

IMPACT OF ENERGY TRANSITION, DIGITAL INTEGRATION, AND FINANCIAL INCLUSION ON EUROPEAN UNION SUSTAINABLE GROWTH

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Abstract. The green and digital transitions are essential priorities in the current context of the European Union's commitment to achieve climate neutrality by 2050 and multiple financial, pandemic, energy crises and international conflicts. The study assesses the relationships between economic, social and environmental variables, using data from 2010–2022 and applying econometric models to analyze the relationships between net greenhouse gas emissions, real Gross Domestic Product (GDP) per capita and factors such as access to digital technology, share of renewable energy, green tax revenues, municipal waste generation and long-term unemployment rate. The results underline the persistent disparities between Member States and the vulnerability of the European Union to external shocks. The novelty of this paper lies in its integrated approach to the relationships between economic, social and environmental variables in the context of the EU's green and digital transition, using econometric models to analyze the influences between greenhouse gas emissions, real GDP per capita and other determinants. The research contributes to the literature by highlighting essential directions for formulating sustainable public policies capable of meeting both the environmental objectives and the economic needs of the European Union in an increasingly uncertain global landscape.

Keywords: energy transition, digitization, sustainability, economic growth, public policies.

JEL Classification: C33, O33, Q56, Q58.

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1. Introduction

In a global context marked by recurrent financial crises, international conflicts and migration, the European Union faces the challenge of continuing its transition to a green, digitized and resilient economy while maintaining its commitments to climate neutrality and sustainable growth. Strategies such as the Green Deal (European Commission, n.d.-a), NextGenerationEU (European Union, n.d.) and Just Transition Fund (European Parliament, 2024b) outline the European Union's commitment to achieve climate neutrality by 2050 and

to ensure sustainable economic growth capable of meeting social needs and environmental challenges. These ambitious targets are affected by the complex dynamics of economic, social and environmental factors, which interact under the influence of external shocks and structural differences between Member States. The interconnectedness of the green and digital transitions introduces both opportunities and challenges. Climate neutrality cannot be achieved without digital technologies that enhance energy efficiency, enable smart infrastructure, and support renewable energy integration. Conversely, digitization itself must be sustainable, requiring energy from clean sources and inclusive access across Member States. However, the EU's structural diversity – in terms of GDP per capita, institutional capacity, technological readiness, and environmental performance – makes this transition asymmetrical. While some countries are front-runners in innovation and clean energy, others face financial and infrastructural constraints that hinder progress.

Figure 1 illustrates the territorial distribution of real GDP per capita (RGDP) and Net Greenhouse Gas Emissions (NETGHG) in the Member States of the European Union for the year 2022, highlighting the significant disparities between them in terms of economic performance and climate sustainability. High levels of GDP per capita are concentrated in North-Western European countries such as Ireland, Luxembourg and the Netherlands, while countries in the South-East of the Union have much lower levels. At the same time, the level of emissions per capita varies widely and is not always directly correlated with economic development – reflecting differences in energy structure, technological efficiency and the application of environmental policies.

This double mapping supports the idea of an asymmetric transition within the European Union: while some economies are simultaneously performing economically and environmentally, others face major challenges in balancing growth and reducing climate impacts. Thus, the evidence underlines the importance of tailored public policies capable of supporting convergence between countries and accelerating the green and digital transition in an inclusive and equitable manner.

Although the literature has extensively examined the relationships between energy transition, digitalization, and sustainability, prior studies tend to address these dimensions in

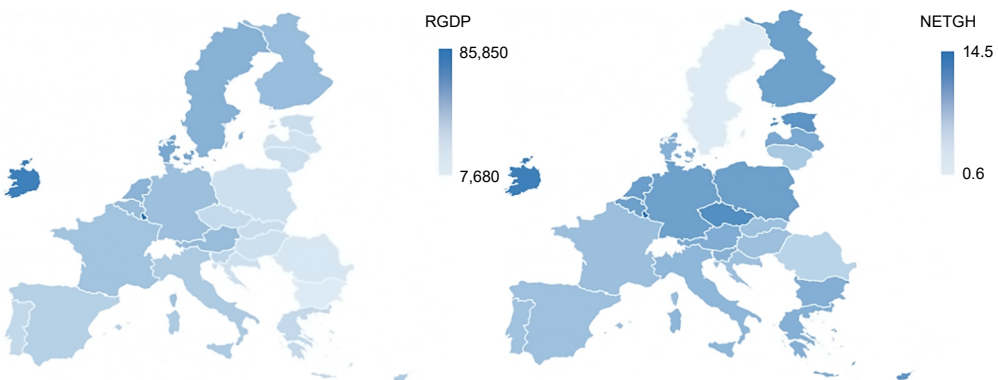


Figure 1. Distribution of real GDP per capita and net greenhouse gas emissions in the Member States of the European Union, 2022 (source: realized by the authors)

isolation or in a linear manner. The lack of an integrated, multidimensional framework that captures the feedback loops and trade-offs between economic, environmental, and social variables leaves a critical gap in both theory and empirical analysis. Moreover, few contributions have examined how these dynamics interact at the regional level across the entire European Union using a long-term, comparative econometric approach.

This study addresses this gap by proposing a novel and comprehensive analytical framework to examine the interrelated impact of green taxation, renewable energy, digital inclusion, and social conditions (e.g., long-term unemployment, waste management) on two core sustainability outcomes: net greenhouse gas emissions and real GDP per capita. The empirical approach is based on two panel data econometric models applied to all 27 EU Member States over the period 2010–2022. This dual-model strategy allows the study to investigate how environmental and digital policy tools jointly influence environmental degradation and economic development.

The contribution of this research is threefold. First, it introduces a unified econometric approach that simultaneously captures the economic, environmental, and social dimensions of sustainability, offering a more holistic view than fragmented analyses in the literature. Second, the paper empirically demonstrates how specific policy levers – such as environmental tax revenues and internet access – interact with broader structural variables to influence the EU's green and digital transitions. Third, it develops differentiated policy recommendations tailored to the diverse capacities and development levels of EU Member States, recognizing that a one-size-fits-all approach is inadequate for achieving EU-wide sustainability objectives.

By integrating these elements into a single analytical framework, this study not only reaffirms existing relationships but also advances the literature by providing a replicable model that can inform adaptive and inclusive public policy. In doing so, it aligns with the strategic vision of the European Union while offering novel empirical insights into how economic and environmental goals can be pursued in tandem, particularly under conditions of structural heterogeneity and external shocks.

This paper aims to assess the impact of public policies on economic and environmental sustainability objectives, highlighting both the progress achieved and the limitations and disparities between Member States.

The main research objectives are:

- O1:** A literature review on the impact of the energy transition, the integration of digital technologies and the promotion of financial inclusion on the dynamics of sustainable economic growth in the European Union.
- O2:** Design of two econometric models respectively Model 1 has as dependent variable Net Greenhouse Gas Emissions (NETGH) and Model 2 has as dependent variable real GDP per capita (RGDP);
- O3:** Formulate public policy recommendations based on the econometric results to develop public strategies to support the green transition, reduce regional disparities and strengthen the economic resilience of the European Union to future challenges.

The paper continues with the literature review, the presentation of the methodology and results, and finally, the formulation of public policies in the context of the EU's green and digital transition.

2. Literature review

The transition to a sustainable and digitized economy is emerging as one of the most significant challenges of the current period, marking a profound and interconnected shift between innovative public policies, rapid technological advances, economic sustainability and social inclusion. As the impact of climate change intensifies and becomes increasingly evident, social inequalities persist, and digitalization is redefining economic paradigms, understanding these complex relationships becomes fundamental to designing strategies and policies capable of responding to these global transformations.

The literature identifies several fundamental directions in analysing the transition towards a sustainable and digitized economy. One of the main themes debated by researchers is the energy transition, with a focus on the integration of renewable energies as a central solution to reduce greenhouse gas emissions and enhance environmental sustainability (Ahmad et al., 2023; B. Chen et al., 2019; Hassan et al., 2024; Kabeyi & Olanrewaju, 2022; Martin et al., 2023; Y. Zhou, 2023). Studies highlight the importance of environmental policies and investments in green energy infrastructure, emphasizing their long-term impact on sustainable development. Another key pillar in the literature is digitization, recognized as a driver of economic growth, innovation and international competitiveness (Abbas et al., 2024; Dabbous et al., 2023; Marti & Puertas, 2023). Developing digital infrastructure and integrating emerging technologies across economic sectors not only boosts productivity but also contributes to reducing economic disparities, facilitating faster convergence between economies (Herman & Oliver, 2023; W. Pan et al., 2022; J. Wang et al., 2022).

According to other authors, financial inclusion and social stability are also topics of significant interest in the economic transition processes (Boachie et al., 2023; Ozturk & Ullah, 2022; Shabir, 2024). Other recent research has emphasized the need for public policies geared towards reducing economic exclusion and ensuring equitable access to financial resources, which are essential to ensure equitable structural transformation (Corti & Vesan, 2023; Hosan et al., 2024; Lopera-Arbeláez & Richter, 2024; Qureshi, 2023). In this context, social inclusion policies complement green transition measures, helping mitigate the social impact of economic transformations.

At the same time, green taxation is identified as a highly effective public policy tool to stimulate sustainable transition (L. K. Chu, 2024; Fatima et al., 2024; Feng & Ge, 2024; Ofori et al., 2023). By discouraging economic practices that have a negative impact on the environment and promoting investment in green innovations, green taxes facilitate both behavioural change and economic development towards a more sustainable model.

Finally, the circular economy and resource efficiency are themes of critical importance in the current context. Specialized studies (Chenavaz & Dimitrov, 2024; Elroi et al., 2023; Vinayagam et al., 2024) underlined the urgency of transforming resource use from a linear to a circular model in which waste is minimized, and materials are reused in extended economic cycles. These transformations support the transition towards sustainability and help reduce economic costs and long-term dependence on primary resources.

These factors, analyzed individually and interdependently, can provide a sound theoretical basis for understanding and addressing the multidimensionality of the economic and ecological transition.

To review the advances and gaps identified in the recent literature and to provide a solid theoretical basis for contextualizing and underpinning its empirical approach, the literature section of this article focuses on the analysis of five key areas: the energy transition and environmental sustainability, the impact of digitalization on economic growth, financial inclusion and social stability, green taxation and economic impacts, and circular economy and waste management. Energy transition and environmental sustainability are necessary responses to the global climate crisis, and the integration of renewables is seen as crucial to reducing greenhouse gas emissions. Digitization is recognized as a catalyst for economic growth and innovation, but a better understanding of its impact on regional disparities is needed. Financial inclusion is critical to reducing inequalities and supporting equitable economic transformations, an issue intensely debated in the context of economic globalization. Green taxation is seen as a powerful tool to combat environmental degradation, but the current literature further explores its effectiveness in different economies. Finally, the circular economy and waste management are emerging as priority themes, given the pressures on natural resources and the need to minimize the environmental impact of waste. These interconnected themes require detailed analysis to inform effective public policies and support the transition towards sustainability.

2.1. Energy transition and environmental sustainability

The energy transition is a crucial process for tackling climate change and achieving global sustainability goals and is a central theme in contemporary academic and policy debates. It involves transforming the energy structure of an economy by reducing dependence on fossil fuels and switching to renewable energy sources such as solar, wind, hydro and biofuels. The share of renewable energy in final energy consumption represents the degree to which clean energy sources displace fossil fuels, contributing indirectly to CO₂ emission reductions. Recent studies underline that renewables are the most promising sources of energy for achieving decarbonization targets (Araújo et al., 2024; Pivetta et al., 2024; Rahman et al., 2023; B. Yu et al., 2023). For example, solar and wind are now considered the most cost-effective forms of energy, especially in developed economies, according to current studies (Akpahou et al., 2024; Atawi et al., 2024; Faqe Ibrahim et al., 2024; Hassan et al., 2023). According to studies by Rao et al. (2024), Wang et al. (2024), Obobisa and Ahakwa (2024), significant investments in renewable energy technology have led to significant decreases in carbon emissions, and subsidy policies and financial incentives have helped to accelerate their deployment.

On the other hand, the economic and political challenges related to energy infrastructure also need to be addressed to support the energy transition on a large scale. Also, integrating renewable energy into a stable electricity grid requires the development of innovative solutions such as energy storage and increasing the flexibility of distribution networks. In this respect, recent research (Bashir et al., 2024b; Chatzistamoulou & Koundouri, 2024; Saqib et al., 2023; K. Yang et al., 2024) have shown that carbon taxes and emissions trading schemes have become key policy instruments to stimulate the energy transition, helping to internalize environmental costs and create an enabling environment for green energy development. Equity and social justice are other key factors in the energy transition, especially in emerging economies that may struggle to adopt green technologies due to a lack of financial resources

or infrastructure. According to recent studies (Bray et al., 2022; Chengyi et al., 2024; Davidson, 2023; Meyer et al., 2023), equitable deployment of renewables requires policies that support not only technological development but also training and retraining of the workforce, especially in traditional sectors such as mining and fossil fuel industries.

Although a growing body of literature supports the positive role of renewable energy in reducing greenhouse gas emissions (Boiko et al., 2025; Gazeloğlu & Erkiçi, 2025; Perone, 2024), findings across studies remain inconsistent, particularly when comparing countries with different levels of economic development and energy dependency. For instance, while developed economies often report significant emission reductions following green investments, emerging economies may experience slower progress due to infrastructural limitations and delayed policy implementation (D’Orazio, 2025; Mahalik et al., 2024; M. Yu et al., 2022). Moreover, only a limited number of studies explore the joint dynamics between energy transition, economic growth, and taxation, despite their evident interdependence.

Against this backdrop, this study hypothesizes (H1) that real GDP per capita is positively associated with net greenhouse gas emissions, reflecting structural economic patterns where higher output levels are often tied to greater energy consumption and industrial intensity. Furthermore, building on recent fiscal-environmental literature, we posit (H2) that energy taxation can be an effective tool for reducing emissions by promoting efficiency and discouraging fossil fuel use. By modeling these relationships across all EU Member States over a 12-year period, this study seeks to fill an important empirical gap regarding the combined role of economic structure and fiscal instruments in shaping environmental outcomes.

2.2. Impact of digitization on economic growth

Digitization is one of the most critical determinants of economic progress, impacting how economies operate, innovate and evolve. In the literature, digitalization is recognized as a major catalyst for productivity, innovation and economic inclusion (Marín et al., 2023; B. Zhang & Chen, 2024). Digital transformation reduces operational costs, optimizes processes and broadens access to global markets, contributing to faster and more sustainable economic growth (Akbari, 2024; Y. Chu et al., 2023). Adopting advanced digital technologies, such as artificial intelligence, automation, big data analytics and blockchain technology, has changed economic paradigms, facilitating the transition to knowledge-based industries and reducing dependence on traditional sectors. Current studies (Herman & Oliver, 2023; Ma & Zhu, 2022; Magoutas et al., 2024; J. Wang et al., 2022) have highlighted the strong correlation between investment in digital infrastructure and GDP growth, particularly in emerging economies, where the penetration of digital technologies accelerates economic convergence with developed economies.

Digitization significantly increases economic productivity by optimizing processes and reducing operational costs in various sectors. Investments in digital infrastructure, such as high-speed internet networks, have a multiplier effect on the economy. Improved connectivity enables the integration of advanced digital solutions in commerce, education and health, increasing efficiency and access to resources and services. Recent studies show that economies that devote significant resources to the development of digital infrastructure benefit from

accelerated GDP growth, in particular, due to the creation of compelling digital ecosystems that connect the public and private sectors (Hanna, 2024; Hao et al., 2024; Zahra et al., 2023; Zheng & Gong, 2024). In Europe, the digitization of public services (e-governance) has significantly improved the efficiency of local administrations, increasing public sector productivity by 15% in the last decade (OECD, 2023a). Digital technologies are the key driver of innovation, facilitating the development of new products and services and lowering barriers to entry in global markets. Automating industrial processes and integrating Artificial Intelligence (AI) help create sustainable competitive advantages (Javaid et al., 2022; Krakowski et al., 2023; Kulkov et al., 2024). Blockchain and big data technologies also enable more efficient resource management, reducing risks and improving real-time strategic decisions (Hader et al., 2022; Narwane et al., 2023; Rane & Narvel, 2022). A study published by McKinsey (McKinsey Global Institute, 2022) shows that firms adopting AI and IoT (Internet of Things) technologies have seen an average 25% increase in competitiveness in international markets.

Digitization also significantly bridges economic gaps between urban and rural regions, facilitating access to resources and economic opportunities for disadvantaged communities. Extending high-speed internet networks to underdeveloped areas improves connectivity and creates the conditions for integrating these regions into the digital economy. Through access to online platforms, rural residents can benefit from more efficient education, health and administrative services, and new economic opportunities such as e-commerce or self-employment (Dong et al., 2024; Seet et al., 2023). Another key aspect of digitalization is its contribution to the transformation of agriculture by adopting intelligent farming technologies (Giua et al., 2022; Jerhamre et al., 2022). IoT sensors, drones and data analytics platforms help farmers optimize production, reduce losses and become more competitive in local and international markets. At the same time, other studies (Fu et al., 2024; Safdar et al., 2022) have shown that digitization of the rural education system is increasing young people's access to modern educational resources, thus reducing urban-rural disparities and preparing a more skilled workforce. These developments contribute to higher local incomes, reduced migration to cities and more balanced economic development between regions.

Despite the general agreement that digitalization fosters innovation and enhances productivity, the empirical literature reveals mixed findings regarding its effects on economic growth, especially in the context of structural disparities between regions. Some studies (B. Behera et al., 2024; Iqbal et al., 2023; Magoutas et al., 2024) highlight the strong positive correlation between investment in digital infrastructure and GDP growth, particularly in highly developed economies. However, other studies (Coco et al., 2024; David et al., 2025; Le Quoc, 2024) emphasize that digital expansion does not always translate into inclusive growth, especially in areas with limited institutional capacity or low digital literacy. These contradictions suggest that digitalization alone is not a panacea and that its impact depends on complementary factors such as education, infrastructure, and governance.

In this study, we examine the hypothesis (H4) that increasing household internet access – used here as a proxy for digital inclusion – has a positive and significant impact on real GDP per capita. This relationship is grounded in the Diffusion of Innovation Theory, which argues that the adoption and diffusion of digital technologies can stimulate economic activity, provided that supportive conditions are in place. By incorporating this variable into

a broader econometric model alongside environmental and fiscal indicators, our approach offers a more comprehensive view of how digitalization interacts with sustainability objectives in the European Union.

2.3. Financial inclusion and social stability

Financial inclusion is fundamental in reducing economic inequality and underpinning social stability. Universal access to essential financial services such as bank accounts, credit and insurance enables individuals and businesses to participate actively in the economy, manage risks and invest in their long-term development, and better access to these services stimulates consumption, increases productivity and reduces economic vulnerability to external shocks (World Bank Group, 2023; Yap et al., 2023). A key indicator of economic and social exclusion is long-term unemployment, which affects people's ability to access essential financial resources, perpetuating the cycle of inequality. In this context, financial inclusion policies become indispensable for the economic integration of vulnerable groups. Investments in financial education programs and financial services infrastructure play a key role in supporting these people, enabling them to access resources for development and participate more actively in the formal economic system. Recent studies confirm the positive impact of financial inclusion on economic resilience (Dragomir-Constantin et al., 2025; Okyere et al., 2024; Z. Yu et al., 2023). Access to digital banking services during the COVID-19 pandemic was a determining factor in keeping small and medium-sized enterprises operational, significantly mitigating the adverse economic effects (Restrepo-Morales et al., 2024; Y. Zhang et al., 2023). At the same time, other studies (Anu et al., 2023; Cevik et al., 2023; S. Gao et al., 2024) emphasized that countries with strong social policies that support financial inclusion had a greater capacity to implement the green transition. These countries have invested in re-skilling programs and training an adaptable workforce for green industries, thereby reducing structural unemployment and supporting sustainable development. Financial inclusion is, therefore, not only a tool for social equity but also a strategic pillar for sustainable economic growth and for mitigating the impact of inequalities on social stability. Investing in this area contributes to building a more resilient economy capable of responding to the complex economic and ecological transition challenges.

While the literature generally acknowledges that financial inclusion promotes economic participation and reduces vulnerability (Chletsos & Sintos, 2023; Khan & Sahu, 2025; Settle, 2022; Shen et al., 2024), its macroeconomic impact remains debated. Some studies argue that inclusive financial systems support consumption, entrepreneurship, and investment, thereby contributing to long-term growth (Becha et al., 2025; Z. Gao et al., 2025; Qamruzzaman, 2025). However, other research highlights that without adequate institutional and fiscal coordination, the benefits of financial inclusion may be offset by increased inequality, inefficiencies, or limited fiscal space in less developed economies (G. Chen & Li, 2024; Halili & Rodriguez Gonzalez, 2025; Wenjuan & Zhao, 2023).

In particular, the interaction between financial inclusion and environmental fiscal policies has been largely overlooked. Environmental tax revenues, while essential for funding green initiatives and discouraging pollution, may impose additional burdens on households and businesses, especially in economies with low financial resilience. Based on this premise, we

hypothesize (H5) that environmental tax revenues have a negative impact on real GDP per capita, reflecting potential cost pressures on economic activity. This study explores this relationship in a panel data framework to capture both the economic and distributive implications of green fiscal policies across the European Union.

2.4. Green taxation and economic effects

Ecological or green taxation has become one of the most powerful tools to promote economic and environmental sustainability. It is key to achieving the goals of reducing greenhouse gas emissions and conserving natural resources. It stimulates responsible economic behaviour by discouraging environmentally damaging practices and supports the transition to a low-carbon economy. Mechanisms such as carbon taxes, renewable energy subsidies and taxes on the use of natural resources are fundamental to achieving these objectives. Carbon taxes are one of the most effective fiscal instruments to reduce emissions and are applied in many developed economies (Bai et al., 2024; Cheng et al., 2024; Köppl & Schratzenstaller, 2023; Timilsina, 2022; Xu et al., 2023). They create economic incentives encouraging companies and individuals to reduce fossil fuel use and switch to cleaner energy sources. Studies show that in countries such as Sweden and Denmark, early implementation of such taxes has led to a significant reduction in CO₂ emissions without negatively affecting economic competitiveness (Köppl & Schratzenstaller, 2023; Stameski et al., 2024; Wolde-Rufael & Mulat-weldemeskel, 2023). In parallel, renewable energy subsidies, such as those for solar and wind energy, provide financial support for the development and deployment of green technologies, thus facilitating the transition to a sustainable economic model (Hashemizadeh et al., 2024; Sampene et al., 2024; Song et al., 2024; S. Wang et al., 2022). Other studies emphasize the importance of using green tax revenues, with countries that reinvest these revenues in renewable energy R&D and green infrastructure reaping the greatest long-term economic benefits (He et al., 2023; Miao et al., 2023). These investments boost technological innovation, create jobs and strengthen competitiveness in international markets. Studies by the authors P. Behera et al. (2024) Nyangon and Darekar (Nyangon & Darekar, 2024) emphasized that properly designed green taxation has the potential to generate significant benefits, particularly in innovative sectors such as advanced energy technologies. Tax policies that consider each country's economic and industrial specificities are considered more effective in promoting overall economic performance, contributing to the transition towards sustainability. Analysis of environmental taxation can be deepened by exploring its impact on polluting industries, especially in regions where resource-intensive sectors dominate the economic structure. Integrating recent research examining the use of tax revenues to support technological innovation and reduce environmental impacts provides a solid basis for understanding how tax policies can become a catalyst for the green transition. Comparisons between economies that have implemented different models of green taxation highlight the role of strategic investments in creating resilient and globally competitive economies (Ao et al., 2023; Qamruzzaman & Karim, 2024).

Although green taxation is widely recognized as an effective instrument for promoting environmental sustainability, empirical evidence reveals important variations in its effectiveness across countries and sectors. For instance, studies such as Salite et al. (2024) and show that early adopters of carbon taxes, like Sweden and Denmark, achieved significant emission

reductions without compromising competitiveness. However, in less developed economies or those with energy-intensive industries, environmental taxes may lead to increased production costs and lower economic output, as highlighted by J. Pan et al. (2024). Moreover, the design and reinvestment mechanisms of these taxes are critical – countries that redirect revenues toward innovation and green infrastructure appear to reap greater long-term benefits.

These divergent findings highlight the dual nature of environmental taxes: on one hand, they can act as effective tools for curbing emissions (H2); on the other, they may impose cost pressures that constrain economic activity, especially when not accompanied by compensatory measures (H5). To better understand this trade-off, our analysis investigates the simultaneous effects of environmental and energy taxation on both net greenhouse gas emissions and real GDP per capita across EU Member States. By doing so, the study offers empirical insights into the complex balance between environmental ambition and economic performance.

2.5. Circular economy and waste management

The circular economy redefines traditional economic paradigms, offering a sustainable model that prioritizes resource efficiency and waste minimization through reuse, recycling and extending the life of materials. This concept reduces pressure on natural resources and stimulates economic innovation, supporting the development of recycling, materials processing and sustainable manufacturing industries. Specialized studies (Kandpal et al., 2024; Rodríguez-Espíndola et al., 2022; M. Yang et al., 2023) highlight that implementing the circular economy has significant economic and social benefits, including reducing emissions, creating jobs and improving economic competitiveness. Waste generation per capita is a crucial indicator of economic efficiency and sustainability, and strategies to reduce it are being intensively studied (Ram & Bracci, 2024; Velis et al., 2023). Standard measures include separate collection programs, using biodegradable materials, and introducing policies to reduce plastic consumption. For example, the study by the authors Chioatto and Sospiro (Chioatto & Sospiro, 2023) shows that circular economy policies in the European Union have led to a reduction of more than 25% in waste generated by industrial sectors, demonstrating the effectiveness of this model. These results underline the potential of the circular economy to contribute to the transition towards sustainability by reducing negative environmental impacts and using resources more efficiently.

Another relevant example is the Circular Economy Action Plan (European Commission, n.d.-b) at the EU level, which provides a legislative and financial framework to support the implementation of the circular economy in all Member States. This plan encourages the reuse of materials and the adoption of innovative technologies, thereby promoting pollution reduction and the development of industries based on circular economic models. Furthermore, this framework emphasizes the importance of cross-border cooperation and investment in research and development to improve recycling processes and reduce waste. The circular economy, therefore, not only supports sustainability goals but also becomes a catalyst for transforming traditional economies into more resilient, efficient and innovative systems research studies (Giannetti et al., 2023; Perramon et al., 2024; Wielopolski & Bulthuis,

2023) reinforcing the importance of these policies, underlining the need for their widespread adoption to respond to the economic and environmental challenges of this century.

The literature review highlights the importance of an integrated approach in transitioning to a sustainable and digitized economy, where public policy, technological innovation and economic and social sustainability are interconnected. The analysis of these dimensions emphasizes the need for extensive collaboration between the public and private sectors, supported by academic and empirical research, to guide the implementation of effective solutions. The insights provided by the reviewed literature highlight both the progress made and the existing gaps, especially in adapting to the regional specificities of emerging economies. The focus on the interactions between the energy transition, digitization, financial inclusion, green taxation and the circular economy also outlines a future research agenda that can support more informed policy making. This theoretical framework underpins our understanding of current challenges and provides clear directions for exploring innovative and adaptable solutions that respond to global economic, social and environmental transformations.

The circular economy is increasingly presented as a transformative model for sustainable development, with numerous studies confirming its potential to reduce environmental pressures and support innovation (Al Halbusi et al., 2024; Mishra et al., 2024; Osei et al., 2024; Socol et al., 2025). However, the effectiveness of circular practices remains uneven across regions, and empirical evidence regarding their impact on macroeconomic performance is still developing. While some research demonstrates a decoupling between economic growth and resource use (Ding et al., 2024; Naz et al., 2024; Z. Zhou et al., 2024), other studies note that high-income countries continue to generate substantial amounts of waste, reflecting consumption-driven patterns that are not easily offset by recycling or reuse (Nhunh Thang & Nguyen, 2025; Reppmann et al., 2024).

In this context, the generation of municipal waste per capita can be interpreted as a proxy for both consumption levels and resource inefficiency. Building on this view, we hypothesize (H3) that waste generation is positively associated with real GDP per capita, reflecting the tendency of more developed economies to generate more waste due to higher levels of consumption. By including this variable in both environmental and economic models, our study seeks to assess to what extent current waste levels are structurally linked to economic performance and whether circular strategies are sufficient to alter this dynamic.

2.6. Research gap

Although the literature has made considerable progress in exploring the links between energy transition, digitalization, and sustainable development, there is still a fragmented understanding of how these dimensions interact in an integrated and dynamic framework. Most studies tend to analyze these components separately or through simplified models that overlook the feedback loops and trade-offs between environmental, economic, and social variables (Bakhsh et al., 2024b; Chipangamate & Nwaila, 2024; Guandalini, 2022; Hariram et al., 2023). Additionally, existing research often focuses on national case studies or limited geographic areas, lacking a comprehensive comparative analysis across the entire European Union (Alatawi et al., 2023; Cheba et al., 2024; van der Jagt et al., 2023). Very few contributions combine variables such as green taxation, digital inclusion, renewable energy adoption, and

social indicators (e.g., long-term unemployment, waste generation) within a single empirical model, applied over a long time span and across all EU Member States (Fabra et al., 2024; Georgescu et al., 2025; Imran et al., 2024; Nademi & Sedaghat Kalmarzi, 2025; OECD, 2023b).

This gap is particularly important in the context of the EU's 2050 climate neutrality objective, where achieving convergence in sustainability outcomes requires a nuanced understanding of cross-country heterogeneity. There is a need for robust econometric models capable of capturing how policy instruments and structural differences influence both environmental and economic performance in parallel.

The present study addresses this research gap by proposing an integrated panel data approach, covering all 27 EU countries from 2010 to 2022, to jointly assess the impact of public policies and structural factors on real GDP per capita and net greenhouse gas emissions. In doing so, it contributes to the literature by offering a holistic and policy-relevant perspective that can support differentiated and effective strategies for green and digital transitions across the EU.

3. Methodology

3.1. Research design and description of variables

This study employs a research design based on panel data regression model estimation to analyze the impact of environmental and digital transition policies on economic growth and environmental sustainability in the European Union. The empirical framework is structured around two dependent variables – real GDP per capita and net greenhouse gas emissions per capita – which serve as indicators for economic and environmental performance, respectively.

The empirical analysis is performed using an unbalanced panel dataset covering the 27 EU Member States over the period 2010–2022. The selection of this time span is motivated by both methodological and substantive considerations. Methodologically, this period ensures the availability and comparability of data for a wide range of sustainability indicators as compiled by Eurostat. In substantive terms, it corresponds to a critical phase in the EU policy landscape, marked by the transition from the Europe 2020 Strategy- which emphasized smart, sustainable and inclusive growth – to the consolidation of the European Green Deal and Digital Compass frameworks. The chosen timeframe captures the institutionalization and operationalization of environmental taxation, renewable energy targets, the expansion of digital infrastructure and broader climate commitments in line with the EU's 2050 goal of climate neutrality.

In addition, the period encompasses several major economic and geopolitical disruptions – including the European sovereign debt crisis, the Brexit process and the COVID-19 pandemic – that allow for empirical examination of how these shocks have interacted with sustainability trajectories in different national contexts.

All variables included in the study are sourced from the Eurostat database, ensuring harmonization, transparency and statistical consistency across countries. The dataset includes macro-economic indicators (real GDP per capita, environmental tax revenues), environmental measures (net GHG emissions, municipal waste generation) and digital and social variables (internet access, long-term unemployment), allowing an integrated assessment of sustainability from a multidimensional perspective.

The empirical analysis employs the Ordinary Least Squares (OLS) regression method to estimate the relationships between economic, environmental, fiscal, and digital variables across the 27 EU Member States over the period 2010–2022. The models are estimated using pooled OLS, assuming homogeneity in the slope coefficients across countries and over time.

Table 1. Presentation of indicators (source: prepared by authors based on Eurostat data)

Variables	Symbol	Measurement	Source
Net greenhouse gas emissions	NETGH	Tonnes per capita	Eurostat (n.d.-d)
Real GDP per capita	RGDP	Euro per capita	Eurostat (n.d.-e)
Level of internet access – household	LEVI	Percentage	Eurostat (n.d.-c)
Long-term unemployment rate	UNEMP	Percentage	Eurostat (n.d.-h)
Environmental tax revenues	TAXENV	Percentage of total revenues from taxes and social contributions	Eurostat (n.d.-f)
Share of renewable energy in gross final energy consumption	RENEW	Percentage	Eurostat (n.d.-g)
Energy taxes	TAXEN	Million euro	Eurostat (n.d.-a)
Generation of municipal waste per capita	WASTM	Kilograms per capita	Eurostat (n.d.-b)

These indicators are central pillars in the structure of the EU's green and social transition policies and help to understand how the economy can be adapted to reduce emissions and support sustainable growth. Using the Eurostat platform for 12 years (2010–2022), as shown in Table 1, the model captures both the impact of political and economic changes and the long-term trends that characterize the EU's energy transition. In addition, this approach identifies the cumulative effects of technological innovation and the implementation of environmental taxes, providing policy makers with important information for adjusting and optimizing public policies.

The choice of indicators for the proposed econometric models is based on their relevance in the analysis of economic sustainability and impact on greenhouse gas emissions and economic growth. Each indicator reflects important aspects of the European Union's environmental, economic and social policies in the energy transition period 2010–2022.

The selection of the independent variables is grounded in recent empirical literature focused on the interplay between economic growth, environmental sustainability, and digital and fiscal policies within the European Union. Each variable included in the model has been previously employed in comparable studies and reflects one of the three sustainability pillars – economic, environmental, and social.

Real GDP per capita (RGDP) is used as a proxy for economic performance and well-being, and has frequently been analyzed in relation to emissions or environmental degradation (Bekun et al., 2023; Magazzino et al., 2022; Ohajionu et al., 2022). The expected sign in relation to greenhouse gas emissions is positive.

Net greenhouse gas emissions (NETGH) represent the environmental output targeted by climate policies and are considered a core sustainability indicator in EU-level studies (European Environment Agency, 2025a 2025b; Varadi et al., 2025).

Energy taxes (TAXEN) are included as fiscal tools to stimulate energy efficiency, with multiple studies confirming their negative effect on emissions due to price-based disincentives (Bakhsh et al., 2024a; Rosales-Asensio et al., 2024; Setiawan et al., 2022).

Municipal waste per capita (WASTM) is a consumption-driven environmental indicator. Prior studies (Arif et al., 2023; Liu et al., 2024; Satrovic et al., 2024) find that increased economic activity tends to correlate with higher waste generation, suggesting a positive relationship with RGDP.

Household internet access is used as a proxy for digital inclusion, in line with research (Baffour Gyau et al., 2025a; de Clercq et al., 2023; Hashemizadeh et al., 2023) showing that internet access facilitates economic participation. The expected impact on GDP is positive.

Environmental tax revenues (TAXENV) are analyzed as part of green fiscal strategies. While intended to support sustainability, they can impose cost burdens, especially in low-resilience economies (Esen et al., 2021; European Environment Agency, 2025c; Hu et al., 2024; Stameski et al., 2024), suggesting a negative association with GDP per capita.

Long-term unemployment rate (UNEMP) and share of renewable energy in final energy consumption (RENEW) are included as control variables, representing the social and energy components of the sustainability framework. Higher renewable energy use is expected to reduce emissions (negative sign), while high unemployment is assumed to lower GDP and increase emissions due to social exclusion and reduced efficiency.

This selection aligns with prior empirical models applied in sustainability research and enables a balanced and policy-relevant interpretation of the results in the context of the European Union's green and digital transformation.

The choice of these indicators allows the analysis of economic, social and environmental factors, reflecting how energy transition and digitalization policies influence both environmental sustainability and economic growth in the EU.

We formulated the equations for the two models. Model 1 has Net Emissions of Greenhouse Gases (NETGHG) as the dependent variable, and Model 2 has Real GDP per capita (RGDP) as the dependent variable.

Model 1:

$$\begin{aligned} NETGH_t = & \beta_0 + \beta_1 RGDP_t + \beta_2 WASTM_t + \beta_3 LEVI_t + \beta_4 UNEMP_t + \\ & \beta_5 RENEW_t + \beta_6 TAXENV_t + \beta_7 TAXEN_t + \varepsilon_t, \end{aligned} \quad (1)$$

where, $NETGH_t$ – is the net greenhouse gas emissions in period t (dependent variable); β_0 – model constant; $\beta_1, \beta_2, \beta_n$ – are the coefficients for each independent variable, ε_t – is the error term for period t .

Model 2:

$$\begin{aligned} RGDP_t = & \alpha_0 + \alpha_1 NETGH_t + \alpha_2 WASTM_t + \alpha_3 LEVI_t + \alpha_4 UNEMP_t + \\ & \alpha_5 RENEW_t + \alpha_6 TAXENV_t + \alpha_7 TAXEN_t + \gamma_t, \end{aligned} \quad (2)$$

where, $RGDP_t$ – is real GDP per capita in period t (dependent variable); α_0 – model constant; $\alpha_1, \alpha_2, \alpha_n$ – are the coefficients for each independent variable, γ_t – is the error term for period t .

We hypothesized the following:

- H1:** *Real GDP per capita is positively associated with net greenhouse gas emissions, reflecting structural economic patterns.*
- H2:** *Increased energy taxes are associated with reduced net greenhouse gas emissions, stimulating energy efficiency.*
- H3:** *Municipal waste generation per capita is positively associated with real GDP per capita, reflecting consumption-driven waste generation.*
- H4:** *Increasing household internet access has a positive impact on real GDP per capita, reflecting the role of digital inclusion in economic activity.*
- H5:** *Environmental tax revenues have a negative impact on real GDP per capita, reflecting potential cost pressures on economic activity.*

In order to capture the temporal dynamics and control for this structural heterogeneity across member states, the research extends the OLS model by adopting a Fixed Effects (FE) specification, which is appropriate for situations where there are unobserved factors that are invariant over time but potentially correlated with the explanatory variables (Baltagi, 2021; Wooldridge, 2010).

The fixed effects model allows the estimation of economic relationships based on intra-country variation over time, eliminating the influence of constant components for each cross-sectional unit.

This approach leads to consistent coefficients that reflect how changes in the explanatory variables in a given country over the period analyzed affect the dependent variable, regardless of structural differences between countries.

The general form of the fixed effects model is expressed as follows:

$$Y_{it} = \alpha_i + \delta_t + \beta' X_{it} + \varepsilon_{it}, \quad (3)$$

where, Y_{it} represents the dependent variable for country i in year t ; α_i is the country-specific intercept (individual fixed effect), which captures national characteristics that are constant over time; δ_t reflects the fixed temporal effects (year effects), which capture economic, social, or public policy shocks common to all countries (such as the sovereign debt crisis, the COVID-19 pandemic, or regulatory changes in the energy sector); X_{it} is the vector of explanatory variables that vary both over time and across countries; β is the vector of parameters to be estimated; and ε_{it} represents the idiosyncratic error term, independent over time and across units after controlling for fixed effects.

The combined use of the OLS and fixed effects models allows for a rigorous and comparative analysis: the OLS model provides an overview of the average relationships between variables at the aggregate level; the FE model allows for the identification of internal effects specific to each state over time, correcting for potential problems of unobserved variable omission and improving the consistency of estimates. Therefore, the inclusion of both approaches provides a comprehensive picture of the mechanisms through which fiscal policies, energy performance, and resource use simultaneously influence economic growth and environmental sustainability in European Union member states.

3.2. Stationarity and cointegration analysis

Before estimating the econometric models, it is essential to assess the statistical properties of the panel data series to avoid spurious regression results. In this regard, we first test for the presence of unit roots to determine whether the variables are stationary in levels. Given that many macroeconomic and environmental time series exhibit non-stationarity, the detection of long-run equilibrium relationships becomes necessary. Therefore, we proceed with panel cointegration analysis to verify the existence of stable relationships among the variables over time.

To test the stationarity of the panel data series, we applied the Hadri LM test, which evaluates the null hypothesis that all panels are stationary against the alternative that some panels contain unit roots. As shown in Table 2, the test statistics for all variables are highly significant, with p-values equal to 0.0000, leading to the rejection of the null hypothesis at the 1% significance level for each individual variable.

Table 2. Hadri LM Test (source: elaborated by the authors using Stata 18 program)

H0: All panels are stationary		Number of panels = 27	
Ha: Some panels contain unit roots		Number of periods = 13	
Time trend: Not included		Asymptotics: T, N → Infinity sequentially	
Heteroskedasticity: Not robust LR variance: (not used)			
Variables	Statistic	p-value	
WASTM	21.9532	0.0000	
LEVI	35.2949	0.0000	
RGDP	33.1913	0.0000	
UNEMP	24.1612	0.0000	
NETGH	21.1037	0.0000	
RENEW	31.3218	0.0000	
TAXENV	17.8447	0.0000	
TAXEN	19.3934	0.0000	

This result implies that all variables – real GDP per capita (RGDP), net greenhouse gas emissions (NETGH), energy taxes (TAXEN), environmental tax revenues (TAXENV), household internet access (LEVI), long-term unemployment (UNEMP), municipal waste per capita (WASTM), and share of renewable energy in final energy consumption (RENEW) – are non-stationary in levels. The presence of unit roots indicates that the data series exhibit stochastic trends and that direct estimation of level relationships without further testing may lead to spurious results.

Consequently, to determine whether there exists a long-run equilibrium relationship among the variables despite their non-stationarity, we proceed with panel cointegration testing in the next section.

Table 3. Kao test for cointegration (source: elaborated by the authors using Stata 18 program)

H0: No cointegration	Number of panels = 27	
Ha: All panels are cointegrated	Number of periods = 11	
Cointegrating vector: Same		
Panel means: Included	Kernel: Bartlett	
Time trend: Not included	Lags: 1.52 (Newey-West)	
AR parameter: Same	Augmented lags: 1	
	Statistic	p-value
Modified Dickey-Fuller t	3.5597	0.0002
Dickey-Fuller t	5.0136	0.0000
Augmented Dickey-Fuller t	4.3368	0.0000
Unadjusted modified Dickey-Fuller t	2.7865	0.0027
Unadjusted Dickey-Fuller t	3.8106	0.0001

To assess whether a long-run equilibrium relationship exists among the non-stationary variables identified in the previous section, we applied the Kao test for cointegration, which is suitable for panel data with homogeneous cointegrating vectors across cross-sections. The results presented in Table 3 show that all five test statistics – including the Modified Dickey-Fuller t, Dickey-Fuller t, Augmented Dickey-Fuller t, and their unadjusted versions – are statistically significant at the 1% level (p-values < 0.01).

These results lead to the rejection of the null hypothesis of no cointegration, confirming that the variables included in the model are cointegrated. In other words, despite being individually non-stationary, the series move together over time in a manner consistent with a stable long-run relationship.

By focusing on comparable metrics, the analysis ensures that the results are interpretable and usable for policy-making, better addressing trade-offs between growth and environmental objectives. It also emphasizes the role of digitization in supporting economic growth and efficiency without having a negative effect on emissions, which is important for policies to stimulate the digital economy as part of the EU's sustainable development strategy.

3.3. Cross-sectional dependence test

In empirical analyses based on macro-panel datasets, particularly those encompassing the European Union Member States, the assessment of Cross-Sectional Dependence (CSD) represents an essential diagnostic procedure aimed at ensuring the statistical validity and robustness of econometric estimations. The existence of cross-sectional dependence is a common feature of highly integrated economies, where shared policy frameworks, trade linkages, and exposure to common shocks – such as economic crises, environmental regulations, or energy market volatility – can generate contemporaneous correlations across units. When such interdependencies are ignored, traditional panel estimators like Pooled OLS or Fixed Effects may yield biased and inefficient parameter estimates, compromising the reliability of empirical conclusions.

To examine whether the models estimated in this study are affected by cross-sectional dependence, the Pesaran Cross-sectional Dependence (CD) test (Pesaran, 2021) was applied. This test evaluates the null hypothesis of cross-sectional independence against the alternative hypothesis of contemporaneous correlation among residuals across cross-sectional units. The results, reported in Table 4, indicate that for both econometric specifications, the p-values are above the conventional significance thresholds ($p > 0.05$), suggesting that the null hypothesis of cross-sectional independence cannot be rejected.

Table 4. Cross-sectional dependence test results (Pesaran CD test) (source: elaborated by the authors using Stata 18 program)

Model	Pesaran CD statistic	p-value
Model 1 (NETGH as dependent)	-1.000	0.317
Model 2 (RGDP as dependent)	-0.947	0.343

The empirical evidence demonstrates that the residuals are not contemporaneously correlated across countries, implying that no significant unobserved common shocks or spatial spillover effects are present within the sample period. This finding supports the assumption of cross-sectional independence, validating the use of conventional panel estimators as statistically appropriate and consistent for the purposes of this research. Moreover, the absence of cross-sectional dependence reinforces the robustness and internal validity of the econometric framework, indicating that the relationships identified between environmental performance, fiscal instruments, and economic development are not driven by common, unobserved factors. Consistent with the methodological guidance provided by Hoechle (2007), the application of second-generation estimators or robust standard error corrections would only be required in the presence of statistically significant CSD, an issue that does not arise in this case. Therefore, the adopted specification remains theoretically sound and empirically credible within the analytical context of the European Union.

4. Results

4.1. Descriptive statistics

In the economic, social and environmental context in which the European Union is moving towards energy transition and sustainability, it is important to analyze descriptive statistics of indicators from 2010–2022. Table 5 presents the mean, standard deviation, and minimum and maximum values for variables such as real GDP per capita, greenhouse gas emissions, long-term unemployment rate, internet access, share of renewable energy, and level of environmental and energy taxes. These indicators are relevant for assessing the sustainability of EU economies and understanding the region's economic and environmental diversity. The resulting statistical values reflect both achievements and challenges faced by Member States in their green transition efforts.

According to Table 5, the EU average GDP per capita is €26,020 per capita, but there is considerable variability between countries, with a high standard deviation (€17,080 per capita).

Table 5. Descriptive statistics (source: realized by the authors using Stata 18)

Variable	Mean	Std. Dev.	Min	Max
RGDP	26020.598	17080.025	5080	86540
NETGH	8.456	4.008	0.1	26.1
WASTM	499.615	133.842	247	918
LEVI	81.537	12.034	40.525	100.21
UNEMP	3.852	3.111	0.5	17.5
RENEW	20.816	11.819	0.979	66.002
TAXENV	7.36	1.998	3.19	15.32
TAXEN	8638.552	13384.859	106.36	58152.9

The large differences between the minimum and maximum reflect economic discrepancies between Member States, with some strong economies exceeding €80,000 per capita per inhabitant per capita and others at significantly lower levels. This variability may influence the energy transition as more developed economies have more resources for investment in green technologies. Net greenhouse gas emissions per capita vary considerably between EU countries, averaging 8.46 tons per capita. The minimum of 0.1 tons per capita and the maximum of 26.1 tons per capita indicate major differences in pollution levels. This can be explained by variations in countries' energy and industrial structure. Countries with higher emissions face greater challenges in meeting emission reduction targets. The amount of municipal waste generated per capita averages almost 500 kilograms, varying between 247 kilograms and 918 kilograms per capita. These differences suggest that EU countries' consumption levels and waste management differ significantly.

Countries with higher waste generation may be more exposed to environmental problems, requiring them to manage waste more efficiently to support sustainability goals. Internet access in households averages 81.54%, indicating a significant uptake of EU-level digital technologies. However, the differences in access, from a low of 40.53% to a high of over 100%, indicate that there are countries with lower levels of digitization, which could limit the economic benefits and growth opportunities in those countries. Low internet access can hinder economic and social inclusion, limiting technological progress and innovation. Long-term unemployment rates vary significantly between EU countries, from a low of 0.5% to a high of 17.5%. The average of 3.85% suggests that social inclusion problems and differences between countries could impact economic performance and their ability to invest in the green transition. High long-term unemployment can negatively affect economic growth and social sustainability and indicate regional disparities. The average share of renewable energy in final energy consumption is 20.82%, indicating a general shift towards more sustainable energy sources.

The large differences (from a low of less than 1% to a high of 66%) suggest that the energy transition varies considerably between countries, with some countries highly dependent on traditional energy sources. States with a high share of renewable energy have a solid basis for meeting sustainability targets, helping to reduce emissions and fossil fuel dependence. The average environmental tax revenue is 7.36% of GDP, significantly varying between

countries. This reflects differences in environmental tax policies between EU countries. States with higher revenues from environmental taxes may have additional resources to finance the energy transition. Still, at the same time, these taxes can negatively affect GDP per capita in countries with less developed economies. Energy taxes vary significantly between Member States, with an average of € 8,638.55 and a large standard deviation, indicating large differences in the structure and level of energy taxes across the EU. High energy tax levels may encourage energy efficiency and renewables in Member States, but this incentive may be less effective in countries with lower taxes.

These statistics suggest the need for differentiated policies tailored to the specificities of each Member State to ensure a fair and sustainable transition at the European level in the context of the EU's 2050 climate neutrality objective.

4.2. Correlation matrix and Variance inflation factor (VIF)

The analysis of pairwise correlations between the variables included in the models provides important insights into the direct relationships between economic, social and environmental factors at the EU level. Table 6 presents the correlations between variables.

The positive and significant correlation between real GDP per capita (RGDP) and net greenhouse gas emissions (NETGH), with a coefficient of 0.556, suggests that increasing economic welfare is associated with high emissions levels, highlighting a potential tension between economic growth and pollution reduction commitments. This relationship reflects the challenges developed economies face in reconciling economic progress with environmental objectives, implying a need for economic policies to support the ecological transition. Also, the significant positive correlation between real GDP per capita and municipal waste generation per capita (WASTM), evidenced by a coefficient of 0.671, illustrates the close link between the level of economic development and resource consumption. This association underlines the importance of implementing efficient waste management strategies in more economically developed Member States to minimize the environmental impacts of high consumption levels and corresponding waste generation.

In addition, the positive correlation between household internet access (LEVI) and real GDP per capita (0.582) suggests that more developed economies benefit from a robust digital infrastructure, which contributes to economic growth and innovation, including facilitating

Table 6. Pairwise correlations (source: realized by the authors using Stata 18)

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) RGDP	1.000							
(2) NETGH	0.556***	1.000						
(3) WASTM	0.671***	0.374***	1.000					
(4) LEVI	0.582***	0.232***	0.408***	1.000				
(5) UNEMP	-0.349***	-0.156***	-0.265***	-0.585***	1.000			
(6) RENEW	-0.068	-0.495***	-0.107**	0.182***	-0.159***	1.000		
(7) TAXENV	-0.475***	-0.081	-0.241***	-0.369***	0.398***	-0.037	1.000	
(8) TAXEN	0.144***	-0.026	0.140***	0.159***	-0.031	-0.143***	-0.333***	1.000

Note: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

access to education and employment opportunities. The inverse relationship between the long-term Unemployment Rate (UNEMP) and real GDP per capita (-0.349) suggests that more prosperous economies can integrate the labour force, thereby reducing the long-term unemployment rate. This negative correlation points to a possible interdependence between economic welfare and labour market stability, which is essential for sustainable growth. Moreover, the negative correlation between the unemployment rate and internet access (-0.585) reveals the importance of digital inclusion in tackling unemployment, as internet access can facilitate lifelong learning and new economic opportunities for the workforce. The significant negative correlation between the share of renewable energy in final energy consumption (RENEW) and net emissions of greenhouse gases (NETGH) of -0.495 highlights the contribution of renewable energy to reducing emissions, suggesting that countries that have invested more in the green transition have been able to reduce their polluting impact. This finding reinforces the argument that the transition to clean energy sources is fundamental to a sustainable energy strategy. At the same time, the negative correlation between revenues from environmental taxes (TAXENV) and real GDP per capita (-0.475) indicates that countries with more developed economies tend to rely less on environmental taxes, perhaps preferring other fiscal strategies to support the national budget. The positive relationship between household internet access (LEVI) and energy taxes (TAXEN), with a coefficient of 0.159 , suggests that states with an advanced digital infrastructure are generally more inclined to impose energy taxes, which may reflect a preference for promoting energy efficiency through fiscal measures in digitalized economies. At the same time, the negative correlation between environmental tax revenues and energy taxes (-0.333) indicates differences in tax structures across Member States, suggesting diverging approaches in the use of fiscal policies to stimulate the green transition.

Thus, these correlations highlight the complexity of the relationships between economic, social and environmental variables within the European Union, the diversity in levels of development and fiscal and energy strategies between Member States, emphasizing the need for flexible and tailor-made policies to ensure a fair and efficient transition to a sustainable and green economy.

The analysis of the matrix of correlations between variables for the European Union in 2010–2022 highlights the challenges and opportunities for achieving a sustainable transition at the regional level. The results are presented in Table 7.

Table 7. Matrix of correlations (source: realized by the authors using Stata 18)

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1) RGDP	1.000							
(2) NETGH	0.556	1.000						
(3) WASTM	0.671	0.374	1.000					
(4) LEVI	0.582	0.232	0.408	1.000				
(5) UNEMP	-0.349	-0.156	-0.265	-0.585	1.000			
(6) RENEW	-0.068	-0.495	-0.107	0.182	-0.159	1.000		
(7) TAXENV	-0.475	-0.081	-0.241	-0.369	0.398	-0.037	1.000	
(8) TAXEN	0.144	-0.026	0.140	0.159	-0.031	-0.143	-0.333	1.000

According to Table 7, the significant positive correlation between real GDP per capita (RGDP) and net emissions of greenhouse gases (NETGH) reflects a potential trade-off between economic growth and reduced environmental impacts. This relationship suggests that developed economies within the European Union face a structural challenge: while economic welfare is a central objective, maintaining high levels of economic growth may increase greenhouse gas emissions. This result shows the importance of integrated strategies supporting economic growth and pollution reduction through investments in green technologies and the transition towards a sustainable development model. The strong positive correlation between GDP per capita and the amount of municipal waste generated per capita indicates that economic growth is often accompanied by higher resource consumption and waste generation. This result highlights the need to adopt sustainable waste management practices, promote the circular economy, and stimulate more responsible consumption behaviour, particularly in advanced economies where the environmental impact of consumption is more pronounced. The negative correlation between the share of renewable energy (RENEW) and greenhouse gas emissions also highlights the role of renewable energy sources in reducing pollution. This relationship underlines that investments in renewable energy significantly contribute to achieving the EU's environmental objectives as a component of national and regional green transition strategies.

States that increase their share of renewable energy can thus reduce their environmental impact, contributing to an overall reduction in regional emissions. The negative correlation between the long-term unemployment rate (UNEMP) and internet access (LEVI) reflects the link between digitization and economic inclusion, suggesting that access to digital infrastructure can support creating new economic opportunities and reducing social inequality. This relationship indicates that digitization is an important factor for inclusion in the labour force, particularly in regions with high unemployment, and that developing digital infrastructure could stimulate more equitable and sustainable economic growth. The transition to a sustainable economy in the European Union requires integrated policies that include measures to boost digitization and economic inclusion and sustained investment in renewable energy and green technologies. Such an approach will help to ease the tensions between growth and environmental protection, thus facilitating a green transition and a more sustainable economic framework.

Table 8 shows the values of the influence factors for model 1, where the dependent variable is NETGH.

Table 8. Variance inflation factor (Model 1) (source: Realized by the authors using Stata 18)

Variable	VIF	1/VIF
RGDP	2.733	0.36
LEVI	2.172	0.46
WASTM	1.892	0.52
UNEMP	1.684	0.59
TAXENV	1.625	0.61
TAXEN	1.212	0.82
RENEW	1.136	0.88
Mean VIF	1.779	.

Variance inflation factor (VIF) analysis measures how much the variance of the regression coefficient estimates is increased due to collinearity between the explanatory variables. A VIF greater than 10 generally suggests collinearity between variables, while values below 5 are considered acceptable, and values below 3 indicate very low collinearity. The mean VIF, at 1.779, is significantly below the threshold of 10 and even below the threshold of 3, indicating very low overall collinearity between the explanatory variables in Model 1. These values suggest that the model is well specified and that the independent variables can be interpreted individually without risk of collinearity, thus contributing to reliable coefficient estimates. Hence, Model 1 has good statistical significance, allowing a clear and independent interpretation of the influence of each variable on the dependent variable.

Table 9 presents the values of the influence factors for Model 2, where the dependent variable is RGDP.

Table 9. Variance inflation factor (Model 2) (source: realized by the authors using Stata 18)

Variable	VIF	1/VIF
LEVI	1.914	0.52
NETGH	1.735	0.57
UNEMP	1.666	0.60
RENEW	1.630	0.61
TAXENV	1.387	0.72
WASTM	1.358	0.73
TAXEN	1.244	0.80
Mean VIF	1.562	.

According to Table 9, the mean VIF of 1.562 indicates low overall collinearity in Model 2, emphasizing that the explanatory variables can be interpreted independently without the risk of amplifying the estimates' variance due to collinearity. These VIF values suggest that the model is well-specified and robust, allowing a reliable interpretation of the coefficients of each variable, as all VIF values are below the threshold of 2. Thus, Model 2 benefits from high statistical significance, with each variable contributing its distinct influence on the dependent variable.

4.3. Regression analysis

In the context of the European Union's efforts to achieve climate neutrality and ensure sustainable economic growth, looking at the relationships between economic, social and environmental indicators is becoming increasingly important. The European Union faces a number of challenges related to the transition to a green economy, where economic growth objectives need to be balanced with those of environmental protection and digital inclusion. This model explores the impact of variables such as real GDP per capita, net greenhouse gas emissions, internet access, unemployment rates, the share of renewable energy and the level of energy and environmental taxes on the economic and environmental development of Member States. The model results are presented in Table 10.

Table 10. Regression analysis (Model 1 and Model 2) (source: Realized by the authors using Stata 18)

Variable	(Model 1) NETGH	(Model 2) RGDP
RGDP	0.000151*** (11.07)	
WASTM	-0.00232 (-1.60)	49.07*** (11.77)
LEVI	0.00186 (0.11)	374.5*** (6.80)
UNEMP	0.137* (-2.33)	601.0** (3.03)
RENEW	-0.165*** (-12.98)	190.1*** (3.68)
TAXENV	0.389*** (4.32)	-2536.5*** (-8.99)
TAXEN	-0.0000352** (-3.04)	-0.0226 (-0.57)
NETGH		1742.2*** (11.07)
cons	6.936*** (4.36)	31170.9*** (-5.89)
N	351	351
R-sq	0.575	0.730

Notes: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$; t statistics in parentheses.

According to hypothesis H1, the relationship between real per capita GDP growth (RGDP) and net greenhouse gas emissions (NETGH) is confirmed by the positive and significant coefficient for RGDP in Model 1 (coefficient of 0.000151, $p < 0.001$). This positive relationship indicates increased emissions with economic prosperity, reflecting a structural difficulty in balancing economic expansion and environmental objectives. This association shows that EU Member States, especially those with advanced economies, are prone to higher emissions during periods of economic growth. To counteract this, economic policies must include incentives for investment in low-emission technologies and sustainable economic practices, thereby supporting economic growth that does not compromise environmental objectives. For hypothesis H2, Model 1 shows that energy taxes (TAXEN) are associated with a reduction in net greenhouse gas emissions (coefficient of -0.0000352 , $p < 0.01$), confirming the hypothesis that increasing these taxes can play a significant role in reducing pollution.

Energy taxes' negative and significant impact on emissions suggests that fiscal policies oriented towards higher costs for fossil fuels and other conventional energy sources effectively discourage their consumption and stimulate energy efficiency (Akbar et al., 2022; Bashir et al., 2024a; Dai et al., 2025; Okorie & Wesseh, 2024). In this context, the European Union should benefit from strengthening green fiscal policies, emphasizing energy taxes to promote a faster transition to renewable energy sources and green technology in line with climate neutrality objectives (Chatzistamoulou & Dimakopoulou, 2025; Fatima et al., 2024;

Nadiri et al., 2024). Hypothesis H3 is supported by Model 2, which shows that an increase in the amount of municipal waste per capita (WASTM) is positively and significantly associated with real GDP per capita (coefficient of 49.07, $p < 0.001$).

This suggests that high levels of waste generation affect economic growth and intensive consumption, especially in developed economies (Bao & Lu, 2023; Chioatto & Sospiro, 2023; R. Wang et al., 2023). This relationship underlines the importance of waste management policies and the promotion of the circular economy to reduce the negative environmental impacts of consumption, particularly in the context of sustained economic growth. Thus, the European Union should implement regulations that minimise waste generation and encourage reuse and recycling, integrating sustainability into economic growth (Agovino et al., 2024; Halkos & Aslanidis, 2023; Sikder et al., 2024; Üsas et al., 2025). Hypothesis H4 is confirmed by the positive and significant coefficient of the LEVI variable in Model 2 (coefficient of 374.5, $p < 0.001$), showing that household internet access is associated with higher real GDP per capita. This relationship underscores that digitization and access to internet infrastructure support economic growth by facilitating innovation, information access, and new economic opportunities (Z. Chen & Xing, 2025; Marti & Puertas, 2023; Tutak & Brodny, 2024). Digitization is essential for boosting economic competitiveness and reducing inequality, contributing to a more resilient and dynamic economy (Baffour Gyau et al., 2025b; Shi & Wei, 2024).

In this sense, the European Union should continue to promote internet access and the development of digital infrastructure as part of growth strategies, mainstream digitization in all sectors of the economy, and support digital inclusion in all Member States (European Commission, n.d.-c; Sánchez-García et al., 2024; Senna et al., 2023). For hypothesis H5, model 2 shows that revenues from environmental taxes (TAXENV) are negatively and significantly associated with real GDP per capita (coefficient of -2536.5 , $p < 0.001$), confirming the hypothesis that these taxes have a restrictive effect on economic growth. This relationship suggests that environmental taxes, although necessary to reduce polluting activities, may increase operational costs for firms and households, negatively influencing economic growth (Imran et al., 2024; Obobisa & Ahakwa, 2024; Samour et al., 2024). This result points to a challenge for policy makers: maintaining a balance between environmental fiscal measures and economic growth. Thus, to minimize the negative impact on GDP, the European Union should develop complementary tax policies encouraging innovation and investment in green technologies, thereby reducing reliance on environmental taxes and supporting a sustainable economic transition (Chatzistamoulou & Koundouri, 2024; Cutcu et al., 2024; Ebaidalla, 2024).

These results highlight challenges for achieving a green transition in the European Union, showing that economic growth objectives may conflict with environmental goals without appropriate public policies. The European Union should implement public policies that support sustainable economic growth, enabling an efficient transition to a green and resilient economy in line with its long-term climate and development goals.

4.4. Results of fixed effects (FE) estimates

The results obtained by estimating fixed-effects models, presented in Table 11, provide a detailed insight into the mechanisms governing the interaction between economic performance, environmental pressures, and fiscal instruments within the European Union for the period 2010–2022.

Table 11. Results of fixed effects (FE) estimates (Model 1 and Model 2) (source: realized by the authors using Stata 18)

Variable	Model FE 1 NETGH	Model FE 2 RGDP
RGDP	0.000 (0.000)	
WASTM	0.002 (0.001)	-3.701 (2.920)
LEVI	0.037*** (0.014)	-39.420 (34.429)
UNEMP	-0.147*** (0.041)	-472.013*** (96.381)
RENEW	-0.077** (0.034)	-33.504 (81.134)
TAXENV	0.195** (0.086)	-1085.365*** (195.507)
TAXEN	-0.000 (0.000)	0.082 (0.084)
NETGH		79.950 (135.661)
2010		
2011	-0.167 (0.270)	340.076 (641.286)
2012	-0.342 (0.289)	316.959 (685.417)
2013	-0.420 (0.312)	566.169 (741.568)
2014	-0.606* (0.336)	1077.288 (799.463)
2015	-0.778** (0.361)	1824.238** (856.793)
2016	-0.893** (0.385)	2144.703** (913.377)
2017	-0.738* (0.421)	2414.532** (993.553)
2018	-0.800* (0.461)	2576.510** (1087.714)
2019	-1.387*** (0.504)	3004.088** (1197.575)
2020	-2.301*** (0.569)	1754.750 (1380.071)
2021	-1.858*** (0.621)	3470.393** (1480.250)
2022	-1.961*** (0.647)	4052.121*** (1539.345)
Constant	6.296*** (1.823)	38388.439*** (3818.667)
Observations	351	351
R-squared	0.358	0.469

Notes: * p < 0.1, ** p < 0.05, *** p < 0.01; standard errors in parentheses.

In *Model 1*, where the dependent variable is *NETGH* (net greenhouse gas emissions per capita), a number of economically and statistically significant relationships are highlighted. The coefficient associated with *RGDP* is positive but not statistically significant, suggesting that, during the period analyzed, economic growth did not automatically translate into increased pressure on the environment, signaling an incipient process of decoupling between economic development and carbon emissions – a trend increasingly observed in developed economies (Veugelers et al., 2024). The results of *Model 1* confirm that the environmental performance of Member States depends on the interaction between labor market dynamics, tax structure, and the degree of penetration of renewable sources, outlining a gradual but structural process of greening European economies. In *Model 2*, where the dependent variable is *RGDP* (real GDP per capita), the relationships identified reflect the determinants of economic growth in the context of the green transition. The coefficient associated with *NETGH* is positive but insignificant, suggesting that emissions intensity is no longer a major explanatory factor for economic dynamics, which confirms the structural decoupling hypothesis.

The variable *UNEMP* has a negative and significant impact (-472.013 ; $p < 0.01$), confirming the classic link between employment and growth, while the negative coefficients associated with *RENEW* and *TAXENV* indicate possible transition effects, respectively, the temporary costs generated by energy restructuring and the implementation of environmental taxation on economic activity. The evolution of the temporal coefficients (δt) reveals a structural effect of the 2010–2013 economic crisis, followed by a significant recovery after 2015 and an acceleration of economic performance in the period 2020–2022, in line with the European Union’s green recovery policies (NextGenerationEU) (European Union, n.d).

The Hausman test, summarized in Table 12, validates the methodological choice of fixed-effects models. The test statistics reject the null hypothesis that the differences between random-effects and fixed-effects estimates would be insignificant. This confirms that the explanatory variables are correlated with country-specific effects and that the use of FE estimates ensures the consistency and efficiency of the results.

Table 12. Hausman test (source: realized by the authors using Stata 18)

	Model Test Statistic p-value	
Model 1 (<i>NETGH</i>)	27.436	0.0006
Model 2 (<i>RGDP</i>)	18.923	0.0085

Overall, the results of the fixed-effects models confirm the existence of a complex, but structural relationship between economic performance, environmental taxation, and energy transition, highlighting the fact that sustainability in the European Union does not automatically result from economic growth, but from the ability of Member States to coherently integrate fiscal, technological, and institutional instruments that harmonize economic development with long-term climate objectives.

5. Discussions and policy recommendations

The results of the econometric analysis reveal the complex interactions between economic performance, fiscal policy, and environmental sustainability within the European Union, illustrating both the progress made and the persistent asymmetries on the path to green and digital transition. The use of complementary OLS and Fixed Effects (FE) estimates has allowed for a nuanced understanding of these dynamics, capturing both cross-country aggregate patterns and intra-country temporal adjustments.

Overall, the findings confirm that economic growth in the EU remains partially associated with greenhouse gas emissions, reflecting the structural legacy of high-carbon production systems. This result is consistent with previous studies, such as Magazzino et al. (2022) and Dahmani (2024), which highlight that, despite regulatory progress, the decoupling of economic growth from emissions remains incomplete in several Member States. However, the attenuation of this relationship in the FE model suggests that countries with advanced technological capabilities and well-designed fiscal policies, such as Sweden, Denmark, and Finland, are gradually achieving relative decoupling, confirming the evidence presented by Veugelers et al. (2024) and Greiner et al. (2025). These findings highlight the uneven pace of the European transition and the importance of institutional capacity in translating environmental objectives into measurable results.

The negative association between energy taxation and emissions observed in both models confirms the effectiveness of fiscal instruments as environmental policy tools. This result is consistent with the theoretical arguments of Bovenberg and de Mooij (1994) and the empirical findings of Fatima et al. (2024) and Nyangon and Darekar (2024), which show that higher energy taxes can contribute to reducing emissions, provided they are complemented by reinvestments in renewable energy and technological innovation. At the same time, the persistence of heterogeneity across countries in terms of estimated effects reflects the unequal fiscal capacities of EU Member States and highlights the need for differentiated approaches to environmental taxation that take into account local economic structures and social conditions.

The results also confirm the role of digitalization as a transformative driver of economic growth and institutional modernization. The positive and significant influence of internet access on GDP supports the arguments of Marti and Puertas (2023) and Z. Chen and Xing (2025), who found that digital connectivity promotes productivity growth, increases information efficiency, and accelerates the diffusion of innovation across all sectors. However, as noted by Longato et al. (2024) and Scheer et al. (2025), the persistence of the digital divide between Western and Eastern European regions risks amplifying structural inequalities unless digital expansion is accompanied by specific education and capacity-building programs. The findings thus highlight that digital transformation should not be viewed as an isolated policy pillar, but as an integral part of the transition to sustainability, amplifying both environmental and economic outcomes.

From an environmental perspective, the significant but heterogeneous effects of renewable energy use and environmental taxation confirm the conclusions of Bekun et al. (2023)

and Fatima et al. (2024), who emphasized that renewable energy use reduces emissions while strengthening energy security and resilience. The results further support the view of Fabra and Reguant (2024) that tax revenues from environmental taxes should be recycled into innovation, low-carbon infrastructure, and social inclusion measures to enhance both effectiveness and public acceptance.

In the context of the European Union, analysing the evolution of economic, environmental and social indicators in the period 2010–2022 is important to analyze the transition dynamics towards a sustainable and digitalized economy. Figure 2 provides an overview of the leading indicators monitored, such as greenhouse gas emissions, real GDP per capita, municipal waste generation, internet access, long-term unemployment rate, share of renewable energy, environmental tax revenues and energy taxes. The data highlights the progress made in the areas of European sustainability and the remaining challenges for implementing equitable and effective development policies at the regional level.

According to Figure 2, the analysis of net emissions of greenhouse gases (NETGHG) over the period 2010–2022 shows a sustained downward trend, marking steady progress towards pollution reduction at the EU level. This gradual decrease in emissions suggests the effectiveness of the public policy measures and environmental regulations implemented over the period. However, high values' persistence in the distribution's upper part indicates significant differences between Member States. Thus, some countries show limited progress compared to the regional average, implying the need for more country-specific strategies to achieve climate neutrality targets. Real GDP per capita (RGDP) shows a steady and sustained increase in most studied years, reflecting a positive trend in EU economic growth.

This development signals a gradual economic consolidation, with a concentration of values in higher ranges over time, especially after 2015. Significant economic disparities between Member States are visible in the distribution's upper and lower ranges, suggesting disparities in development across EU countries. These differences imply more convergent economic policies to support the lower-performing countries and ensure equitable economic growth.

Municipal waste generation per capita (WASTM) over 2010–2022 remains relatively constant, indicating stagnating progress. This stability highlights a challenge in reducing regional waste. It suggests a continued need to strengthen measures to manage waste and promote the circular economy, particularly in the context of economic growth and increased consumption. Developments in the Household Internet Access Indicator (LEVI) reflect rapid and uniform progress in the digitization of the EU population, with a significant increase in internet access, particularly in the recent years under review. This growing trend suggests that digitization is becoming more widespread across the EU, helping to reduce digital divides and integrate the digital economy into the economic and social fabric of the region. The long-term unemployment rate (UNEMP) has shown a significant decrease, especially since 2014, suggesting a gradual improvement in labour market conditions in the European Union and economic recovery after the financial crisis.

The reduction in cross-country variability in long-term unemployment underlines a gradual convergence in labour market conditions, although some regional disparities persist. This favourable development suggests increased economic stability and inclusion at the Union level.

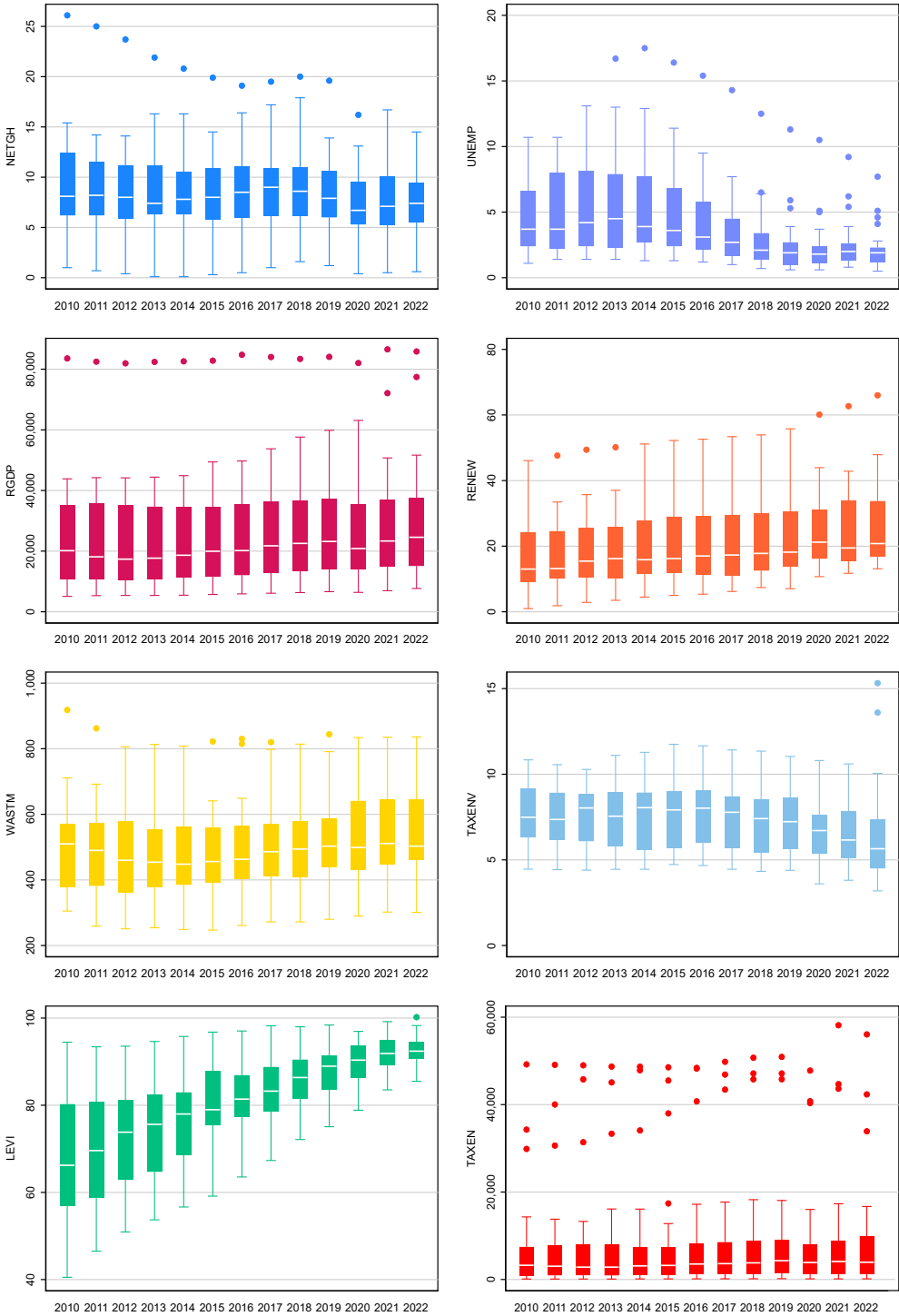


Figure 2. Distribution of analyzed indicators over the period 2010–2022 at EU level
(source: realized by the authors using Stata 18)

The renewable energy share (RENEW) in the final energy consumption indicator shows a steady upward trend, reflecting Member States' commitment to transitioning to a green economy and reducing dependence on conventional energy sources. This increase in the share of renewable energy is a positive indicator of the alignment of national energy policies with European climate objectives, suggesting that renewables are becoming increasingly important in the region's energy mix. Revenues from environmental taxes (TAXENV) remain relatively constant over the analyzed period 2010–2022, with a slight downward trend towards the end of the period, indicating a stagnation in the adjustment of environmental taxes in Member States' fiscal policies. This steady evolution of environmental tax revenues reflects a uniform application of environmental taxes, but differences between countries suggest the diversity of approaches to environmental taxation in the region.

In the case of the energy taxation indicator (TAXEN), the high variability of values across Member States suggests a heterogeneous application of energy taxation policies, with considerable differences between EU countries.

The European Union needs to adapt its public policies to support a resilient green and digital transition to cope with unforeseen events in recent global challenges such as migration, financial and pandemic crises, and international conflicts. Thus, the European Union must develop a flexible framework to enable rapid and effective responses to these crises while building on ongoing European initiatives such as Green Deal (European Commission, n.d.-a), NextGenerationEU (European Union, n.d.), Just Transition Fund (European Parliament, n.d.-b) and Digital Europe (European Parliament, n.d.-a), to ensure sustainable development and economic stability.

Given the unpredictable nature of energy and economic risks, the EU should prioritize accelerating the green transition and deepening market integration through the expansion of the Emissions Trading System (ETS) and the calibration of emission allowances to external disruptions. This would stabilize carbon pricing and enhance market predictability, complementing the evidence of Fabra and Reguant (2024) that regulatory credibility is key to sustaining investment in renewable technologies. In parallel, Green Deal and Just Transition funds should focus on building both technological capacity and social resilience in regions disproportionately affected by industrial restructuring, thereby reducing the socio-economic costs of the green transition.

Concerning the circular economy, the stagnation in waste reduction observed in the data calls for stricter regulatory targets and stronger fiscal incentives to promote material reuse and recycling. The literature on circular transitions (Chioatto & Sospiro, 2023; Rodríguez-Espíndola et al., 2022) emphasizes that progress in this area depends on integrating economic and environmental policy instruments. Grants, tax incentives, and investment support for circular business models should therefore be expanded under NextGenerationEU and the Green Deal. Moreover, education and public awareness campaigns play a crucial role in transforming consumption behaviors and embedding sustainability as a societal norm, an aspect often overlooked in economic modeling but essential for policy implementation.

In the digital domain, the EU should consolidate its efforts toward a resilient and inclusive digital economy. Expanding broadband infrastructure, promoting digital literacy, and strengthening cybersecurity are indispensable for ensuring equitable access and public trust

in digital services. This is consistent with the evidence that digital innovation amplifies productivity and energy efficiency while reducing regional disparities, as documented by Z. Chen and Xing (2025). The integration of digital policies into the sustainability agenda would also enhance the EU's ability to monitor emissions, manage energy systems, and respond swiftly to crises.

Labor market adaptation remains another essential pillar of resilience. As the study indicates, improvements in employment and digital connectivity are intertwined with sustainable growth. Investments in retraining and upskilling programs, financed through NextGenerationEU and the Just Transition Fund, would accelerate workforce adaptation to the evolving technological landscape. Furthermore, promoting employment in sectors such as renewable energy, energy efficiency, and circular production could strengthen the EU's capacity to recover from global shocks while reinforcing its commitment to sustainability.

Energy policy, too, must balance decarbonization with security of supply. Extending financial incentives for renewable energy under the Green Deal, while complementing them with investments in energy storage and smart grids, would help mitigate vulnerabilities to market fluctuations and geopolitical disruptions. Establishing strategic energy reserves and emergency response mechanisms would further enhance resilience. Simultaneously, environmental taxation should remain flexible and responsive, with adjustable minimum thresholds ensuring coherence across Member States while respecting national fiscal autonomy. This approach resonates with the conclusions of Fatima et al. (2024) and Veugelers et al. (2024), who argue that harmonized yet adaptable fiscal instruments can reconcile competitiveness with environmental ambition.

Finally, sustainability governance must explicitly acknowledge structural and institutional asymmetries within the Union. As Dahmani (2024) and Fernández-Miguel et al. (2025) point out, uniform implementation of carbon pricing or renewable targets may impose disproportionate adjustment costs on less industrially diversified economies. Therefore, policy design should incorporate built-in flexibility, enabling differentiated timelines and combining environmental objectives with social compensation mechanisms. Complementary technical assistance and capacity-building programs, especially in Eastern and Southern Europe, would ensure that financial resources are effectively absorbed and that long-term sustainability objectives are met.

By adopting these integrated public policies and aligning them with the objectives of existing European programs, the European Union can strengthen its capacity to move towards a green and resilient economy. This will enable it to address current economic and environmental challenges and prepare for future external shocks, ensuring sustainable development and environmental protection in line with the objectives of climate neutrality and long-term sustainability.

6. Conclusions

The findings of this study highlight the complexity between economic, social and environmental factors within the European Union, revealing both the progress made towards a sustainable transition and the persistent challenges amplified by global and regional crises

such as mass migration, international conflicts and economic vulnerability. The analysis of econometric models provides insights into how economic growth, renewable energy, green taxation, and digitization influence the level of greenhouse gas emissions and real GDP per capita in the European Union, highlighting the need for an integrated approach to public policies.

The first econometric model shows that, despite progress in reducing emissions, real GDP per capita growth is still closely linked to an increase in greenhouse gas emissions, suggesting a structural trade-off between economic expansion and environmental protection. This relationship points to an urgent need for policies that support the transition to a green economy, reducing dependence on conventional energy sources and stimulating the use of low-emission technologies. At the same time, the significant positive role of renewable energy in reducing emissions underlines the importance of strengthening the energy transition, showing that renewables can become an essential pillar of the European Union's environmental policies.

The second model shows that digitization and the share of renewable energy contribute significantly to real GDP per capita growth, demonstrating that the green and digital transition are environmental priorities and drivers of sustainable economic development. At the same time, the results emphasize the adverse effects of environmental taxes on GDP, suggesting that while environmental taxation is necessary to discourage polluting activities, taxation policies must be accompanied by complementary measures that support innovation and economic competitiveness. This is particularly relevant in international and economic crises, which can increase the vulnerability of certain economic sectors and create tensions between environmental protection objectives and the need for economic stability.

The study underlines the need for integrated public policies supporting economic growth and the EU's sustainability goals. In the long term, the success of the green transition will depend on the EU's ability to stimulate investment in renewables and digitization, adopt balanced fiscal measures that encourage the green transition without harming economic competitiveness, and to ensure digital inclusion and equitable access to economic opportunities for all citizens. These public policies need to be adapted to cope with the impact of external shocks and to build a resilient economy capable of adapting quickly to disruptions and supporting the goals of climate neutrality and sustainable prosperity. In an increasingly uncertain global context, the findings of this research underline the importance of a united and proactive European Union capable of strengthening its leadership in combating climate change and promoting a fair and sustainable economic model.

The limitations of the study are that the time frame analyzed, 2010–2022, while relevant for capturing recent policy developments, may not fully reflect the long-term effects of the processes of environmental, economic and social transformation within the European Union. Structural transitions – such as the ecological transition, digital integration or the convergence of economic performance between Member States – unfold over long periods of time, and a longer time horizon would allow a more comprehensive understanding of their dynamics and lagged effects. From a methodological point of view, although the current analysis uses clustered OLS models to estimate the relationships between economic, environmental, fiscal and digital indicators, it does not incorporate more advanced panel techniques,

dynamic models, GMM or VAR. Another limitation relates to the homogeneous treatment of EU Member States, despite their obvious diversity in terms of economic development, energy dependence, digital maturity and institutional capacity. While the model captures average effects, it does not explicitly account for country-specific trajectories or heterogeneity in policy effectiveness. Future research should explore these asymmetries using multilevel or cluster-based approaches that differentiate between groups of countries (e.g. Eastern vs. Western Europe, high carbon vs. low carbon economies). Future research could therefore improve the current approach by using more granular econometric strategies at the country level. Moreover, a deeper integration of qualitative institutional data, together with scenario-based policy simulations, could enhance both the explanatory power and policy relevance of future analysis, especially in the context of worsening global challenges such as energy insecurity, inflationary pressures, demographic change and climate shocks.

Disclosure statement

The authors declare no competing interests.

Authors contribution

All authors contributed to the study's conception and design.

Data availability statement

All data generated or analyzed during this study are included in the published article.

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