Inzinerine Ekonomika-Engineering Economics, **2026, 37(4), 416–434**

Cyclical and Structural Drivers of CO_2 Emissions in the European Countries. Annual Panel Evidence for 2000–2023

Raluca Mihaela Drăcea[1*], Raluca Ignat[2], Carmen Lenuța Trică[3], Mihai Dinu[4], Chiva Marilena Papuc[5]

[1,2,3,4]*Faculty of Agrifood and Environmental Economics, Bucharest University of Economic Studies*
Piata Romana, No. 6, Bucharest, Romania
E-mail. raluca.dracea@eam.ase.ro; raluca.ignat@ase.ro, carmen.trica@eam.ase.ro, mihai.dinu@eam.ase.ro*
(Corresponding author)*

[5]*Faculty of Economics and Business Communication, Bucharest University of Economic Studies*
Piata Romana, No. 6, Bucharest, Romania
E-mail. papuc.marilena@economie.ase.ro

https://doi.org/10.5755/j01.ee.37.4.43481

This paper analyses the innovation and regulatory-induced adjustments in European energy systems and their short-term effects on per capita CO_2 emissions for 28 European countries over the period 2000–2023. Empirically, first-difference panel models with country and year fixed effects and Driscoll–Kraay errors are used to capture annual within-country variations and control for common shocks. The results show that the normalized Shannon index, as a generic measure of diversity, has no short-term predictive power, while the actual composition of the energy mix and demand dynamics explain the annual variations in emissions at the sample level. Specifically, a 1 percentage point increase in the share of renewables is associated with approximately −0.85 % in per capita CO_2, and a 1% reduction in the energy intensity of GDP corresponds to a decrease of approximately −0.70 %. Through the estimated (semi)elasticities, the study provides operational benchmarks for the annual calibration of energy policies, but also for managerial decisions regarding investment timing, tariff design, and demand management under budgetary constraints.

Keywords: *Decarbonization; Sustainable Development; Energy Transition; Carbon Intensity; Environmental Performance; Economic Growth.*

Introduction

In the context of achieving emission reduction targets, the episodes of economic contraction in recent decades offer a lesson for mechanisms that operate on an annual horizon. In 2009, in the midst of the global financial crisis, the real GDP of the EU 27 fell by 4.3 %, and later, in 2020, with the onset of the Covid-19 pandemic, the decline was much higher, at -5.6 % (Eurostat, 2025a). In both cases, however, CO_2 emissions fell simultaneously with energy demand. According to European Environment Agency data (EEA 2010, 2024), in 2009, energy emissions fell by 7 % compared to the previous year, and gross available energy by 6.1 %, while in 2020, GHG emissions fell by about 10 %, and final energy consumption was about 8% lower than the previous year (own calculation derived from Eurostat, 2021).

These developments suggest that emissions react in the short term both to changes in economic activity and to the way economic activity is supported from an energy perspective. In practice, governments apply gradual policies of adjustment of the energy mix and enhance energy efficiency; therefore, decision-making requires that the effects should be observable at the annual level.

Developments over the last decade show that the energy transition has accelerated and reordered the political agenda (e.g., the adoption of the European Green Deal, 2019; European Climate Law, 2021; Fit for 55 packages, 2021–2023; Repower EU, 2022). The acceleration of the regulatory framework has not, however, uniformly translated into implementation, and thus, gaps between design and execution remain visible at the Member State level, especially where administrative capacity is limited. At the European level, a number of efficiency gaps remain evident (Dracea *et al.*, 2020a; Chovancova *et al.*, 2024; Stern, 2012), while globally, the structure of the energy mix tends to gradually shift towards sources with low carbon emissions. In parallel, governments are simultaneously managing the trilemma of security of supply, affordability, and protection of vulnerable consumers, in a context of increasing geopolitical risks (Dong *et al.*, 2020; Chen *et al.*, 2022; Pehl *et al.*, 2017; Batlle *et al.*, 2022).

At the micro level, energy companies are adjusting their capital structure, intensifying innovation efforts, and responding more strictly to regulatory requirements associated with operational performance and resilience to price shocks (Noja *et al.*, 2023; Morina *et al.*, 2021; Dopierała *et al.*, 2022). In parallel, both the size of public environmental budgets and the quality of policy design and implementation jointly determine system-level outcomes (Dracea *et al.*, 2020b).

In this landscape dominated by legislative changes and economic pressures at the European level, this study proposes to quantify the annual variations in CO_2 emissions from energy per capita for 28 European countries during the period 2000–2023. The analysis was carried out through the

lens of the three transmission channels, namely, final energy demand, energy intensity of GDP, and the structure of the energy mix. Data from Eurostat and the Energy Institute were used to construct structural indicators based on Gross Inland Consumption (GIC) and the normalized Shannon index (Shannon, 1948). The methodological design considers the estimation of panel models in first differences with fixed effects per country and year, an approach that is considered suitable for identifying the annual frequency and which is consistent with the methodological standards in the specialized literature (Wooldridge, 2010; Hsiao, 2022; Baltagi, 2021).

The elasticities that are mapped in the study based on GIC constitute an operational tool for managing energy decisions, as they measure the marginal response of emissions to changes in the energy mix and energy intensity. Consequently, the calculated coefficients are useful for managerial choices regarding the calibration of efficiency measures. On the other hand, the usefulness of these indicators also depends on a clear and transparent budgetary framework that prioritizes actions that support the well-being of citizens.

Through the results obtained, the study offers three main contributions. The first aims at the annual decomposition of the links between economic activity, energy performance, and the composition of energy sources. The second contribution consists of rigorously testing the utility of the normalized Shannon index as a short-term predictor of CO_2 emissions per capita, and demonstrates that the practical relevance lies in the real structure of the energy mix and the carbon content of the sources, rather than in "diversity" per se. Finally, the third contribution aims at calculating annual elasticities and semi-elasticities that are directly applicable in policy simulations at the reporting and budgetary frequency of EU Member States.

Theoretical Considerations

In recent decades, the evolution of CO_2 emissions from energy has been closely linked to the level of economic activity, the efficiency of energy use and the composition of energy supply, as these dimensions together shape national emission profiles (Kaya & Yokobori, 1997; Intergovernmental Panel on Climate Change - IPCC, 2007, Ch. 1, Sec. 1.3.1.2), the Kaya identity being the reference framework that formalizes this tripartite relationship.

In this framework, economic development, measured by GDP per capita, acts mainly through final energy demand and the structure of the energy mix, rather than as an autonomous determinant of emissions, and, at the European level, annual variations in emissions systematically reflect policy adjustments operating through these channels (IPCC, 2022, Ch. 2; EEA, 2024).

The empirical literature on the energy-income nexus (Miketa & Mulder, 2005; Mulder & de Groot, 2012; Csereklyei *et al.*, 2016; Stern, 2012) consistently documents sub-unit elasticities of energy demand with income, but also a long-term decline in energy intensity as capital modernization and structural change deepen. Miketa & Mulder (2005) conducted an empirical analysis of energy productivity convergence over the period 1971-1995 for 56 developed and developing countries, the results suggesting that energy productivity tends to be convergent across countries in most sectors, while energy prices have little explanatory power for cross-country variations. Similar results are obtained from an analysis carried out for 50 sectors in 18 OECD countries during the period 1970–2005 (Mulder & de Groot, 2012). The authors documented that energy intensity is decreasing in most sectors, and aggregate convergence comes almost exclusively from intra-sectoral convergence, not from changes in the composition of the economy. These results are also confirmed by the efficiency indicator systems developed by the International Energy Agency (IEA, 2024), which support the general trend of improving efficiency and reducing energy intensity in developed economies.

Energy intensity remains a major determinant of emissions in the short term, but evidence from the literature shows that efficiency improvements do not always translate into proportional reductions in energy consumption, due to so-called rebound effects that occur when a decrease in energy costs leads to an increase in consumption. Several studies documented these effects at the household and EU economy levels (Freire-Gonzalez, 2017; Balezentis *et al.*, 2021). Freire-Gonzalez (2017) shows, based on an econometric and input-output analysis for the EU-27 countries, that improving energy efficiency generates direct and indirect rebound effects of approx. 70–80 %. The author's results suggest that energy consumption reductions cannot occur automatically in the absence of complementary demand management policies. Similarly, using econometric approaches based on the ODEX index, Balezentis et al. (2021) analyze the rebound effect in the EU residential sector for the period 2000–2015. The authors show that although the rebound effect has decreased over the analyzed period, there are still significant differences between countries, some of which, such as Bulgaria, Estonia, Romania, Hungary, Italy, Slovenia, and Spain, even face reverse effects, i.e., efficiency improvements have generated an increase in energy consumption.

At the same time, studies based on decomposition methods (LMDI and SDA) applied at the European level also show that variations in CO_2 emissions are mainly influenced by changes in both energy efficiency and the structure of the mix. In this sense, the literature documents that the effect of energy efficiency is usually one of reducing emissions, but with a different intensity between sectors and periods (Gonzalez *et al.*, 2014; Karmellos *et al.*, 2016; Bianco *et al.*, 2024).

Based on the LMDI models used to assess the determinants of variations in CO_2 emissions in the EU-27 energy sector for the period 2001-2010, González et al. (2014) show that changes in the structure of the energy mix have the strongest impact on aggregate emissions, while energy intensity provides different results depending on the measurement method (monetary or physical). Similar investigations are also carried out by Karmellos et al (2016), who conducted a study for the period 2000–2012 at the EU-28 level and show that, during the years of economic growth, the decrease in electricity intensity compensated for the effect of the growth of economic activity in most of the analyzed countries.

In contrast, after 2007, the authors show that energy efficiency, the energy mix, and energy trade start to play an increasingly important role in reducing emissions, against the backdrop of political pressures in the post-Kyoto period. Therefore, the results in the literature support the idea that emission reduction does not depend only on technological progress and economic development, but also on the coherence of public policies guiding the energy transition.

On the supply side, the economic literature distinguishes between the structure of the energy mix and diversity. A number of studies use Shannon-type indices to assess the resilience and balance of energy supply (Shannon, 1948; Kruyt *et al.*, 2009; Sovacool & Mukherjee, 2011). The transparency of these indicators is useful for diagnosis, but is insufficient to capture the carbon intensity of sources, which makes them poor predictors of annual emissions variations (Stirling, 1998; 2007).

In contrast, several studies document that when the actual shares of low-emission sources (e.g., the shares of renewables and nuclear) are included in the models, the relationship with emissions is negative and more robust, as the indicator directly reflects the carbon intensity of the mix (Grubb *et al.*, 2006; Menyah & Wolde-Rufael, 2010; Mahmood, 2022; York, 2012). For example, Menyah & Wolde-Rufael (2010) document the causal relationship between CO_2 emissions, renewable and nuclear energy consumption, and real US GDP for the period 1960–2007, and show that nuclear energy consumption contributes to the mitigation of CO_2 emissions, while renewable energy consumption did not have a significant contribution to reducing emissions over the analyzed period. On the other hand, Mahmood (2022) analyses the role of the transition to nuclear power on CO_2 emissions in 28 nuclear power-producing countries over the period 1996–2019. The author shows that, in the long run, the transition to nuclear energy contributes to reducing emissions, especially in upper-middle and high-income economies; in less developed economies, this effect is not observed.

On the demand side, however, energy efficiency remains the main predictor of CO_2 emissions per capita. The literature and official reports (Csereklyei *et al.*, 2016; IPCC, 2022, chap. 2) document that improvements in energy intensity are closely linked to annual emission reductions. In this direction, Csereklyei et al (2016) conducted an analysis based on a panel data set on 99 countries, from 1971 to 2010, and showed that energy intensity tended to decrease in high-income countries. Also, in the long term, the authors highlight the conditional convergence of energy intensity, with the reduction of dispersion between countries towards a stationary distribution.

In the specialized literature, a series of panel studies that use a systemic approach to emissions were identified by estimating them in a single framework. For example, Marra et al. (2024) used a first-difference PVAR model for 34 OECD countries (1994–2019) and showed that improving energy intensity reduces emissions in the short term, while structural transformations of the economy favour the emergence and adoption of low-emission technologies. Chovancova et al. (2024) had similar concerns. The authors used data for 1992–2019 on a panel of 22 European countries and applied state-of-the-art estimation methods, such as Common Correlated Effects (CCE) and panel models with instrumental variables and common factor. The analyses identify two central determinants of CO_2 emissions, namely, energy consumption and the intensity of economic activity.

From a legislative point of view, the RED III package pursues a mandatory target of at least 42.5 % energy from renewable sources in gross final consumption for 2030. In addition, the EEA tracks the progress of states in decarbonization, efficiency, and the expansion of renewables (EU, 2023b; EEA, 2024). This regulatory framework sets the stage for climate change mitigation, but does not indicate the share of renewables, efficiency, and intensity of economic activity in reducing emissions.

In practice, energy statistics use indicators derived from Gross Inland Consumption (GIC), while the RED III targets are related to Gross Final Consumption (GFEC). The absence of a one-to-one correspondence without explicit conversions does not change the interpretation of elasticities, but conditions of their application in policy design, where coefficients formulated on GFEC can directly guide the planning of fossil fuel substitution. GIC offers systemic comparability, but reduces the direct transferability of coefficients to the RED III architecture, formulated on the GFEC. In conclusion, the literature reports heterogeneous findings. But regardless of the focus on one or another of the emission transmission channels, the literature agrees that, at the annual horizon, the dominant channels remain final energy demand and energy intensity. However, there is still a gap in studies that quantify the magnitude of the dominant channels, the calculation of elasticities being a contribution of the study that adds value to already existing studies.

Data and Methodology

Data and Indicators Employed in the Empirical Analysis

The analysis includes 26 EU member states (with the exception of Malta, for which no data are reported) and two non-EU states (Norway and Iceland). The analyzed period is 2000-2023, due to the availability of Eurostat data, but also the fact that this period captures both the 2009 and 2020 shocks that shaped the current energy landscape. Norway and Iceland were included in the sample because of the specificity of their energy mix. Thus, Norway has a hydropower-dominated energy system with strong integration into the EU electricity market (IEA, 2022; Norwegian Ministry of Petroleum and Energy, 2025), while Iceland has very high shares of hydropower and geothermal energy, combined with a high energy-intensive industrial base (OECD, 2025).

The indicators were chosen in line with the practices used by the IPCC, the EEA, and Eurostat, to cover the main dimensions of the energy transition. Final energy consumption, the structure of the energy mix, and CO_2 emissions from energy are defined according to the IEA and Eurostat methodologies (Energy Institute, 2025; EEA, 2024; Eurostat, 2025b; IPCC, 2022; IEA, 2020; EU, 2023a; OECD, 2017).

The data are collected from Eurostat and the Energy Institute Statistical Review. Based on these, derived indicators were constructed, such as the shares of different energy sources in the total supply and the Shannon diversity index (along with its normalized version) to assess the distribution of the energy mix. Table 1 briefly presents the variables used in the analysis.

Table 1

Variables Used in the Empirical Analysis

Code	Indicator/Source	Unit of Measurement
POP	Population/Eurostat (demo_pjan)	persons
CO_2_pc	CO_2 emissions per capita/ Energy Institute, own calculation	t CO_2/capita
GDP_pc	Real GDP per capita/ Eurostat (sdg_08_10)	Euro/capita (chain-linked volumes, 2020)
EI_GDP	Energy intensity of GDP/ Eurostat (nrg_ind_ei)	kgoe/1000 EUR GDP
FC	Final energy consumption/ Eurostat (nrg_bal_c)	ktoe
FC_pc	Final energy consumption per capita/ Own calculation based on FC and POP	GJ/capita
Oil_price	Oil price (Brent crude)/ Energy Institute	USD/barrel
GIC	Gross inland consumption/ Eurostat (nrg_bal_c)	ktoe
Shannon	Shannon diversity index (energy mix)/ Own calculation	index (>0)
Norm_Shannon	Normalized Shannon index/ Own calculation	index (0–1)
Coal_share	Share of coal/ Own calculation based on Eurostat (nrg_bal_c)	proportion (0–1)
Gas_share	Share of gas/ Own calculation	proportion (0–1)
Oil_share	Share of oil/ Own calculation	proportion (0–1)
Renew_share	Share of renewables/ Own calculation	proportion (0–1)
Nuclear_share	Share of nuclear energy/ Own calculation	proportion (0–1)
Shale_share	Share of oil shale & oil sands/ Own calculation	proportion (0–1)

Notes: Shares are fractions in [0,1]. CO_2 covers energy-use emissions only, excluding non-energy sources
Source: Authors' compilation

In this study, the shares of energy sources were calculated on the basis of Gross Inland Consumption (GIC), not on the basis of Gross Final Energy Consumption (GFEC), to which the RED III objectives of the European Union (EU, 2023b) refer. The difference between GIC and GFEC comes from transformation losses, own consumption in the energy sector, and distribution losses, according to Eurostat energy balances.

Although the RED III objectives are formulated in terms of GFEC, GIC was preferred as this indicator does not depend on country-specific final consumption allocation rules. Even if this choice is not in line with EU policy indicators, this approach ensures real comparability.

Also, for cross-country comparability, per capita indicators were used for the basic variables, because they directly capture the environmental impact of energy use and are used in the empirical literature as standardized measures for populations of different sizes. All empirical estimates are based on the full sample of 28 European countries. The grouping of countries shown in Figure 1 is not used in the estimates, but only to illustrate some recurring patterns of the energy transition.

Figure 1 reports the evolution of the main indicators (renewable energy share, energy intensity of GDP, CO_2 emission per capita, and real GDP per capita) that reflect the energy transition profile of the sample countries. The countries were divided into three panels as follows:

- Western Europe Group, including Belgium, Denmark, France, Germany, and the Netherlands;
- Central and Eastern Europe Group, including Latvia, Hungary, Poland, Slovakia, and Slovenia;
- Nordic Group, including Norway, Iceland, Sweden, and Finland.

The graphical representation of the indicators (Figure 1) reveals four distinct patterns in the energy transition of the states. *The first pattern* is specific to countries where the share of low-emission energy sources has increased rapidly (e.g. Denmark, Germany, and the Netherlands), while CO_2 emissions per capita have decreased significantly. Within this group, it is observed that Denmark has the highest growth rate in the share of renewables (34.81 pp in 2023 compared to 2000), simultaneously with a reduction of 6 t per capita in CO_2 emissions and energy intensity by 37.11 kgoe/1000 EUR. We also observe the same trend in Germany (increase in renewables by 16.61 pp, simultaneously with a reduction of 3.52 t of CO_2/capita and energy intensity by 54.74 kgoe/1000 EUR), but also in the Netherlands (+12.16 pp in renewables, simultaneously with -4.87t CO_2 per capita and -64.68 kgoe/1000 EUR).

The second model includes countries with an increasing share of renewables (France, Slovakia, Hungary) and with emissions that are reducing more slowly. France and Slovakia register an increase in renewables in the mix by 8.87 pp, respectively 9.75 pp, while Hungary has an increase slightly above them (+10.40 pp), simultaneously with an improvement in energy intensity (-133.44 kgoe/1000 EUR).

A third pattern is characteristic of countries with a strong dependence on fossil fuels (in particular, the Central and Eastern European Group). These economies started in the 2000s from relatively high levels of energy intensity (e.g., in 2000, Latvia had an energy intensity of 286.41 kgoe/1000 euros, Lithuania 369.53 kgoe/1000 euros, and Poland 350.83 kgoe/1000 euros), and their emissions have decreased at a rather slow pace.

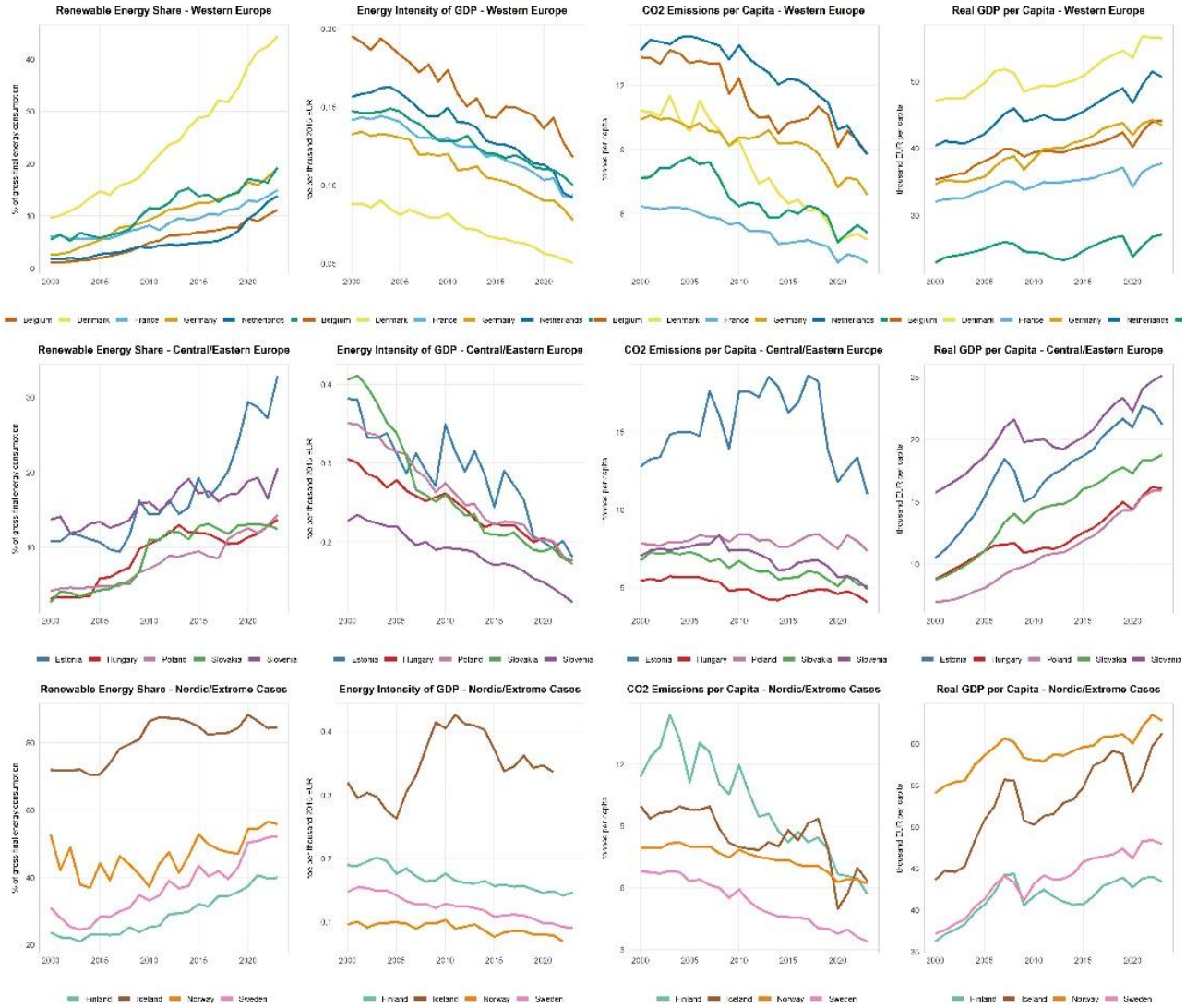

Figure 1. Key Variable Trends in Representative Countries from the Selected Sample
Source: authors' processing in R 4.4.1, based on Annex E

The last pattern is the one that appears within the Nordic group of hydropower-dominant countries (Norway, Iceland), which have high shares of low-emission energy. The highest rate of renewables in the mix is in Sweden (+21.35 pp) and Finland (+16.3 pp), both states at the same time maintaining negative changes in CO_2 emissions per capita (−3.39 t and −5.68 t).

In this context, four mechanisms of energy transition were tested, formalized by hypotheses H1-H4 targeting the annual horizon:

- *H1: An increase in the diversity of the energy mix, as measured by the normalized Shannon index, is associated with a reduction in the energy intensity of GDP;*
- *H2: An increase in the share of low-carbon energy sources in gross inland consumption (GIC) corresponds to a decrease in per capita CO_2 emissions from energy use. This hypothesis is tested using two complementary specifications: (a) by including the shares of low-emission sources in the energy mix (i.e., renewables share and nuclear share); (b) by including the normalized Shannon index as a proxy for energy mix diversity;*
- *H3: Higher energy intensity of GDP is linked to higher per capita CO_2 emissions, for a given level of GDP per capita;*
- *H4: An increase in final energy consumption per capita is associated with an increase in CO_2 emissions per capita.*

Methodology

The research methodology adopted to achieve the set objectives aims at estimating panel models with fixed effects at the country and year levels. The choice is motivated by the need to absorb time-invariant heterogeneity and common shocks, but also to mitigate omitted variable errors, in accordance with the literature documentation (Wooldridge, 2010; Baltagi, 2021; Mundlak, 1978; Hausman, 1978). Table 2 presents the mapping of the hypotheses.

Table 2

Mapping of Hypotheses

Hypotheses	Dependent variable (y)	Main explanatory variables (X)	Control variable(s)
H1	ln(EI_GDP)	Norm_Shannon	ln(GDP_pc)
H2a	ln(CO_2_pc)	Renew_share, Nuclear_share	ln(GDP_pc)
H2b	ln(CO_2_pc)	Norm_Shannon	ln(GDP_pc)
H3	ln(CO_2_pc)	ln(EI_GDP)	ln(GDP_pc)
H4	ln(CO_2_pc)	ln(FC_pc)	ln(GDP_pc)

Notes: H2a and H2b represent alternative specifications and are not estimated jointly
Source: Authors' compilation

In three out of the four hypotheses, energy-related CO_2 emissions per capita are the dependent variable. However, each specification was designed to test a different transmission mechanism, namely, the role of energy mix diversity, the specific contribution of low-emission sources, the influence of energy intensity, and, separately, the effect of final energy consumption per capita (Kaya & Yokobori, 1997; IPCC, 2022, Chapter 2).

For Hypothesis H1, the dependent variable was changed to energy intensity of GDP, a choice motivated by the relevant literature on energy system diversity and performance (Stirling, 1998; Grubb et al., 2006; Sovacool & Mukherjee, 2011). Figure 2 presents the conceptual framework linking energy mix diversity, energy efficiency, and CO_2 emissions per capita.

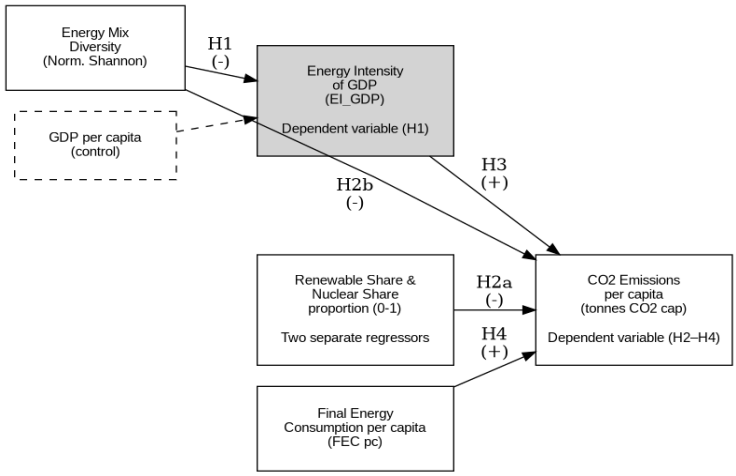

Figure 2. Conceptual Framework Linking Energy Mix Diversity, Energy Efficiency, and CO_2 Emissions per Capita
Source: authors' processing in Python

Hypothesis testing allows us to show to what extent the energy transition in Europe has supported the decoupling process. This approach aims to identify the contribution of increasing the share of low-emission sources and reducing energy intensity to the decrease in CO_2 emissions per capita over the period under review.

The descriptive statistics (Table 3) show a large dispersion of CO_2 per capita, GDP per capita, energy intensity, and final energy consumption per capita, suggesting high variability between the countries under review. These statistics are quite intuitive considering the existence of large differences in development between European countries, but also in the efficiency and structure of the energy mix. Descriptive statistics also show that the normalized Shannon index and the nuclear energy share exhibit strong skewness, indicating that the distributions are unbalanced across countries. Given these observations, in the model specifications, logarithmic transformations were applied for these series that help reduce asymmetry and allow the interpretation of the coefficients as percentage effects (Wooldridge, 2010). The energy mix shares and the normalized Shannon index are already scaled in the range [0,1], and are therefore kept at their original levels. The data set is a balanced panel (no missing values), with 672 observations for each variable. Before estimation, for cross-country dependence and stationarity of the series were checked using established tests (Pesaran, 2015). Continuous series in logarithms are I(1) and become stationary in first differences, according to panel tests (Im *et al.*, 2003; Pesaran, 2007). The weights in the energy mix and the normalized Shannon index show long-term trends, and non-stationarity cannot be rejected at usual levels. Cross-country dependence was detected in the residuals, and panel cointegration tests do not indicate stable long-term relationships over the period 2000–2023 (Westerlund, 2007).

Table 4 summarizes the results of these tests (IPS/CIPS, Pesaran CD, Westerlund), and additional statistics and p-values are provided in Annex A (Tables A1-A5).

Table 3

Descriptive Statistics (Original Units), 2000-2023

	Valid	Mean	Sd	Min.	Max.
CO2_pc	672	8.081	3.959	2.92	27.72
GDP_pc	672	31101.116	21088.847	4160	109090
EI_GDP	672	183.364	99.923	31.85	687
FC_pc	672	109.155	64.31	40.919	369.943
Norm_Shannon	672	0.677	0.164	0.09	0.89
Renew_share	672	0.182	0.168	0.01	0.88
Nuclear_share	672	0.089	0.119	0	0.44

Note: Mix shares are expressed as proportions in the [0–1] interval
Source: Authors' contribution in Stata 14

Table 4

Diagnostic Tests and Preliminary Results

Test	Result	Implication for Model
Stationarity (IPS/CIPS)	Series are I(1); stationary in Δ	First-difference models
Cross-sectional dep. (CD)	Present	Driscoll-Kraay errors; FE
Cointegration (Westerlund)	Not confirmed	No long-run relationship (no ECM term)

Based on the diagnostic results, all models are estimated in first differences (Δ), with fixed effects at the country and year levels. Driscoll–Kraay robust standard errors (lag 2) are applied to address heteroskedasticity, serial correlation, and cross-sectional dependence (Driscoll & Kraay, 1998; Hoechle, 2007). Coefficients on logged variables are interpreted as short-run elasticities, while coefficients on shares or indices are interpreted as semi-elasticities (Kennedy, 2008; Wooldridge, 2010). To avoid collinearity among energy-mix shares (which sum to 1), not all components are included simultaneously. Instead, either the shares of renewables and nuclear or the normalized Shannon index are tested. Thus, the estimated models are:

$$\Delta \ln(EI_GDP_{it}) = \alpha_i + \gamma_t + \beta_1 \Delta NormShannon_{it} + \beta_2 \Delta \ln(GDP_pc_{it}) + u_{it} \quad \text{(H1)}$$

$$\Delta \ln(CO2_pc_{it}) = \alpha_i + \gamma_t + \beta_1 \Delta Renew_share_{it} + \beta_2 \Delta Nuclear_share_{it} + \beta_3 \Delta \ln(GDP_pc_{it}) + u_{it} \quad \text{(H2a)}$$

$$\Delta \ln(CO2_pc_{it}) = \alpha_i + \gamma_t + \beta_1 \Delta NormShannon_{it} + \beta_2 \Delta \ln(GDP_pc_{it}) + u_{it} \quad \text{(H2b)}$$

$$\Delta \ln(CO2_pc_{it}) = \alpha_i + \gamma_t + \beta_1 \Delta \ln(EI_GDP_{it}) + \beta_2 \Delta \ln(GDP_pc_{it}) + u_{it} \quad \text{(H3)}$$

$$\Delta \ln(CO2_pc_{it}) = \alpha_i + \gamma_t + \beta_1 \Delta \ln(FC_pc_{it}) + \beta_2 \Delta \ln(GDP_pc_{it}) + u_{it} \quad \text{(H4)}$$

where: α_i = country fixed effects; γ_t= year fixed effects.

Results and Discussion

To assess the short-term effects corresponding to hypotheses H1-H4, panel models were estimated with Driscoll-Kraay standard errors and fixed effects per country and year. To support the interpretation of the magnitudes, the synthesis of the main elasticities and semi-elasticities is presented in Table 6, while Table 5 contains the full coefficients of the estimates.

Table 5

Short-Term Estimations (Δ), Country & Year FE, Driscoll–Kraay (lag=2) Errors

Variable	H1: Δln(EI_GDP)	H2a: Δln(CO_2_pc)	H2b: Δln(CO_2_pc)	H3: Δln(CO_2_pc)	H4: Δln(CO_2_pc)
ΔNorm_Shannon	−0.205 (0.228)	N/A	−0.058 (0.178)	N/A	N/A
ΔRenew_share	N/A	−0.853*** (0.189)	N/A	N/A	N/A
ΔNuclear_share	N/A	−0.403*** (0.062)	N/A	N/A	N/A
Δln(EI_GDP)	N/A	NA	N/A	0.702*** (0.080)	N/A
Δln(FC_pc)	N/A	N/A	N/A	NA	0.752*** (0.058)
Δln(GDP_pc)	−0.536***(0.060)	0.410*** (0.095)	0.467*** (0.096)	0.843*** (0.119)	0.197 (0.099)*
Within R^2	0.262	0.537	0.485	0.660	0.587
Observations	644	644	644	644	644
Countries	28	28	28	28	28

*Notes: *** p<0.01; ** p<0.05; * p<0.10; in H4, after including final energy consumption per capita, the Δln(GDP_pc) coefficient is marginal (p=0.059) and does not pass the 5% threshold (see Annex D)*
Source: Authors' contribution in Stata 14

Table 6

Summary of Short-Run Elasticities and Semi-Elasticities

Independent variable	Dependent variable	Elasticity/ Semi-elasticity	95% CI [%]	Interpretation
Renew_share (+1 pp)	CO_2_pc	-0.853***	[-1.245; -0.461]	Decrease of ~0.85% in emissions
Nuclear_share (+1 pp)	CO_2_pc	-0.403***	[-0.532; -0.274]	Decrease of ~0.40% in emissions
EI_GDP (+1%)	CO_2_pc	0.702***	[0.535; 0.867]	Increase of ~0.70% in emissions
FC_pc (+1%)	CO_2_pc	0.752***	[0.631; 0.873]	Increase of ~0.75% in emissions
GDP_pc (+1%)	EI_GDP	-0.536***	[-0.660; -0.412]	Decrease of ~0.54% in energy intensity
Shannon (+0.1)	EI_GDP	-0.021	[-0.068; 0.026]	No significant effect
Shannon (+0.1)	CO_2_pc	-0.006	[-0.043; 0.031]	No significant effect

*Note: *** p<0.01; Semi-elasticities for share-type variables represent the effect of a 1 pp increase. Elasticities for log-transformed variables are interpreted as percent changes*
Source: Authors' estimates in Stata 14

The results show the existence of robust and statistically significant relationships between the selected energy variables and CO_2 emissions per capita. In the analyzed panel, it is observed that a 1 pp increase in the share of renewables is associated with a 0.85 % reduction in emissions, and a +1 pp increase in the share of nuclear energy with a smaller reduction, of approximately −0.40 %. Moreover, energy intensity and final consumption per capita have a similar trend with emissions, a +1 % each correlating with +0.70 % and +0.75 % in CO_2, respectively.

These findings support the existence of a direct link between pollution and reduced energy efficiency. On the income side, estimates show that +1 % in GDP per capita is associated with −0.54 % in energy intensity, which is an indication of partial decoupling between economic growth and energy consumption. In addition, the Shannon index remains insignificant for both energy intensity and emissions.

To support the quantitative relationships identified econometrically, Figure 3 illustrates the changes in the structure of the analyzed variables.

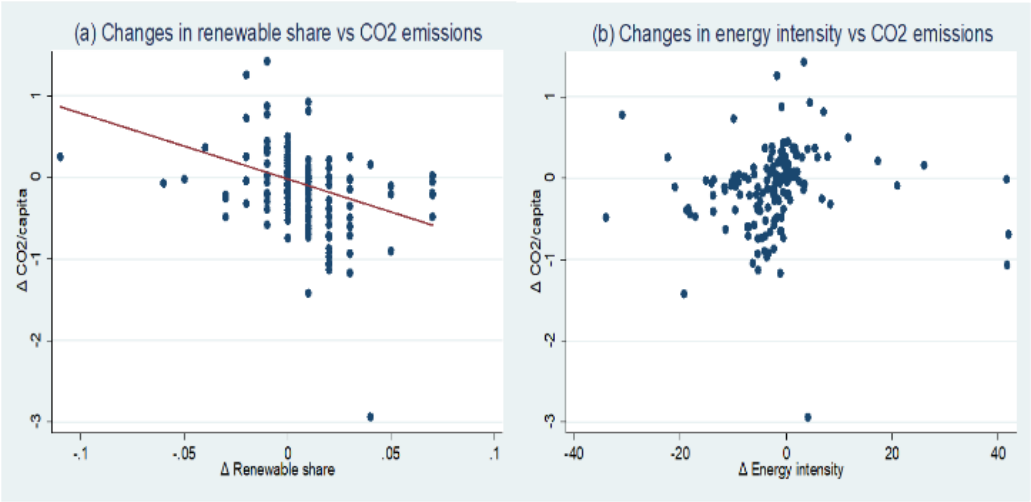

Figure 3(a)(b). Bivariate Relationships in Panel Data (First Differences)
Source: authors' contribution in Stata 14

Figure 3(a) shows the negative relationship between annual changes in the share of renewable energy sources and per capita CO_2 emissions, while Figure 3(b) illustrates the positive relationship between changes in energy intensity and per capita CO_2 emissions. Although the wider dispersion suggests the heterogeneity of efficiency shocks within the panel, the upward trend remains observable.

To translate the estimated impacts into operational terms and compare across intervention options, the short-term coefficients were converted into policy scenarios, quantifying the response of per capita CO_2 emissions to marginal changes in energy variables within the panel (Table 7). Contrary to the idea frequently encountered in the literature (Marques *et al*, 2019; Hagemejer & Zolkiewski, 2012) that short-term adjustments are difficult to translate into policy targets, the scenarios in Table 7 provide elasticities and semi-elasticities that allow the ranking of managerial measures according to the estimated impact of the changes and also facilitate the assessment of cost-effectiveness on annual budgets.

With the exception of mixed diversity (measured by Shannon), for which no significant effect was obtained in the analyzed interval, all other tested scenarios provide consistent signals for the design of short-term policies. These results can be used both for setting targets and for sizing the budgets necessary to achieve the balance between decarbonization and energy security objectives

Table 7

Simulated Short-Term Marginal Effects on Δln(CO_2 Per Capita)

Scenario	Estimated Effect [%]	95% CI[%]
H2a: +5 pp in Renew_share	−4.27	[−6.12; −2.42]
H2a: +2 pp in Nuclear_share	−0.81	[−1.05; −0.56]
H3: −3% in EI_GDP	−2.11	[−2.58; −1.64]
H4: −4% in FC_pc	−3.01	[−3.49; −2.52]

Source: Authors' estimates in Stata 14

Testing the short-term hypothesis H1 reveals that the diversity of the energy mix (measured by the normalized Shannon index) does not have a statistically significant effect on the energy intensity of GDP over the annual horizon. As a result, Hypothesis H1 is not confirmed. The results obtained are consistent with European reports (IPCC, 2022, Chapter 2; EEA, 2024) and with the economic literature that documents in a series of studies the importance of technological progress and structural policies in reducing energy intensity, without finding solid evidence that diversity itself is a determining factor (Miketa & Mulder, 2005; Mulder & de Groot, 2012; Stern, 2012; Csereklyei *et al.*, 2016).

In contrast, the composition of the energy mix has a direct impact on emissions, which confirms Hypothesis H2a in the short-term. This result is quite intuitive, but the econometric analysis confirms the magnitude of this impact. Thus, as the energy transition moves towards low-emission sources instead of fossil fuels (as is the case in countries such as Germany, Denmark, France, and Sweden), the effect begins to become observable on an annual horizon. In this context, managerial decisions regarding the direction of investments, but also decisions on the allocation of public budgets, become essential pillars for accelerating this transition, as documented by both the specialized literature and European synthesis reports (Beerten *et al.*, 2009; York, 2012; Sovacool *et al.*, 2020; Mahmood *et al.*, 2022; IPCC, 2022, chap. 6).

If we align the results with the EU decarbonisation policy scenarios, a 5 pp increase in the share of renewables is associated with an average reduction of 4.3 % in CO_2 emissions per capita, while a 2 pp increase in the share of nuclear power is associated with an estimated reduction of 0.8 % (see Table 7). For confirmation, the effects are robust to alternative specifications (lead-lag structures and AB-GMM estimates), the sign and magnitude of the coefficients being maintained.

Of course, the energy transition is not uniform for all European countries, and their response is different depending on the energy policies, level of economic development, consumption habits, energy mix, and technical infrastructure they have.

In this regard, Figure 4 highlights the variations between countries and their positioning within the energy transition. It is observed that Denmark has the best position on the line of decarbonization based on renewable sources, due to the expansion of wind energy and the gradual withdrawal of fossil sources. Germany, in turn, follows a similar trajectory, in this case with feed-in tariffs as the mainstay of supporting the expansion of low-emission capacity. Finally, Spain and Iceland are making moderate progress, each recording an increase of around 13 pp in the share of renewable sources, accompanied by substantial emission reductions (-2.55 t CO_2 per capita in Spain and -3.65 t in Iceland; see Annex E).

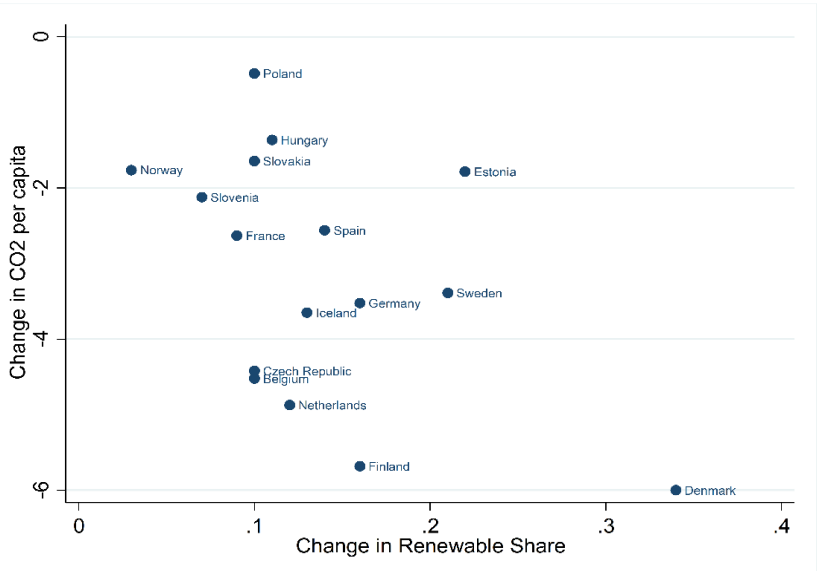

Figure 4. National Responses to Energy Transition in Representative Countries from the Sample, 2000–2023

Source: Authors' illustration in Stata 14

In the case of Hypothesis H2b, the same relationship between emissions and energy mix was examined, but replaced the individual energy source weights with the normalized Shannon index as an indicator of diversity. Similar to the results obtained from testing H1, energy mix does not explain the annual variation in CO_2 emissions per capita, and, therefore, Hypothesis H2b is not supported in the short-term. The effect is statistically insignificant ($p = 0.75$), and even though the Shannon index is changed by 0.10 units, the response of CO_2 emissions per capita is below 1 %. Similar results are obtained by other authors who show in their studies that generic diversity indices capture statistical equilibrium (Stirling, 2007; Kruyt *et al.*, 2009), less the carbon content of energy sources (Beerten *et al.*, 2009; Pehl *et al.*, 2017) or the effective replacement of fossil fuel-based energy generation (Menyah and Wolde-Rufael, 2010; York, 2012).

Pursuing the research objective, Hypothesis H3 tested whether lower energy consumption per unit of GDP correlates with lower emissions. The obtained coefficients support Hypothesis H3 and show that an improvement in the energy intensity of GDP is associated with annual reductions in CO_2 emissions per capita ($p < 0.001$; $R^2 = 0.66$). A 1 % reduction in energy intensity is associated, on average, with a reduction of about 0.7 % in CO_2 emissions per capita, and a 3 % reduction corresponds to a more consistent decrease of 2.1 % (Table 7). In contrast, if countries experience an increase in the level of economic development and GDP per capita increases by 2 %, the net effect remains quite modest, at about -0.4 %.

Thus, overall, energy efficiency acts as an immediate predictor of decarbonization, and when energy consumption per unit of GDP decreases, emissions follow the same direction. In this context, it is quite clear that the most suitable instruments for rapid and quantifiable effects remain minimum performance standards, process optimization, and systematic energy management, as also noted in European reports (IPCC, 2022, Chapter 2; IEA, 2024). These measures directly link efficiency targets to expected emission reductions and provide operational benchmarks for short-term policy calibration.

This result is consistent with authors documenting that energy intensity reductions occur as economies grow and modernize their capital (Miketa & Mulder, 2005; Mulder & de Groot, 2012; Stern, 2012; Csereklyei *et al.*, 2016). Furthermore, at a managerial level, this finding may help countries understand the importance of adopting minimum performance standards and implementing more coherent energy management.

Finally, Hypothesis H4 explicitly tested whether final energy consumption per capita is directly correlated with CO_2 emissions per capita. The results obtained suggest a strong link ($p < 0.001$; $R^2 = 0.59$) and thus Hypothesis H4 is confirmed. This appears to be the main channel through which economic activity is transmitted into annual variations in emissions. Specifically, a 1 % increase in final energy consumption per capita is associated with a 0.75 % increase in emissions per capita, and a 4 % reduction corresponds to a decrease of approximately 3.0 %. Similar results are obtained by other authors, who show that emissions per capita closely follow annual variations in final energy consumption (Csereklyei *et al.*, 2016).

To isolate the mechanism by which economic activity affects emissions, this channel is explicitly included in the model, with the result that the marginal effect of GDP per capita becomes statistically insignificant ($p = 0.059$), suggesting that, in the short run, emissions follow real energy consumption. This finding is consistent with the Kaya decomposition and the econometric practice of isolating emission channels (Kaya & Yokobori, 1997; Wooldridge, 2010), and additional collinearity checks and residualization exercises support this interpretation (see Annex C).

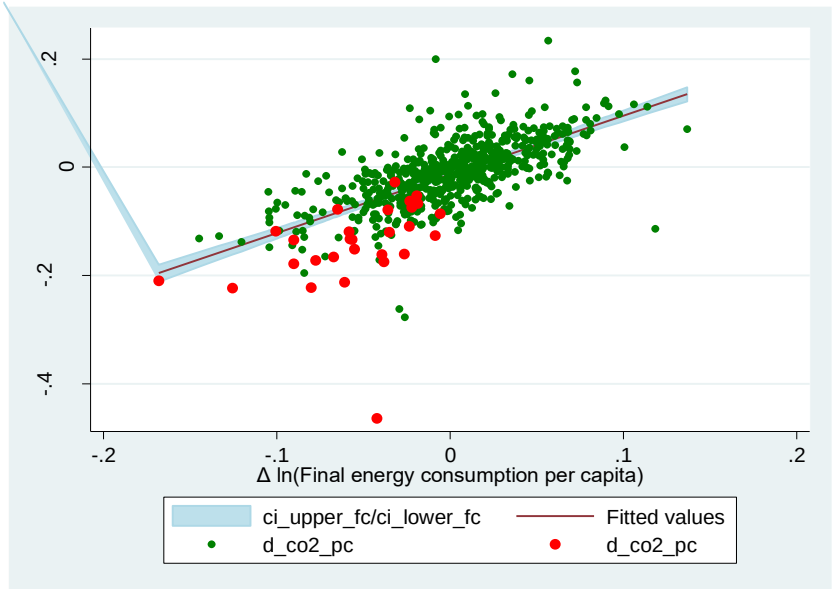

Figure 5. Changes in Final Consumption vs CO_2 Emissions

Note: $\beta = 0.752$, $p < 0.001$.
Source: authors' illustration in Stata 14

Figure 5 shows the direct relationship between final energy consumption per capita and CO_2 emissions. The year 2020 was marked in red, and note that, in almost all the analyzed countries, the decrease in consumption during the COVID-19 period was accompanied by a visible reduction in emissions.

Of course, this phenomenon reflects the response of emissions to the cyclicality of the economy and should not be confused with structural changes. Nevertheless, the signal is useful and visible. It follows that demand-side measures (such as improving efficiency in households and industry, flexible consumption management, and the implementation of time-based tariffs) can produce visible effects on the annual horizon.

To validate the reliability and generalizability of the main findings, robustness checks were conducted targeting temporal causality, identification of alternative models, treatment of common shocks, definition of the diversity index, and potential collinearity, especially in model H4.

Temporal causality between the energy mix and CO_2 emissions was tested by including both lagged and lead values of ΔRenew_share and ΔNuclear_share in the baseline specification. The lead terms were not statistically significant, while the contemporaneous coefficients remained stable in both sign and magnitude. This provides no indication of anticipation effects or reverse causality at an annual frequency (Annex B, Table B1; see Wooldridge, 2010).

Estimation method sensitivity was assessed using the Arellano–Bond Generalized Method of Moments (AB-GMM) in first differences, where changes in the share of renewables and nuclear energy were treated as endogenous, energy intensity as predetermined, and per capita final energy consumption as exogenous. The AB-GMM specifications met standard diagnostic tests, including AR(2) and the Hansen test (Annex B, Table B3; see Arellano & Bond, 1991; Windmeijer, 2005; Roodman, 2009), and coefficient signs remained consistent.

Common shocks were accounted for by estimating models both with and without year fixed effects using Driscoll–Kraay standard errors (Annex B, Table B2; see Driscoll & Kraay, 1998; Hoechle, 2007). The short-term elasticities remained qualitatively unchanged. In addition, estimation using the Common Correlated Effects Mean Group (CCEMG) estimator (Pesaran, 2006) and robustness checks excluding atypical years (2020–2022) further confirmed the stability of the results (see Annex B, Table B4–B5).

Diversity index robustness was tested by recalculating the normalized Shannon index excluding the "oil shale & oil sands" category and renormalizing with ln(5) as the denominator. The results were unchanged, reinforcing the finding that, in short-run models, the explanatory power lies in the specific shares of low-emission sources (renewables and nuclear), while the overall diversity index does not exhibit a statistically significant effect.

Collinearity tests showed that the link between final energy consumption and emissions remains robust, regardless of the level of economic development (measured by GDP per capita), confirming the central role of energy demand in determining emissions. In the full specification, with fixed effects on country and year, the coefficient on GDP per capita becomes statistically insignificant once final energy consumption is included, suggesting that the latter is the dominant channel through which economic activity is transmitted to emissions in the short term (Annex C, Tables C1-C3; Annex D).

In conclusion, the robustness tests consistently support the stability and interpretability of the study's core econometric results. Complete methodological details and extended robustness outputs are provided in Annex B (Tables B1–B5), Annex C (Tables C1–C3), and Annex D.

Conclusions and Managerial and Policy Implications

The experience of 2009 and 2020 clearly showed that emissions and energy demand follow the same downward trend on an annual horizon, against the background of an external shock. Although this cyclical component cannot be ignored, this study focuses on how the composition of the energy mix and the dynamics of demand shape CO_2 emissions per capita in 28 European countries. We argue that the evaluation of policies must be anchored in their transmission channels without confusing cyclical declines with structural progress generated by the energy transition. In this regard and within this paper, the "energy transition" has an operational sense, more like as a set of observable annual adjustments rather than long-term structural equilibrium process.

The empirical chosen design starts, on the one hand, from the presence of unit roots in the level, and on the other hand, from the absence of cointegration and the need to control for common shocks. Accordingly, first-difference models were estimated, with fixed effects per country and per year, to capture the annual response of per capita CO_2 emissions to changes in GDP per capita, GDP energy intensity, per capita final consumption, and the share of low-emission sources. Differentiation eliminates stochastic trends and, together with fixed effects and robust errors, limits the influence of extreme values. Our results describe the European trend at annual frequency. Based on the results, the effective structure of supply and demand appears to govern the short-term dynamics of emissions, while generic mix diversity does not play a distinct role. In this framework, the results should be viewed as short-term relationships, visible at the annual level. First-difference models capture short-term emissions responses to changes in demand, efficiency and energy mix composition. By default, they do not capture long-term structural decarbonization processes, as differentiation attenuates the slow and cumulative components of the energy transition.

The normalized Shannon index does not explain annual variations in either per capita emissions or energy intensity. Therefore, hypotheses H1 and H2b are not confirmed. In contrast, the composition of the mix, expressed in terms of the weights of low-emission sources, shows consistent associations, which are visible across the entire sample and are robust in tests, which confirms Hypothesis H2a.

On the demand side, energy efficiency functions as an immediate channel for decarbonization. Thus, when energy systems become more efficient, emissions decrease visibly in the same year, indicating a rapid response of CO_2 emissions to efficiency improvements. Basically, at the

same level of analysis, what matters is the energy actually consumed. Once final consumption was explicitly introduced into the model, GDP per capita no longer brings additional statistical information (H4 is confirmed). Although it would seem that the level of economic activity directly determines the variations in emissions, our analysis shows the opposite. This finding supports that the cyclical signal related to economic activity disappears once the size of demand is explicitly controlled for. Consequently, in the European sample, the annual dynamics of emissions are predominantly governed by demand and the way energy is used, not by the average level of income (H3 is confirmed).

These findings could be directly translated into annual policy coordinates (see also Istudor *et al.*, 2025).

In terms of policy, the results show that an identical decarbonisation strategy cannot be equally effective in all European countries. The effects of policies depend on the structure of the economy and the starting energy mix.

In *the Nordic countries*, where the mix is already diversified and emissions are low, additional reductions are achieved primarily through limiting consumption and increasing energy efficiency. Shifts in behaviour and the way energy is used become essential, while supply adjustments play a secondary role.

In countries where fossil fuels still dominate the supply, especially in some *countries in Central and Eastern Europe*, such as Poland, Hungary, Bulgaria, Romania or Slovakia, the fastest emission reductions are achieved by directly replacing high-emission sources. Without this substantive change, diversification remains largely formal.

Western Europe is in between these two situations. Although energy mixes are more advanced, high levels of consumption require a combination of supply-side policies with clear demand-side measures. Stand-alone approaches are insufficient.

Overall, the findings imply the need for a more pragmatic interpretation of the European Green Deal. The almost exclusive focus on long-term objectives risks obscuring the lack of real progress. The results support the introduction of clear annual benchmarks, linked to both consumption and supply structures, that would allow distinguishing between cyclical emissions reductions and real structural transformations.

On the supply side, objectives should be formulated as annual variations in the share of low-emission sources in the GIC, in the logic of RED III (EU, 2023b), but without advocating a mechanical equivalence between the GIC and the GFEC. In this framework, the elasticities estimated in this paper are useful for calibrating interventions. In order not to create confusion, it is important to mention that the operational message does not depend on the exact value of the coefficients, but on the demonstrated associations. Thus, at the annual horizon, a higher share of renewables and nuclear is consistently associated with lower emissions per capita, after controlling for the size of demand and the phases of the economic cycle.

Starting from the fact that, on the demand side, the Energy Efficiency Directive (EED) (EU, 2023a) sets consumption reductions and progressive savings obligations until 2030, the shift from input-oriented to output-oriented planning receives strong justification. In this way, efficiency improvements are reflected more quickly in the CO_2 inventory and can be tracked annually.

Under the EU Emissions Trading System (ETS), the 2023 revision (EU, 2023c) consolidates the capping trajectory until 2030, thus providing a coherent reference framework for calibrating policies. In this logic, measures can be formulated to temper demand while increasing the share of low-emission sources directly in the form of consumption quotas. Then these measures can be translated into expected changes in per capita emissions, based on elasticities.

For non-ETS sectors, the Effort Sharing Regulation-ESR (EU, 2018) sets out annual national trajectories, which leads us to argue that interventions should be anchored in reducing demand and increasing the share of low-emission sources, not in accounting adjustments. In this direction, the selected indicators for this analysis could reflect much more faithfully the real change in the system, and not just a statistical picture.

Finally, the implementation of reforms, such as the new electricity market design from 2024 (EU, 2024a; EU, 2024b; Hernnas *et al.*, 2023) and REPowerEU (EC, 2022; EU, 2023d), provides the contractual framework to translate annual decarbonisation targets into effective fossil fuel substitution and flexibility based on non-fossil resources. This framework complements our estimates and does not affect the fact that the results were calibrated using actions defined in the GIC, not in the GFEC. On the contrary, reporting to the GIC removes a number of operational ambiguities and makes comparability across countries much easier. In this context, the idea is reiterated that the results strongly support the formulation of annual pp targets in the GIC for low-emission sources, together with setting countries' efforts towards investments in system infrastructure that allow for the full integration of low-emission generation. Of course, European countries are at different stages of the energy transition, have uneven development, limited resources, and budgetary constraints, but this does not prevent an acceleration of investments through established instruments (feed-in tariffs, contracts for difference, green certificates).

Alongside monitoring progress using direct decarbonisation indicators (CO_2 per kWh generated and CO_2 per capita), these measures are considered more likely to deliver consistent year-on-year emission reductions, strengthen compliance under the EU ETS and the ESR, and stabilise investor expectations. In parallel, energy-efficiency programmes and demand-response measures are recommended to be explicitly linked to reductions in the energy intensity of GDP and in final energy consumption per capita, and that annual planning align with obligations under the EED (EU, 2023a).

The recommendations made are strengthened both on the basis of the robustness tests performed, namely, the lead-lag tests, the exclusion of the pandemic years (2020-2022), and the consistency between the FE, AB-GMM, and CCE estimates supporting the reported economic magnitudes.

The main limitations stem from the empirical design. The first-order difference models with fixed effects at the country and year levels (and without evidence of

cointegration) identify annual elasticities, i.e., short-run associations, rather than equilibrium or causal relationships. Despite the Driscoll-Kraay, CCE, and AB-GMM errors, residual common shocks and endogeneity cannot be completely ruled out. The Shannon index measures diversity, not carbon intensity. Thus, together with the aggregation and compositional nature of the stocks, this constrains the interpretation.

These factors do not invalidate the results, but rather limit the scope of the findings. The estimates remain useful for calibrating and monitoring annual decarbonization targets and for characterizing short-term linkages between energy mix composition, efficiency, consumption, and emissions. Assertions about strict causality or long-term trajectories should be made with caution.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used Grammarly to assist with text translation and language refinement. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Acknowledgements

This work was supported by the project "Renewable Plants Integrated with Pumped Thermal Energy Storage for Sustainable Satisfaction of Energy and Agricultural Needs of African Communities (REPTES)", UEFISCDI Contract No. 14/2024, under LEAP-RE (Europe–Africa Partnership for Renewable Energy).

Annexes

Annex A. Diagnostic Tests Results

Table A1

IPS Tests on Levels, With and Without Trend (Log-Transformed Variables), 2000–2023

Variable	W-t-bar (level)	p-value	W-t-bar (level, trend)	p-value
ln(CO_2_pc)	1.1666	0.8783	0.8099	0.7910
ln(GDP_pc)	0.2167	0.5858	0.6711	0.7489
ln(EI_GDP)	−0.9165	0.1797	−0.0233	0.4907
ln(FC_pc)	1.7438	0.9594	1.9793	0.9761

Notes: H_0: series has a unit root (non-stationary). None of the variables reject H_0 in levels (all are non-stationary).
Source: Authors' calculations

Table A2

IPS Tests on First Differences (Log-Transformed Variables), 2000–2023

Variable (Δ)	W-t-bar	p-value
Δln(CO_2_pc)	−8.3460	0.0000
Δln(GDP_pc)	−4.0057	0.0000
Δln(EI_GDP)	−7.5782	0.0000
Δln(FC_pc)	−5.9323	0.0000

Notes: All first differences reject H_0 at the 1% level; series are I(1)
Source: Authors' calculations

Table A3

IPS Tests on Levels for Variables in [0–1] (Non-Log-Transformed), 2000–2023

Variable	W-t-bar (level)	p-value
Norm_Shannon	3.7220	0.9999
Renew_share	2.8762	0.9980
Nuclear_share	1.0691	0.8575

Notes: None of the [0–1] variables reject H_0 in levels (all are non-stationary)
Source: Authors' calculations

Table A4

ADF Test for Brent Price, Annual Series (2000–2023)

Specification	Z(t)	p-value
Without trend, lags(1)	−2.476	0.1215
With trend, lags(1)	−2.295	0.4367

Notes: Non-stationary in levels under both specifications
Source: Authors' calculations

Table A5

Pesaran CD Tests on Residuals (Country FE + Year Dummies)

Dependent variable	Specification	CD	p-value	Average correlation	Result
ln(CO_2_pc)	xtreg lnCO2_pc i.year, fe	−2.083	0.0372	0.422	CSD at 5%
ln(EI_GDP)	xtreg lnei_gdp i.year, fe	−1.897	0.0579	0.434	CSD at 10% (marginal)

Source: Authors' calculations

Table A6

Westerlund Cointegration Tests (2000–2023, Lags = 1, Leads = 1, Constant)

Dependent variable	Covariates	Gt (p)	Ga (p)	Pt (p)	Pa (p)
ln(CO_2_pc)	lngdp_pc, renew_share, nuclear_share	−2.140 (0.700)	−3.836 (1.000)	−5.758 (1.000)	−2.462 (1.000)
ln(CO_2_pc)	lngdp_pc, norm_shannon	−1.569 (0.996)	−2.850 (1.000)	−6.105 (0.998)	−2.128 (1.000)
ln(CO_2_pc)	lnei_gdp, lngdp_pc	−1.923 (0.739)	−5.759 (0.998)	−7.690 (0.909)	−3.936 (0.966)
ln(CO_2_pc)	lnfc_pc, lngdp_pc	−1.788 (0.922)	−4.940 (1.000)	−7.032 (0.976)	−3.034 (0.996)

Notes: H_0: no cointegration. None of Gt, Ga, Pt, Pa reject H_0.
Source: Authors' calculations

Annex B. Robustness Tests

Table B1

Temporal Direction (Lead–Lag), H2a

Variable	Coefficient	(SE)
ΔRenew_share	−1.042***	(0.198)
L1 ΔRenew_share	−0.300*	(0.144)
F1 ΔRenew_share	−0.080	(0.118)
ΔNuclear_share	−0.428***	(0.078)
L1 ΔNuclear_share	−0.033	(0.109)
F1 ΔNuclear_share	−0.088	(0.077)
Δln(GDP_pc)	0.374***	(0.097)

Observations (N) = 588; Countries = 28; Within R^2 = 0.535 Note: Country and year fixed effects; Driscoll–Kraay standard errors (lag = 2). *** p < 0.01, ** p < 0.05, * p < 0.10; Lead terms (F1) test reverse causality.
Source: Authors' calculations

Table B2

Robustness to Common Shocks - Comparison Without Year FE + Δln(Brent) vs. With Year FE (Without Brent)

Variable	(1) No Year FE + Δln(Brent)	(2) With Year FE (Brent excluded)
ΔRenew_share	−1.180*** (0.161)	−0.853*** (0.189)
ΔNuclear_share	−0.607*** (0.073)	−0.403*** (0.062)
Δln(GDP_pc)	0.673*** (0.166)	0.410*** (0.095)
Δln(Brent)	0.032 (0.026)	-
Observations (N)	616	644
Countries	28	28
Within R^2	0.408	0.537

Notes: In (2), common shocks are absorbed by year dummies (Brent is excluded explicitly); *** p < 0.01, ** p < 0.05, * p < 0.10. N varies due to Δln(Brent) availability.
Source: Authors' calculations

Table B3

AB-GMM in Differences for Δln(CO_2 Per Capita); Collapsed Internal Instruments, Lags 2–3; Time Fixed Effects Included

Variable	AB-GMM (Δln(CO_2_pc))
L1Δln(CO_2_pc)	0.293 (0.249)
ΔRenew_share	−3.301* (1.282)
ΔNuclear_share	−0.863*** (0.198)
Δln(EI_GDP)	0.322* (0.129)
Δln(FC_pc)	0.922*** (0.222)
Observations	587
Countries	28

Notes: *** p < 0.01, ** p < 0.05, * p < 0.10; Tests: AR(2) p = 0.373; Hansen p = 0.496; Instruments = 13.
Source: Authors' calculations

Table B4

Robustness: CCE (Common Correlated Effects Mean Group)

Variable	FE with fixed effects (original)	CCE Mean Group
ΔRenew_share	−0.853*** (0.189)	−1.449*** (0.233)
ΔNuclear_share	−0.403*** (0.062)	−0.428** (0.194)
Δln(GDP_pc)	0.410*** (0.095)	0.446*** (0.126)
Observations	644	644
Countries	28	28
Within R^2	0.537	-
RMSE	-	0.0336

Note: Dependent variable: Δln(CO_2_pc) *Source: Authors' calculations*

Table B5

Sensitivity to Exclusion of Atypical Years

Specification	ΔRenew_share coef (SE) p	ΔNuclear_share coef (SE) p	Δln(GDP_pc) coef (SE) p	Obs.	Within R^2
Without 2021–2022	−0.757 (0.369) p = 0.050	−0.400 (0.139) p = 0.008	0.369 (0.125) p = 0.006	588	0.529
Without 2020	−0.842 (0.369) p = 0.031	−0.394 (0.119) p = 0.003	0.364 (0.102) p = 0.001	616	0.463

Notes: All specifications include year dummies; interpretation remains semi-elasticity for shares and elasticity for log-transformed variables.
Source: Authors' calculations

Annex C. Multicollinearity Tests for H4, Within Correlation and Residualization

Table C1

Within Correlation

Pair	ρ
Δln(FC_pc) vs. Δln(GDP_pc)	0.300

Note: correlation calculated on residuals after removing country and year fixed effects.
Source: Authors' calculations

Table C2

OLS on the Within Matrix (Residualization)

Regressor	Coefficient	SE	p-value	95 % CI
r_fc	0.752	0.092	<0.001	[0.572; 0.932]
r_gdp	0.197	0.110	0.073	[−0.018; 0.413]
Constant	−0.0148	0.0025	<0.001	[−0.0196; −0.0100]

Notes: Dependent variable: Δln(CO_2/capita); N = 644, R^2 = 0.120, Root MSE = 0.0625
Source: Authors' calculations

Table C3

Multicollinearity Diagnostics (VIF on Within Matrix)

Variable	VIF	1/VIF
r_fc	1.10	0.91
r_gdp	1.10	0.91

Source: Authors' calculations

Annex D.

Testing the Marginal Effect of GDP per Capita in the Presence of Final Energy Consumption (H4)

Regressor	Coef.	SE (DK)	t	p	95 % CI
Δln(FC_pc)	0.752	0.058	12.87	0.000	[0.631; 0.873]
Δln(GDP_pc)	0.197	0.099	1.99	0.059	[−0.008; 0.403]

Notes: Wald test for Δln(GDP_pc): F(1,22) = 3.96, p = 0.059
90% CI for Δln(GDP_pc): [0.034; 0.360] (positive, but significant only at 10%)
Source: Authors' calculations

Annex E.

2000–2023 Differences in Key Indicators by Country (Δ = 2023–2000, Shares in GIC)

Country	Δ Renewable share (pp)	Δ Nuclear share (pp)	Δ CO_2/capita (t)	Δ Energy intensity (kgoe/1000 EUR2005)	Δ Final consumption/capita (GJ)
Austria	13.18	0.00	-2.15	-22.10	-4.37
Belgium	10.10	-4.77	-4.52	-77.42	-31.17
Bulgaria	10.45	-0.86	0.20	-379.17	17.89
Croatia	8.99	0.00	0.26	-89.68	20.16
Cyprus	10.22	0.00	-3.49	-81.46	-11.49
Czech Republic	9.72	11.21	-4.42	-162.16	-9.85
Denmark	34.81	0.00	-6.00	-37.11	-18.37
Estonia	22.00	0.00	-1.77	-201.32	6.67
Finland	16.30	6.39	-5.68	-42.86	-19.56

Country	Δ Renewable share (pp)	Δ Nuclear share (pp)	Δ CO_2/capita (t)	Δ Energy intensity (kgoe/1000 EUR2005)	Δ Final consumption/capita (GJ)
France	8.87	-2.52	-2.63	-48.16	-21.51
Germany	16.61	-12.05	-3.52	-54.74	-15.04
Greece	13.80	0.00	-3.82	-63.86	-9.15
Hungary	10.40	1.85	-1.35	-133.44	8.09
Iceland	12.65	0.00	-3.65	:	67.95
Ireland	12.23	0.00	-5.15	-66.21	-26.05
Italy	14.75	0.00	-2.52	-25.58	-11.46
Latvia	14.23	0.00	0.55	-130.03	26.94
Lithuania	18.22	-31.66	0.96	-218.16	33.40
Luxembourg	10.87	0.00	-8.32	-42.72	-122.56
Netherlands	12.16	0.13	-4.87	-64.68	-35.87
Norway	3.07	0.00	-1.76	:	-15.76
Poland	10.06	0.00	-0.48	-179.50	20.01
Portugal	17.39	0.00	-2.22	-42.51	-4.76
Romania	9.43	5.49	-0.82	-253.18	10.29
Slovakia	9.75	4.79	-1.64	-229.02	-6.13
Slovenia	6.80	2.95	-2.11	-102.95	-6.11
Spain	13.79	-0.24	-2.55	-47.34	-11.37
Sweden	21.35	-5.33	-3.39	-56.88	-34.94

Source: Authors' calculations

References

Arellano, M., & Bond, S. (1991). Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. *The Review of Economic Studies*, 58(2), 277–297. https://doi.org/10.2307/2297968

Balezentis, T., Butkus, M., Streimikiene, D., & Shen, Z. (2021). Exploring the limits for increasing energy efficiency in the residential sector of the European Union: Insights from the rebound effect. *Energy Policy*, 149, 112063. https://doi.org/10.1016/j.enpol.2020.112063

Baltagi, B. H. (2021). Limited dependent variables and panel data. In Econometric analysis of panel data (pp. 291–335). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-53953-5

Batlle, C., Schittekatte, T., & Knittel, C. R. (2022). Power price crisis in the EU: Unveiling current policy responses and proposing a balanced regulatory remedy. MIT Center for Energy and Environmental Policy Research.

Beerten, J., Laes, E., Meskens, G., & D'haeseleer, W. (2009). Greenhouse gas emissions in the nuclear life cycle: A balanced appraisal. *Energy Policy*, 37(12), 5056–5068. https://doi.org/10.1016/j.enpol.2009.06.073

Bianco, V., Cascetta, F., & Nardini, S. (2024). Analysis of the carbon emissions trend in European Union. A decomposition and decoupling approach. *Science of The Total Environment*, 909, 168528. https://doi.org/10.1016/j.scitotenv.2023.168528

Chen, C., Pinar, M., & Stengos, T. (2022). Renewable energy and CO_2 emissions: New evidence with the panel threshold model. *Renewable Energy*, 194, 117–128. https://doi.org/10.1016/j.renene.2022.05.095

Chovancova, J., Petruska, I., Rovnak, M., & Barlak, J. (2024). Investigating the drivers of CO_2 emissions in the EU: Advanced estimation with common correlated effects and common factors models. *Energy Reports*, 11, 937–950. https://doi.org/10.1016/j.egyr.2023.12.057

Csereklyei, Z., Rubio-Varas, M. D. M., & Stern, D. I. (2016). Energy and economic growth: The stylized facts. *The Energy Journal*, 37(2), 223–256. https://doi.org/10.5547/01956574.37.2.zcse

Dong, K., Dong, X., & Jiang, Q. (2020). How renewable energy consumption lower global CO_2 emissions? Evidence from countries with different income levels. The World Economy, 43(6), 1665–1698. https://doi.org/10.1111/twec.12898

Dopierala, L., Mosionek-Schweda, M., Laskowicz, T., & Ilczuk, D. (2022). Financial performance of renewable energy producers: A panel data analysis from the Baltic Sea Region. *Energy Reports*, 8, 11492–11503. https://doi.org/10.1016/j.egyr.2022.09.009

Drăcea, R. M., Ignat, R., Trică, C. L., Teodor, C., & Nedelcu, A. C. (2020a). Energy Efficiency of EU Member States: A Panel Data Analysis. *Economic Computation & Economic Cybernetics Studies & Research*, 54(4). https://doi.org/10.24818/18423264/54.4.20.10

Dracea, R. M., Ciobanu, L., & Buziernescu, A. A. (2020b). The Impact of Environmental Protection Expenditure on Environmental Protection in Romania. Empirical Analysis. *Strategica*, 106, 1.

Driscoll, J. C., & Kraay, A. C. (1998). Consistent covariance matrix estimation with spatially dependent panel data. *Review of Economics and Statistics*, 80(4), 549–560. https://doi.org/10.1162/003465398557825

Energy Institute. (2025). Statistical Review of World Energy 2025. https://www.energyinst.org/statistical-review

European Commission. (2022). REPowerEU Plan (COM(2022) 230 final). https://eur-lex.europa.eu/legal-content/EN/TXT/? uri=CELEX:52022DC0230

European Environment Agency (EEA). (2010). Why did greenhouse gas emissions fall in the EU in 2009? EEA analysis in brief. Copenhagen: European Environment Agency

European Environment Agency (EEA). (2024). Trends and Projections in Europe 2024. https://www.eea.europa.eu/en/analysis/ publications/trends-and-projections-in-europe-2024

European Union. (2018). Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement. *Official Journal of the European Union*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018R0842

European Union. (2023a). Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency. Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L1791

European Union. (2023b). Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L2413

European Union. (2023c). Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union. *Official Journal of the European Union*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L0959

European Union. (2023d). Regulation (EU) 2023/435 of the European Parliament and of the Council of 27 February 2023 amending Regulation (EU) 2021/241 as regards REPowerEU chapters in recovery and resilience plans. *Official Journal of the European Union*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R0435

European Union. (2024a). Directive (EU) 2024/1711 of the European Parliament and of the Council of 13 June 2024 amending Directives (EU) 2018/2001 and (EU) 2019/944 as regards improving the Union's electricity market design. *Official Journal of the European Union*. https://eur-lex.europa.eu/eli/dir/2024/1711/oj/eng

European Union. (2024b). Regulation (EU) 2024/1747 of the European Parliament and of the Council of 13 June 2024 amending Regulations (EU) 2019/942 and (EU) 2019/943 as regards improving the Union's electricity market design. *Official Journal of the European Union*. https://eur-lex.europa.eu/eli/reg/2024/1747/oj/eng

Eurostat. (2025a). Gross domestic product (GDP) and main components (nama_10_gdp).

Eurostat. (2025b). Energy balances (nrg_bal_c).

Freire-González, J. (2017). Evidence of direct and indirect rebound effect in households in EU-27 countries. *Energy Policy*, 102, 270–276. https://doi.org/10.1016/j.enpol.2016.12.002

Gonzalez, P. F., Landajo, M., & Presno, M. J. (2014). Tracking European Union CO_2 emissions through LMDI (logarithmic-mean Divisia index) decomposition. The activity revaluation approach. *Energy*, 73, 741–750. https://doi.org/10.1016/j.energy.2014.06.078

Grubb, M., Butler, L., & Twomey, P. (2006). Diversity and security in UK electricity generation: The influence of low-carbon objectives. *Energy Policy*, 34(18), 4050–4062. https://doi.org/10.1016/j.enpol.2005.09.004

Hagemejer, J., & Zolkiewski, Z. (2012). Short-run impact of the EU Climate and Energy Package on the Polish Economy (No. 4368). EcoMod.

Hausman, J. A. (1978). Specification tests in econometrics. *Econometrica*, 46(6), 1251–1271. https://doi.org/10.2307/1913827

Hernnas, H., Johannesson-Lindén, Å., Kasdorp, R., & Spooner, M. (2023). II. Pass-through in EU electricity and gas markets. European Commission, Directorate-General for Economic and Financial Affairs. https://economy-finance.ec.europa.eu/system/files/2023-07/ip254_en_chapter%20II_0.pdf

Hoechle, D. (2007). Robust standard errors for panel regressions with cross-sectional dependence. *The Stata Journal*, 7(3), 281–312. https://doi.org/10.1177/1536867X0700700301

Hsiao, C. (2022). Analysis of panel data (No. 64). Cambridge University Press.

Im, K. S., Pesaran, M. H., & Shin, Y. (2003). Testing for unit roots in heterogeneous panels. *Journal of Econometrics*, 115(1), 53–74. https://doi.org/10.1016/S0304-4076(03)00092-7

International Energy Agency (IEA). (2020). CO_2 Emissions from Fuel Combustion: Highlights. Paris: IEA Publishing. https://iea.blob.core.windows.net/assets/474cf91a-636b-4fde-b416-56064e0c7042/WorldCO2_Documentation.pdf

International Energy Agency (IEA). (2022). Norway 2022: Energy Policy Review. Paris: IEA Publishing. https://www.iea.org/reports/norway-2022/executive-summary

International Energy Agency. (2024). Energy End-uses and Efficiency Indicators: Database Documentation, December 2024 edition. Paris: IEA. https://iea.blob.core.windows.net/assets/2841dbf5-df26-4ef7-b542-57ff348aec98/IEA-EnergyEnd-usesandEfficiencyIndicatorsdatabase-DocumentationDecember2024-Update.pdf

Intergovernmental Panel on Climate Change (IPCC). (2007). Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, & L. A. Meyer, Eds.). Cambridge University Press. https://www.ipcc.ch/ report/ar4/wg3/

Intergovernmental Panel on Climate Change (IPCC). (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the IPCC. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/

Istudor, N., Constantin, M., Privitera, D., Ignat, R., Petrescu, I. E., & Teodor, C. (2025). Systemic Competitiveness in the EU Cereal Value Chain: A Network Perspective for Policy Alignment. Land, 14(4), 731. https://doi.org/10.3390/land14040731

Kaya, Y., & Yokobori, K. (Eds.). (1997). Environment, energy, and economy: Strategies for sustainability (Vol. 4). Tokyo, Japan: United Nations University Press.

Karmellos, M., Kopidou, D., & Diakoulaki, D. (2016). A decomposition analysis of the driving factors of CO_2 (Carbon dioxide) emissions from the power sector in the European Union countries. *Energy*, 94, 680–692. https://doi.org/10.1016/j.energy.2015.10.145

Kennedy, P. (2008). A guide to econometrics. John Wiley & Sons.

Kruyt, B., Van Vuuren, D. P., de Vries, H. J., & Groenenberg, H. (2009). Indicators for energy security. *Energy Policy*, 37(6), 2166–2181. https://doi.org/10.1016/j.enpol.2009.02.006

Mahmood, H. (2022). Nuclear energy transition and CO_2 emissions nexus in 28 nuclear electricity-producing countries with different income levels. PeerJ, 10, e13780. https://doi.org/10.7717/peerj.13780

Marques, A. C., Fuinhas, J. A., & Pereira, D. S. (2019). The dynamics of the short and long-run effects of public policies supporting renewable energy: A comparative study of installed capacity and electricity generation. *Economic analysis and policy*, 63, 188-206.https:// doi.org/10.1016/j.eap.2019.06.004

Marra, A., Colantonio, E., Cucculelli, M., & Nissi, E. (2024). The 'complex' transition: Energy intensity and CO_2 emissions amidst technological and structural shifts. Evidence from OECD countries. *Energy Economics*, 136, 107702. https://doi.org/10.1016/j.eneco.2024.107702

McWilliams, B., Sgaravatti, G., Tagliapietra, S., & Zachmann, G. (2022). A grand bargain to steer through the European Union's energy crisis (No. 14/2022). Bruegel Policy Contribution.

Menyah, K., & Wolde-Rufael, Y. (2010). CO_2 emissions, nuclear energy, renewable energy and economic growth in the US. *Energy Policy*, 38(6), 2911–2915. https://doi.org/10.1016/j.enpol.2010.01.024

Miketa, A., & Mulder, P. (2005). Energy productivity across developed and developing countries in 10 manufacturing sectors: Patterns of growth and convergence. *Energy Economics*, 27(3), 429–453. https://doi.org/10.1016/j.eneco.2005.01.004

Morina, F., Ergün, U., & Hysa, E. (2021). Understanding drivers of renewable energy firm's performance. Environmental Research, Engineering and Management, 77(3), 32-49

Mulder, P., & De Groot, H. L. (2012). Structural change and convergence of energy intensity across OECD countries, 1970–2005. *Energy Economics*, 34(6), 1910–1921. https://doi.org/10.1016/j.eneco.2012.07.023

Mundlak, Y. (1978). On the pooling of time series and cross section data. Econometrica, 46(1), 69–85. https://doi.org/10.2307 /1913646

Noja, G. G., Cristea, M., Pirtea, M. G., Panait, M., Drăcea, R. M., & Abrudan, D. (2023). Drivers of firms' financial performance in the energy sector: A comparative approach between the conventional and renewable energy fields. *Engineering Economics*, 34(2), 205–222. https://doi.org/10.5755/j01.ee.34.2.31274

OECD. (2017). Green Growth Indicators 2017. Paris: OECD Publishing. https://www.oecd.org/content/dam/oecd/en/publications/reports/2017/06/green-growth-indicators-2017_g1g7495e/9789264268586-en.pdf

OECD. (2025). OECD Economic Surveys: Iceland 2025. https://www.oecd.org/en/publications/oecd-economic-surveys-iceland-2025_890dbe05-en/full-report/powering-the-electricity-sector-in-the-face-of-climate-change_d6d2a4b9.html

Pehl, M., Arvesen, A., Humpenöder, F., Popp, A., Hertwich, E. G., & Luderer, G. (2017). Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, 2(12), 939–945. https://doi.org/10.1038/s41560-017-0032-9

Pesaran, M. H. (2006). Estimation and inference in large heterogeneous panels with a multifactor error structure. *Econometrica*, 74(4), 967–1012. https://doi.org/10.1111/j.1468-0262.2006.00692.x

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of Applied Econometrics*, 22(2), 265–312. https://doi.org/10.1002/jae.951

Pesaran, M. H. (2015). Testing weak cross-sectional dependence in large panels. *Econometric reviews*, 34(6-10), 1089-1117. https://doi.org/10.1080/07474938.2014.956623

Roodman, D. (2009). A note on the theme of too many instruments. *Oxford Bulletin of Economics and Statistics*, 71(1), 135–158. https://doi.org/10.1111/j.1468-0084.2008.00542.x

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, 27(3), 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

Sovacool, B. K., & Mukherjee, I. (2011). Conceptualizing and measuring energy security: A synthesized approach. *Energy*, 36(8), 5343–5355. https://doi.org/10.1016/j.energy.2011.06.043

Stern, D. I. (2012). Modeling international trends in energy efficiency. *Energy Economics*, 34(6), 2200–2208. https://doi.org/10.1016/j.eneco.2012.03.009

Stirling, A. (1998). On the economics and analysis of diversity. *SPRU Electronic Working Papers*, Paper 28, 1–156.

Stirling, A. (2007). A general framework for analysing diversity in science, technology and society. *Journal of the Royal Society Interface*, 4(15), 707–719. https://doi.org/10.1098/rsif.2007.0213

Westerlund, J. (2007). Testing for error correction in panel data. *Oxford Bulletin of Economics and Statistics*, 69(6), 709–748. https://doi.org/10.1111/j.1468-0084.2007.00477.x

Windmeijer, F. (2005). A finite sample correction for the variance of linear efficient two-step GMM estimators. *Journal of Econometrics*, 126(1), 25–51. https://doi.org/10.1016/j.jeconom.2004.02.005

Wooldridge, J. M. (2010). Econometric analysis of cross section and panel data (2nd ed.). MIT Press.

York, R. (2012). Do alternative energy sources displace fossil fuels? *Nature Climate Change*, 2(6), 441–443. https://doi.org/10.1038/nclimate1451

Authors' Biographies

Raluca Mihaela Drăcea is a Professor at the Bucharest University of Economic Studies (Faculty of Agri-Food and Environmental Economics), PhD supervisor, and member of the Council of the Doctoral School of Economics II. With 25+ years in academia, she has authored 15 books, 50+ journal articles, and 60+ conference papers. Her work focuses on financing regional and rural development projects, cost–benefit analysis, and sustainable development. She has also participated in national projects on carbon-footprint assessment, sustainability reporting, and the green transition in agri-food and environmental sectors, highlighting links between macroeconomic dynamics, fiscal policy, and environmental performance.

Raluca Ignat is a Professor at the Bucharest University of Economic Studies and Director of the Agri-Food and Environmental Economics Department. Her research and teaching interests include entrepreneurship, management, quality of life, sustainability, and resilience. She has served as team member or project manager in 30+ publicly funded research projects at national and European level, including World Bank–supported grants. She currently serves as Project Director of a Romanian national programme on farm carbon-footprint assessment (farm-level GHG accounting, 2023–2026), focusing on sustainability practices and measurement of environmental performance in agriculture.

Carmen Lenuța Trică is a Professor at the Bucharest University of Economic Studies, Department of Agri-Food and Environmental Economics. Her interests include sustainable development, environmental economics and policy, cost–benefit analysis, environmental impact assessment, and sustainability. In 2022 she contributed to a government evidence-based policy project to streamline waste legislation and simplify procedures in the climate-change sector, and she has been team leader or researcher in 30 research projects.

Mihai Dinu is an Associate Professor of Rural and Regional Development at the Faculty of Agri-Food and Environmental Economics, Bucharest University of Economic Studies. His work spans sustainable development, rural entrepreneurship, and agri-food logistics and trade. His current research focuses on carbon-footprint reduction and on how cyclical and structural forces shape CO_2 emissions and environmental performance across European rural economies.

Chiva Marilena Papuc is an Associate Professor at the Bucharest University of Economic Studies. Her research and teaching span economics, microeconomics, macroeconomics, and management.

The article has been reviewed.

Received in November 2025; accepted in July 2026.

This article is an Open Access article distributed under the terms and conditions of the Creative Commons Attribution 4.0 (CC BY 4.0) License http://creativecommons.org/licenses/by/4.0