bespoke models to plan their energy transition, often mirroring their unique energy profiles, geographical nuances, and development aspirations (Hassan, *et al.*, 2024b).

The countries belong to the bottom third of the EU in terms of their energy needs (Eurostat, 2025a).

Table 13: Renewable energy sources in gross energy consumption in "Diverse economy for common goals" cluster

Share of energy from renewable sources (%)	2015	2022
European Union - 27 countries (from 2020)	17.82	23.058
Cyprus	9.903	19.427
Estonia	28.987	38.542
Croatia	28.969	28.088
Latvia	37.538	43.720
Lithuania	25.748	29.599
Luxembourg	4.987	14.262

Malta	5.119	13.969
Slovakia	12.882	17.481
Slovenia	22.879	25.002
Bulgaria	18.261	19.044

Source: Calculation based on Eurostat database (Eurostat, 2025a)

The members of the fifth cluster are economically diverse, so they use different strategies to achieve sustainability goals, based on their technological and industrial structures.

The countries in the cluster are characterized by their relatively lower energy needs due to their smaller populations and economies (Cyprus, Estonia, Latvia, Lithuania) (Hassan *et al.*, 2024b).

Luxembourg (14.26%) and Malta (13.97%) showed the lowest renewable energy share in gross final energy consumption, while Malta had the lowest energy demand (Eurostat, 2025a).

Bulgaria has a strong energy base in coal-based energy use but is gradually reducing the role of its coal and lignite-based power plants in order to meet EU requirements. The aim is to develop renewable energy sources, especially solar and wind power plants, and increase research and development data to support technological transition (Pavlov, 2022).

4.2.6. *Sustainable energy transition – reducing fossil energy sources, challenges to energy dependency*

Countries in the sixth cluster face serious challenges in energy transition and innovation, but despite all this, their economies continue to grow.

Countries in the sixth cluster are in the middle of the EU in terms of energy consumption. These Member States have successfully reduced GHG emissions, but they still face significant difficulties in reducing the share of fossil energy sources and achieving energy independence. They need to find a solution to reduce their energy dependence, as this will not only be decisive for their further economic development, but also for achieving environmental sustainability. These countries need to apply innovative technologies to increase energy efficiency, while diversifying their energy sources.

Table 14: Change in the economic performance of "Sustainable energy transformation" cluster (2015 and 2022)

Country	Energy consumption Change (%)	GHG emissions Change (%)	GDP Change (%)	GFCF Change (%)	GERD Change (%)
Czech Republic	3.0	(-) 8.2	68.3	81.5	67.0
Denmark	(-) 6.3	(-) 9.3	40.5	61.8	31.4

Finland	(-) 3.4	(-) 17.4	26.6	45.8	30.7
Greece	(-) 3.0	(-) 16.6	18.5	58.6	80.2
Ireland	5.3	3.5	91.1	66.8	55.1
Hungary	6.5	(-) 3.2	49.8	87.6	55.6
Portugal	4.4	(-) 14.5	36.0	78.7	84.6
Romania	10.1	(-) 5.4	75.8	76.6	66.7

Source: Calculation based on Eurostat database (Eurostat, 2025a; 2025b; 2025c; 2025d;2024)

For the countries in the cluster, research and development can be one of the areas – due to continuous developments – that helps the transition to renewable energy sources, reducing their dependence on energy imports and thus contributing to achieving global climate protection goals (Bórawski *et al.*, 2019; Tutak and Brodny, 2022).

Denmark, Portugal and Romania cover a significant part of their energy consumption from renewable energy sources (Eurostat, 2025a).

Table 15: Share of renewable energy sources in gross energy consumption in "Sustainable energy transformation" cluster

Share of energy from renewable sources (%)	2015	2022
European Union - 27 countries (from 2020)	17.82	23.058
Czech Republic	*15.07*	*18.123*
Denmark	30.469	42.383
Finland	39.23	47.740
Greece	*15.69*	22.671
Ireland	*9.083*	*13.068*
Hungary	*14.495*	*15.128*
Portugal	30.514	34.675
Romania	24.785	24.229

Source: Calculation based on Eurostat database (Eurostat, 2025a)

The Czech Republic is heavily dependent on nuclear energy sources but is also increasing its use of solar and wind energy sources. The country is active in innovation and research and development, especially in increasing energy efficiency and reducing hydrocarbon dependence. The country has set itself the goal of reducing energy imports and using sustainable energy technologies (Osička *et al.*, 2021).

Denmark is one of the leading countries in Europe in the development of renewable energy, especially wind power. The country is at the forefront of wind power and innovative energy storage technologies, thereby reducing its energy imports and promoting a sustainable energy transition (Kirikkaleli, 2023).

Finland used its extensive forest resources to produce bioenergy. It produces a significant amount of electricity from hydropower and wind power. In Finland, the share of renewable energy sources in gross final energy consumption was 47% (Ranta *et al.,* 2020).

For Greece, the use of solar energy offers opportunities, taking advantage of the country's natural resources. To reduce its energy imports, it is necessary to develop innovative energy storage technologies (Tsagkari, 2022). Greece sees hydrogen as a future solution, the produced green hydrogen will primarily replace natural gas and partly crude oil in refineries, industry and the transport sector (Nanaki *et al.*, 2024).

Hungary relies heavily on fossil-based energy, primarily lignite and natural gas. It will be necessary to reduce fossil energy imports, which will also contribute to energy independence and thus to climate protection goals. The construction of solar power plants and biomass-based power plants is expected to increase in addition to new nuclear power units (Lipták and Hadházi, 2021). In addition to exploiting the potential of hydropower and expanding the capacity of existing solar power plants, it is essential to support research and development in energy storage and smart grids.

Romania's natural capacity for producing and consuming energy from renewable sources is supported by its geographic position and climate. The primary sources include biomass, which holds the largest share in renewable energy consumption, along with wind and solar power plants. The country also has significant potential for offshore wind farm development and extensive solar energy opportunities (Yuan *et al.,* 2016; Simionescu *et al.,* 2020).

The economies of the EU Member States are diverse, and their opportunities vary, but thanks to their cooperation, they have developed a unified strategy for sustainability challenges. The focus has been on creating a low-carbon economy and improving energy efficiency. For all this, it is essential that the countries of the continent – considering their natural resources – exploit the potential of renewable energy sources. Innovation and research and development play a decisive role.

5. Discussion

The study offers empirical evidence on the evolving relationships between economic growth, innovation, and environmental sustainability in EU-27 Member States from 2015 to 2022, revealing weakening positive correlations between GDP and GHG emissions (from r=0.950 to 0.945), GDP and GERD (0.958 to 0.955), and energy consumption and GDP (0.990 to 0.981), alongside cluster analysis that identifies six distinct pathways. These findings indicate early signs of decoupling consistent with EKC theory, where emissions growth stagnates amid rising renewables (17.82% to 23.58%) and GERD surges (e.g., Germany's +36.8%), yet highlight the modest scale of reductions signalling incomplete structural shifts.

While core EKC reviews by Dinda (2004), Kaika and Zervas (2013), and Stern (2018) affirm an inverted-U pattern sensitive to methodology and context, this analysis extends their framework with post-2015 EU-specific correlations that quantify Green Deal-driven weakening without full reversal — unlike You and Lv (2018)'s global 1985-2013 panels, which miss recent innovation surges and country heterogeneity. Gilli et al. (2013)'s sectoral EU insights, emphasizing Germany's environmental innovation edge, find broader application here through macro-level clusters distinguishing leaders like Spain (+46.7% GERD) from laggards like Slovakia's energy dependency, thus advancing beyond pre-SDG granularity.

The inverse GERD-emissions link (r=0.886-0.909) builds on Rennings (2000) and Horbach et al. (2012)'s foundational claim of green innovation's dual benefits, but contributes novel quantification of SDG-era effects, where research and development growth outpaces GDP to mitigate emissions — contrasting contradictory growth-SDG findings in Thore and Tarverdyan (2022) versus Gazi et al. (2024), and Khan et al. (2025)'s conditional OECD patterns with EU-specific evidence. Similarly, Urban and Hametner (2022)'s GDP-pressure concerns gain precision from this study's energy-GHG stability (r=0.976-0.979), underscoring renewables' role absent in prior qualitative assessments.

6. Conclusion

The study provides that EU Member States are beginning to separate economic growth from GHG emissions. This can be observed in the decrease of the GDP-GHG correlation from 0.950 to 0.945, supported by the increasing importance and role of research and development (GERD, r=0.886–0.909) in reducing emissions. Nonetheless, the progress is still fairly limited in certain countries, anticipating further indispensable changes to meet the SDGs.

Theoretical Implications. By combining correlation analysis with cluster analysis, the study underpins the relevance of EKC theory in the EU after 2015. It suggests that when GERD grows faster than GDP, the link between economic growth and emissions weakens. This supplements to previous research by using granular data of 27 Member States from 2015 to 2022. The method further provides differences in terms of how countries progress towards SDGs, highlighting that GERD and renewable energy usage are key factors in decoupling growth from emissions. The results are based on correlations; not proving cause and effect, nonetheless they provide a strong foundation for future line of research.

Practical Implications. The slight decrease in GDP-energy consumption correlations (from 0.990 to 0.981) indicates early steps toward a more efficient energy usage and relying more on renewable energy sources. However, some countries show negligible growth in GERD, suggesting the need for policies that facilitate green innovation. This should reinforce maintaining economic growth and investments while lowering emissions, underpinning SDG 8 (decent work), SDG 9 (industry and innovation), and SDG 13 (climate action). Sharing experience and best practices across country clusters could contribute to achieve a better balance between economic growth and environmental protection.

Cluster-Specific Recommendations

For Cluster 1, represented by Germany, policymakers should maintain GERD increases of 36.8% with ongoing investments in renewable technologies and innovation exports to sustain emission reductions of 16.7% alongside economic growth. In Cluster 2, including France and Italy, leaders should build on France's nuclear power share above 70% and Italy's renewables growth to 19.1% through hydrogen incentives and energy diversification, aiding GDP rises of 20.6% and 20.1%.

Cluster 3 countries like Spain and Poland need faster decarbonization to 2050, with Spain focusing on solar and wind expansion and Poland shifting from fossil fuels via efficiency improvements and research support to cut high emissions.

Clusters 4, 5, and 6 represent underperforming Member States with persistent innovation gaps, high fossil fuel dependence, and slower sustainability progress, necessitating intensified interventions to achieve energy independence and SDG alignment. Specifically, Cluster 4 states such as Austria, Belgium, the Netherlands, and Sweden should prioritize expansion of offshore wind capacities and bioenergy infrastructure, capitalizing on their geographic advantages and moderate energy demands to accelerate emission reductions beyond current levels. Cluster 5, encompassing diversified smaller economies like Cyprus, Malta, and Greece, must diversify energy sources through aggressive solar and wind deployment alongside demand-side management programs, addressing lower baseline consumption while building resilience against import vulnerabilities. Cluster 6 transition-focused nations, including the Czech Republic, Hungary, and Slovakia, require deployment of advanced battery storage and grid modernization technologies to phase out coal dependency, coupled with GERD incentives targeted at green manufacturing for rapid decoupling of growth from GHG outputs.

These recommendations support the European Green Deal by linking SDGs 8, 9, and 13 through use of local resources for climate neutrality by 2050.

Declarations. *All authors declare that they have no conflicts of interest.*

References

1. Ahmad, N., Du, L., Tian, X. L., Wang, J. (2019). Chinese Growth and Dilemmas: modelling energy consumption, CO_2 emissions and growth in China. *Quality & Quantity*, 53, 315-338. https://doi.org/10.1007/s11135-018-0755-0
2. Alnafrah, I. (2025). Evaluating efficiency of green innovations and renewables for sustainability goals. *Renewable and Sustainable Energy Reviews*, 209, Article 115137. https://doi.org/10.1016/j.rser.2024.115137
3. Amin, N., Shabbir, M. S., Song, H., Farrukh, M. U., Iqbal, S., Abbass, K. (2023). A step towards environmental mitigation: Do green technological innovation and institutional qual-

ity make a difference?. *Technological Forecasting and Social Change*, 190, Article 122413. https://doi.org/10.1016/j.techfore.2023.122413

4. Asiaban, S., Kayedpour, N., Samani, A. E., Bozalakov, D., De Kooning, J. D. M., Crevecoeur, G., Vandevelde, L. (2021). Wind and Solar Intermittency and the Associated Integration Challenges: A Comprehensive Review Including the Status in the Belgian Power System. *Energies*, 14, Article 2630. https://doi.org/10.3390/en14092630
5. Basheer, M., Nechifor, V., Calzadilla, A., Ringler, C., Hulme, D., Harou, J. J. (2022). Balancing national economic policy outomé for sustainable development. *Nature Communications*, 13, Article 5041. https://doi.org/10.1038/s41467-022-32415-9
6. Bórawski, P. Bełdycka-Bórawska, A., Szymańska E. J., Jankowski K. J., Dubis, B., Dunn, J. W. (2019). Development of renewable energy sources market and biofuels in the European Union. *Journal of Cleaner Production*, 228, 467-484. https://doi.org/10.1016/j.jclepro.2019.04.242
7. Burdiuzha, A., Gorokhova, T., & Mamatova, L. (2020). Responsible environmental management as a tool for achieving the sustainable development of European countries. *Intellectual Economics, 14*(1), 161–183. https://doi.org/10.13165/IE-20-14-1-10
8. Canelli, R, Fontana, G., Realfonzo, R., Passarella, M. V. (2024). Energy crisis, economic growth and public finance in Italy. *Energy Economics*, 132, Article 107430. https://doi.org/10.1016/j.eneco.2024.107430
9. Del-Aguila-Arcentales, S., Alvarez-Risco, A., Jaramillo-Arévalo, M., De-la-Cruz-Diaz, M., de las Mercedes Anderson-Seminario, M. (2022). Influence of social, environmental and economic sustainable development goals (SDGs) over continuation of entrepreneurship and competitiveness. *Journal of Open Innovation: Technology, Market, and Complexity*, 8, Article 73. https://doi.org/10.3390/joitmc8020073
10. Dessi, P., Bosch-Vilardell, T., and Puig, S. (2024). CO_2 emissions: A challenge but also a big opportunity for Spain. *Open Research Europe*, 4, Article 65. https://doi.org/10.12688/openreseurope.17116.1
11. Dinda, S. (2004). Environmental Kuznets Curve Hypothesis: A Survey. *Ecological Economics*, 49, 431-455. https://doi.org/10.1016/j.ecolecon.2004.02.011
12. Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 available at: https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng (accessed 23 November 2024)
13. Di Vaio, A., Hassan, R., Chhabra, M., Arrigo, E., Palladino, R (2022). Sustainable entrepreneurship impact and entrepreneurial venture life cycle: a systematic literature review. *Journal of Cleaner Production*, 378 https://doi.org/10.1016/j.jclepro.2022.134469
14. Di Vaio, A., Hassan, R. and Palladino, R., (2023). Blockchain technology and gender equality: a systematic literature review. *International Journal of Information Management*, 68 https://doi.org/10.1016/j.ijinfomgt.2022.102517
15. Erat, S., Telli, A., Ozkendir, O. M., Demir, B. (2021). Turkey's energy transition from fossil-based to renewable up to 2030: milestones, challenges and opportunities. *Clean Technologies and Environmental Policy*, *23*(2), 401-412.https://doi.org/10.1007/s10098-020-01949-1
16. Esposito, L., and Romagnoli, G. (2023). Overview of policy and market dynamics for the de-

ployment of renewable energy sources in Italy: Current status and future prospects. *Heliyon*, 9. https://doi.org/10.1016/j.heliyon.2023.e17406
17. Eurostat (2024). Air emissions accounts totals bridging to emission inventory totals available at: https://ec.europa.eu/eurostat/databrowser/view/env_ac_aibrid_r2__custom_15142397/default/table, (accessed 20.05.2025) https://doi.org/10.2908/ENV_AC_AIBRID_R2
18. Eurostat (2025a). Final energy consumption available at: https://ec.europa.eu/eurostat/databrowser/view/sdg_07_11/default/table, (accessed 20.05.2025) https://doi.org/10.2908/SDG_07_11
19. Eurostat (2025b). Gross domestic product at market prices available at: https://ec.europa.eu/eurostat/databrowser/view/tec00001/default/table, (accessed 20.05.2025) https://doi.org/10.2908/TEC00001
20. Eurostat (2025c). Gross fixed capital formation (investments) available at: https://ec.europa.eu/eurostat/databrowser/view/tec00011/default/table (accessed 20.05.2025) https://doi.org/10.2908/TEC00011
21. Eurostat (2025d): GERD by sector of performance available at: https://ec.europa.eu/eurostat/databrowser/view/rd_e_gerdtot__custom_12119569/default/table (accessed 20.05.2025) https://doi.org/10.2908/RD_E_GERDTOT
22. Fuso Nerini, F., Tomei, J., To, L. S., Bisaga, I., Parikh, P., Black, M., Borrion, A., Spataru, C., Castán Broto, V., Anandarajah, G., Milligan, B., Mulugetta, Y. (2018). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nature Energy,* 3, 10–15. https://doi.org/10.1038/s41560-017-0036-5
23. Gazi, M. A. I., Islam, H., Islam, M. A., Karim, R., Momo, S. M., Senathirajah, A. R. B. S. (2024). Unlocking sustainable development in East Asia Pacific and South Asia: An econometric exploration of ESG initiatives. *Sustainable Environment*, 10. https://doi.org/10.1080/27658511.2024.2366558
24. Georgescu, C. M., Olimid, A. P., Olimid, D. A., & Gherghe, C. L. (2025). A cross sectional review of energy transition, security and climate change policies. *Economics Ecology Socium*, 9(2). https://doi.org/10.61954/2616-7107/2025.9.2-2
25. Gilli, M., Mazzanti, M., and Nicolli, F. (2013). Sustainability and competitiveness in evolutionary perspectives: Environmental innovations, structural change and economic dynamics in the EU. *The Journal of Socio-Economics*, 45, 204-215. https://doi.org/10.1016/j.socec.2013.05.008.
26. Hassan, Q., Nassar, A. K., Al-Jiboory, A. K., Viktor, P., Telba, A. A., Awwad, E. M., Fakhruldeen, A. A. H. F., Algburi, S., Mashkoor, S. C., Jaszczur M., Sameen A., Z., Barakat, M. (2024a). Mapping Europe renewable energy landscape: Insights into solar, wind, hydro, and green hydrogen production. *Technology in Society*, 77, Article 102535. https://doi.org/10.1016/j.techsoc.2024.102535
27. Hassan, Q., Viktor, P., Al-Musawi, T. J., Ali, B. M., Algburi, S., Alzoubi, H. M., Al-Jiboory, A. K., Sameen, A. Z., Salman, H. M., Jaszczur, M. (2024b). The renewable energy role in the global energy Transformations. *Renewable Energy Focus*, 48, Article 100545.https://doi.org/10.1016/j.ref.2024.100545
28. Horbach, J. (2008). Determinants of environmental innovation - New evidence from German panel data sources. *Research Policy,* 37, 163–173. https://doi.org/10.1016/j.respol.2007.08.006
29. Horbach, J., Rammer, C., and Rennings, K. (2012). Determinants of eco-innovations by type

of environmental impact - The role of regulatory push/pull, technology push and market pull. *Ecological Economics,* 78, 112–122. https://doi.org/10.1016/j.ecolecon.2012.04.005
30. Horne, J., Recker, M., Michelfelder, I., Jay, J., Kratzer, J. (2020). Exploring entrepreneurship related to the sustainable development goals-mapping new venture activities with semi-automated content analysis. *Journal of Cleaner Production*, 242., Article 118052.https://doi.org/10.1016/j.jclepro.2019.118052
31. Huang, R. (2023). SDG-oriented sustainability assessment for Central and Eastern European countries. *Environmental and Sustainability Indicators*, 19 https://doi.org/10.1016/j.indic.2023.100268
32. IEA (2021). Energy Policy Review, Spain 2021 International Energy Association, available at: https://www.iea.org/reports/spain-2021 (accessed 21 March 2024).
33. Igliński, B., Pietrzak, M. B., Kiełkowska, U., Skrzatek, M., Kumar, G., Piechota, G. (2022). The assessment of renewable energy in Poland on the background of the world renewable energy sector. *Energy*, *261*, 125319. https://doi.org/10.1016/j.energy.2022.125319
34. Islam, H. (2025). Nexus of economic, social, and environmental factors on sustainable development goals: The moderating role of technological advancement and green innovation. *Innovation and Green Development*, Volume 4, Article 100183. https://doi.org/10.1016/j.igd.2024.100183.
35. Kaczmarek, J., Kolegowicz, K., and Szymla, W. (2022). Restructuring of the coal mining industry and the challenges of energy transition in Poland (1990–2020). *Energies*, 15, Article 3518. https://doi.org/10.3390/en15103518
36. Kaika, D. and Zervas, E. (2013). The Environmental Kuznets Curve (EKC) theory—Part A: Concept, causes and the CO_2 emissions case, *Energy policy*, 62, 1392-1402. https://doi.org/10.1016/j.enpol.2013.07.131
37. Khan, K. A., Subhan, M., Tiwari, S., Anser, M. K., Destek, M. A. (2025). Impacts of natural resources and technological innovation on SDG achievement of OECD countries: How does democracy and globalization behave?. *Technology in Society*, 81, Article 102778. https://doi.org/10.1016/j.techsoc.2024.102778
38. Kirikkaleli, D., Abbasi, K.R. and Oyebanji, M.O. (2023). The asymmetric and long-run effect of environmental innovation and CO_2 intensity of GDP on consumption-based CO_2 emissions in Denmark. *Environmental Science and Pollution Research,* 30, 50110-50124. https://doi.org/10.1007/s11356-023-25811-1
39. Koundouri, P., Alamanos, A., Plataniotis, A., Stavridis, C., Perifanos, K., Devves, S. (2024). Assessing the sustainability of the European Green Deal and its interlinkages with the SDGs. *Climate Action*, 3, Article 23. https://doi.org/10.1038/s44168-024-00104-6
40. Koval, V.; Borodina, O.; Lomachynska, I.; Olczak, P.; Mumladze, A.; Matuszewska, D. Model Analysis of Eco-Innovation for National Decarbonisation Transition in Integrated European Energy System. *Energies* 2022, 15, 3306. https://doi.org/10.3390/en15093306
41. Kuznets, S. (1955). Economic Growth and Income Inequality. *The American Economic Review*, 45, 1-28.
42. Lamei, Y., Zhou, Y., and Shan, L. (2023). Environmental efficiency, climate innovation, and resource rent in China's SDGs: Insights from quantile regressions. *Resources Policy*, 86, Article 104021. https://doi.org/10.1016/j.resourpol.2023.104021
43. Lamichhane, S., Eğilmez, G., Gedik, R., Bhutta, M. K. S., Erenay, B. (2021). Benchmarking OECD countries' sustainable development performance: A goal-specific principal compo-

nent analysis approach. *Journal of Cleaner Prod*uction, 287 https://doi.org/10.1016/j.jclepro.2020.125040
44. Leal, P. H., and Marques, A. C. (2022). The evolution of the environmental Kuznets curve hypothesis assessment: A literature review under a critical analysis perspective. *Heliyon*, 8 https://doi.org/10.1016/j.heliyon.2022.e11521
45. Lipták, R. and Hadházi T. (2021). A villamosenergia-felhasználás változása *Multidiszciplináris tudományok*, 11, 167-174 https://doi.org/10.35925/j.multi.2021.3.19
46. Liu, M., Ren, X., Cheng, C., Wang, Z. (2020). The role of globalization in CO2 emissions: A semi-parametric panel data analysis for G7. *Science of The Total Environment*, 718, Article 137379. https://doi.org/10.1016/j.scitotenv.2020.137379
47. Ma, X., Ahmad, N., and Oei, P. Y. (2021). Environmental Kuznets curve in France and Germany: Role of renewable and nonrenewable energy. *Renewable Energy*, 172, 88-99. https://doi.org/10.1016/j.renene.2021.03.014
48. Meadowcroft, J. (2007). Who is in charge here? Governance for sustainable development in a complex world. *Journal of Environmental Policy & Planning*, 9, 299–314. https://doi.org/10.1080/15239080701631544
49. Nanaki, E. A., Kiartzis, S., and Xydis, G. (2024). Is Greece Ready for a Hydrogen Energy Transition? – Quantifying Relative Costs in Hard to Abate Industries. *Energies*, 17, Article 1722. https://doi.org/10.3390/en17071722
50. Osička, J., Černoch, F., Zapletalová, V., Lehotský, L. (2021). Too good to be true: Sugarcoating nuclear energy in the Czech national energy strategy. *Energy Research & Social Science*, 72, Article 101865. https://doi.org/10.1016/j.erss.2020.101865
51. Ottomano Palmisano, G., Rocchi, L., Negri, L., Piscitelli, L. (2025). Evaluating the Progress of the EU Countries Towards Implementation of the European Green Deal: A Multiple Criteria Approach. *Land*, 14, Article 141. https://doi.org/10.3390/land14010141
52. Oyebanji, M. O., Castanho, R. A., Genc, S. Y., Kirikkaleli, D. (2022). Patents on environmental technologies and environmental sustainability in Spain. *Sustainability*, 14, Article 6670. https://doi.org/10.3390/su14116670
53. Pata, U. K., Erdogan, S., and Ozcan, B. (2023). Evaluating the role of the share and intensity of renewable energy for sustainable development in Germany. *Journal of Cleaner Production*, 421, Article 138482. https://doi.org/10.1016/j.jclepro.2023.138482
54. Pavlov, T. (2022). The political economy of coal in Bulgaria: The silent phase-out. Jacob, M., Steckel, J.C. (Eds.). *The Political Economy of Coal,* Routledge, London, 40-59. https://doi.org/10.4324/9781003044543
55. Paramarta, V., Rahman, A., Priska, L., Gurning, R. R., Purwati, W. A. (2025). Comparative Analysis of K-Means and Gaussian Mixture Model in Clustering Global CO2 Emissions. *bit-Tech*, *8*(1), 998-1008. https://doi.org/10.32877/bt.v8i1.2805
56. Peel, D., McLachlan, G.J. (2000). Robust mixture modelling using the t distribution. *Statistics and Computing* 10, 339–348. https://doi.org/10.1023/A:1008981510081
57. Prokopenko, O., Chechel, A., Koldovskiy, A., & Kldiashvili, M. (2024). Innovative models of green entrepreneurship: Social impact on sustainable developmemt of local economies. *Economics Ecology Socium*, 8(1). https://doi.org/10.61954/2616-7107/2024.8.1-8.
58. Ranta, T., Laihanen, M., Karhunen, A. (2020). Development of the bioenergy as a part of renewable energy in the Nordic countries: A comparative analysis. *Journal of Sustainable Bioenergy Systems*, 10, 92-112. https://doi.org/10.4236/jsbs.2020.103008

59. Ravn Boess, E., and González Del Campo, A. (2023). Motivating a change in environmental assessment practice: Consultant perspectives on SDG integration. *Environmental Impact Assessment Review*, 101, Article 107105. https://doi.org/10.1016/j.eiar.2023.107105
60. Reed, M. S. (2008). Stakeholder participation for environmental management: A literature review. *Biological Conservation*, 141, 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014
61. Rennings, K. (2000). Redefining innovation - eco-innovation research and the contribution from ecological economics. *Ecological Economics,* 32, 319–332. https://doi.org/10.1016/S0921-8009(99)00112-3
62. Ridwan, M., Raihan, A., Ahmad, S., Karmakar, S., Paul, P. (2023). Environmental Sustainability in France: The Role of Alternative and Nuclear Energy, Natural Resources, and Government Spending. *Journal of Environmental and Energy Economics*, 2, 1–16. https://doi.org/10.56946/jeee.v2i2.343
63. Scarlat, N., Dallemand, J. F., Motola, V., Monforti-Ferrario, F. (2013). Bioenergy production and use in Italy: Recent developments, perspectives and potential. *Renewable Energy*, 57, 448-461.https://doi.org/10.1016/j.renene.2013.01.014
64. Simionescu, M., Strielkowski, W., Tvaronavičienė, M. (2020). Renewable Energy in Final Energy Consumption and Income in the EU-28 Countries. *Energies,* 13, Article 2280. https://doi.org/10.3390/en13092280
65. Soergel, B., Kriegler, E., Weindl, I., Rauner, S., Dirnaichner, A., Ruhe, C., Hoffmann, M., Bauer, N., Bertram, C., Bodirsky, L., Leimbach, M., Leininger, J., Levesque, A., Luderer, G., Pehl, M., Wingens, C., Baumstark, L., Beier, F., Dietrich, J. P., Humpenöder, F., von Jeetze, P., Klein, D., Koch, J., Pietzcker, R., Strefler, J., Lotze-Campen, H., Popp, A. (2021). A sustainable development pathway for climate action within the UN 2030 Agenda. *Nature Climate Change*, 11, 656-664. https://doi.org/10.1038/s41558-021-01098-3
66. Stern, D. I. (2018). The environmental Kuznets curve. Castree, N., Hulme, M. and Proctor, J.D. (Eds.). *Companion to Environmental Studies,* Routledge, London, 49-54. https://doi.org/10.4324/9781315640051
67. Talenti, R. (2025). Climate neutrality through green growth? Addressing possible tensions between the European green deal and the precautionary principle. *International Environmental Agreements: Politics, Law and Economics* https://doi.org/10.1007/s10784-025-09675-z
68. Thore, S., and Tarverdyan, R. (2022). Economic growth and sustainability. *Measuring Sustainable Development Goals Performance*, 5–22. https://doi.org/10.1016/b978-0-323-90268-7.00002-5
69. Tomassi, A., Caforio, A., Romano, E., Lamponi, E., Pollini, A. (2024). The development of a competence framework for environmental education complying with the European qualifications framework and the European green deal. *The Journal of Environmental Education*, 55, 153-179. https://doi.org/10.1080/00958964.2023.2259846
70. Tsagkari, M. (2022). Energy Governance in Greece. Knodt, M and Kemmerzell J. (Eds.). *Handbook of Energy Governance in Europe,* Springer Cham. Place of public, 709-736. https://doi.org/10.1007/978-3-030-43250-8
71. Tutak, M., and Brodny, J. (2022). Renewable energy consumption in economic sectors in the EU-27. The impact on economics, environment and conventional energy sources. A 20-year perspective. *Journal of Cleaner Production*, 345, Article 131076. https://doi.org/10.1016/j.jclepro.2022.131076

72. Urban, P., and Hametner, M. (2022). The economy–environment nexus: Sustainable development goals interlinkages in Austria. *Sustainability*, 14, Article 12281. https://doi.org/10.3390/su141912281
73. Van der Loos, A., Normann, H. E., Hanson, J., Hekkert, M. P. (2021). The co-evolution of innovation systems and context: Offshore wind in Norway and the Netherlands. *Renewable and Sustainable Energy Reviews*, 138, Article 110513.https://doi.org/10.1016/j.rser.2020.110513
74. Wolf, S., Teitge, J., Mielke, J., Schütze, F., Jaeger, C. (2021). The European Green Deal - More Than Climate Neutrality, *Intereconomics*, 56, 99–107. https://doi.org/10.1007/s10272-021-0963-z
75. Wu, X., Fu, B., Wang, S., Liu, Y., Yao, Y., Li, Y., Xu, Z., Liu, J. (2023). Three main dimensions reflected by national SDG performance. *The Innovation*, 4, Article 100507. https://doi.org/10.1016/j.xinn.2023.100507
76. Xu, Z., Chau, S. N., Chen, X., Zhang, J., Li, Y., Dietz, T., Wang, J., Winkler, J. A., Fan, F., Huang, B., Li, S., Wu, S., Herzberger, A., Tang, Y., Hong, D., Li, Y., Liu, J. (2020). Assessing progress towards sustainable development over space and time. *Nature,* 577, 74–78. https://doi.org/10.1038/s41586-019-1846-3.
77. Yang, X., Li, N., Mu, H., Pang, J., Zhao, H., Ahmad, M. (2021). Study on the long-term impact of economic globalization and population aging on CO_2 emissions in OECD countries. *Science of the Total Environment*, 787, Article 147625. https://doi.org/10.1016/j.scitotenv.2021.147625
78. You, W. and Lv, Z. (2018). Spillover effects of economic globalization on CO2 emissions: A spatial panel approach. *Energy Economics*, 73, 248-257, https://doi.org/10.1016/j.eneco.2018.05.016.
79. Younas, S., Shoukat, S., Awan, A., Arslan, S. M. (2023). Comparing effects of green innovation and renewable energy on green economy: the metrics of green economy as nucleus of SDGs. *Pakistan Journal of Humanities and Social Sciences*, 11, 1035-1051. https://doi.org/10.52131/pjhss.2023.1102.0415
80. Yuan, C.; Liu, S.; Fang, Z. (2016). Comparison of China's primary energy consumption forecasting by using ARIMA (the autoregressive integrated moving average) model and GM (1,1) model. *Energy*, 100, pp384–390. https://doi.org/10.1016/j.energy.2016.02.001
81. Zhang, J., Wang, S., Zhao, W., Meadows, M. E., Fu, B. (2022). Finding pathways to synergistic development of Sustainable Development Goals in China. *Humanities and Social Sciences Communications*, 9. https://doi.org/10.1057/s41599-022-01036-4.
82. Zuniga, F., and Pincheira, R. (2020). Environmental Kuznets curve bibliographic map: A systematic literature review. *Accounting & Finance*, 61, 1931-1956. https://doi.org/10.1111/acfi.12648
83. Zyadin, A., Natarajan, K., Latva-Käyrä, P., Igliński, B., Iglińska, A., Trishkin, M., ... & Pappinen, A. (2018). Estimation of surplus biomass potential in southern and central Poland using GIS applications. *Renewable and Sustainable Energy Reviews*, *89*, 204-215.https://doi.org/10.1016/j.rser.2018.03.022