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Sustainable Climate and Energy Transition in the European Union: Results, Barriers, and Policy Effectiveness

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Abstract

This study examines progress in the climate and energy transition across the 27 European Union Member States, considering the objectives of the "3 × 20" climate and energy package, the European Green Deal, and the Sustainable Development Goals (SDGs). Using Eurostat data for 2010–2024, the analysis explores changes in greenhouse gas emissions, renewable energy shares, and energy efficiency, complemented by cross-sectional regression models based on selected country observations for 2024. Linear, quadratic, and cubic specifications are estimated to investigate the relationships between GDP per capita, domestic net greenhouse gas emissions, and primary energy consumption, supported by formal model comparisons and sensitivity analyses. For the 10-country greenhouse gas subsample, the cubic specification explains 91.3% of the observed variance ($R^2 = 0.913$), although information criteria favour a more parsimonious linear model. For the broader 14-country subsample, the cubic model yields $R^2 = 0.559$, suggesting a nonlinear relationship that remains sensitive to sample composition. Additional analysis identifies statistically different relationships between income levels and primary energy consumption across two selected seven-country groups, as supported by a pooled interaction test. Bootstrap and country-exclusion analyses further highlight the uncertainty associated with small cross-sectional samples, limiting causal interpretation and generalisation across the EU. A complementary SWOT analysis identifies key strengths, weaknesses, opportunities, and threats affecting the transition, linking the empirical findings to EU emissions trading, renewable energy policies, and just-transition financing. Overall, the findings highlight uneven transition patterns across European economies and underscore the importance of differentiated policy instruments, sustained investment in clean energy and

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technological innovation, and stronger institutional support for an inclusive and sustainable transition.

Keywords: climate and energy package; European Green Deal; greenhouse gas emissions; renewable energy; energy efficiency; green Kuznets curve; polynomial regression; SWOT analysis; Sustainable Development Goals (SDGs)

1. Introduction

The growing challenges posed by climate change, the ongoing degradation of the natural environment, and the need to ensure long-term, sustainable economic growth have prompted the European Union to implement transformative processes. In this context, in December 2019, the European Commission presented a communication on the European Green Deal, which was subsequently approved by the European Council, thereby setting the strategic direction for the EU's development for the coming decades [1–4]. The European Green Deal is viewed as the EU's response to global commitments, including those primarily stemming from the UN 2030 Agenda for Sustainable Development, and thus forms an integral part of the European Commission's strategy for the effective implementation of the Sustainable Development Goals (SDGs) [5–7].

The main premise of the European Green Deal is to transform the EU into a prosperous society with a modern, resource-efficient, and competitive economy in which businesses of all sizes can thrive, while achieving net-zero greenhouse gas emissions by 2050. Economic growth is to be decoupled from the consumption of natural resources. The European Green Deal is therefore a new growth strategy for the EU, aimed at making Europe the first climate-neutral continent while ensuring that this transition is fair and leaves no one behind—one of a number of goals to be achieved through the Just Transition Mechanism [8–11].

Achieving these ambitious goals requires comprehensive action across all sectors of the economy, and the key objectives of the European Green Deal encompass a wide range of initiatives. First, the goal is to achieve climate neutrality by 2050, as enshrined in the European Climate Law. One of the intermediate targets necessary to achieve this much-desired climate neutrality is a significant reduction in net greenhouse gas emissions of at least 55% by 2030 compared to 1990 levels, which is consistent with the widely accepted definition set forth in the "Fit for 55" legislative package [11–14]. Another key objective of the European Green Deal is the so-called transition to a circular economy, which can promote the efficient use of resources by minimizing significant amounts of waste and keeping both the value of products and the necessary materials in the economic cycle for as long as possible. The EU's new action plan for the circular economy, adopted in March 2020, focuses primarily on reducing waste and, consequently, on improving waste management. This covers priority product value chains, which clearly include electronics, plastics, textiles, construction, as well as food and, more broadly, water and nutrients [15–17].

The European Green Deal also aims to protect and restore ecosystems and biodiversity, as discussed in greater detail in the EU Biodiversity Strategy for 2030. It also seeks to achieve "zero pollution" of air, water, and soil, with the goal of protecting both public health and the environment. Among the priorities of the European Green Deal are ensuring healthy food and sustainable agriculture (as outlined in the "Farm to Fork" strategy); promoting clean and affordable energy (with a particular focus on renewable energy sources and energy efficiency); building and modernizing sustainable transportation infrastructure; and mobilizing scientific research, development, and innovation in support

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of the green transition. The announcement of the European Green Deal was accompanied by the publication of the EU Biodiversity Strategy for 2030, bearing the symbolic subtitle "Bringing Nature Back into Our Lives" [18–20]. Both documents were deliberately published simultaneously because they are closely interlinked. This demonstrates that the holistic approach to environmental challenges contained in the European Green Deal is also being implemented in practice. The Biodiversity Strategy for 2030 sets out the long-term priorities of EU nature conservation policy. Its overarching goal is to ensure restoration, resilience, and adequate protection of all ecosystems by 2050. This goal is to be achieved by setting the EU on a path toward ecological restoration by 2030, which will enable the preservation of valuable ecosystems and the restoration of degraded ones [21–24].

Furthermore, the EU aims to take on a global leadership role in the field of biodiversity conservation, which means that if other countries step up their efforts, biodiversity conservation policy could become even more advanced. The 2030 targets are to be achieved through two pillars of action. First, efforts will continue to create a coherent network of protected areas, and second, measures will be taken to develop an ambitious, EU-wide plan for the restoration of natural resources. The climate goals adopted for the coming years are undoubtedly ambitious. The European Commission aims to achieve climate neutrality by 2050 [24–26]. Achieving this goal requires the development of a long-term strategy and a European Climate Law, as well as aligning EU policies with the climate neutrality target while considering the role of individual sectors. These tasks have been accomplished through the implementation of climate regulations and the preparation of the necessary strategic documents [21,23]. Climate targets include reducing greenhouse gas emissions by at least 50%, and potentially as much as 55%, compared to 1990 levels—this is the EU's target for 2030. Achieving this goal required a review of all major climate-related policy instruments and the introduction of changes [27–29]. These measures formed the basis for developing a mechanism to set greenhouse gas emission fees across the entire economy. In the event of discrepancies between EU policy and the policies of other countries, there are plans to introduce a border price adjustment mechanism that takes CO_2 emissions in selected sectors into account, which will help reduce the risk of carbon leakage. Climate goals will also be pursued through adjustments to the tax system, including energy taxation [30,31].

An important element of the European Green Deal is the European Climate Pact, which focuses on three ways to engage the public in climate-related actions. The first involves encouraging the exchange of information on the risks and challenges associated with climate change and environmental degradation, as well as potential solutions. The second involves creating real and virtual opportunities for expressing opinions and taking collective action. The third approach identified by the European Commission is to support grassroots initiatives for climate and environmental protection [22,24].

Reducing the carbon intensity of the energy system is crucial for achieving climate goals as approximately 75% of greenhouse gas emissions in the EU stem from the production and use of energy in the economy. Therefore, EU actions will aim to create an energy sector largely based on renewable sources while phasing out coal and reducing emissions from the gas sector. Achieving these goals requires the involvement of individual member states in preparing national plans for the use of various energy sources. A key priority should be the expansion of offshore wind energy production. Measures will also be taken to reduce emissions in the gas sector, including increased support for research and development in the field of low-emission gases and efforts to reduce methane emissions associated with energy production [32,33].

Energy- and resource-efficient construction and renovation are of paramount importance as buildings account for 40% of energy consumption, while the annual building renovation rate ranges from just 0.4% to 1.2%, depending on the member state. Achieving

the EU's energy efficiency and climate goals requires this rate to be at least doubled, which underscores the need to intensify renovation efforts to reduce energy costs and alleviate energy poverty [30–32].

The pursuit of zero pollution to achieve an environment free of toxic substances is also an important initiative of the European Commission included in the European Green Deal. As part of these efforts, the Commission has emphasised the need for effective monitoring of air, water, soil, and consumer product pollution, as well as the restoration of the natural functions of surface and groundwater bodies. In this area, protecting citizens and the environment from hazardous chemicals is particularly important.

Achieving ambitious climate goals requires changes in the industrial sector and the implementation of solutions consistent with a circular economy, which is another initiative of the European Green Deal. The EU's industrial sector accounts for 20% of the Union's greenhouse gas emissions. The industrial sector remains dependent on the processing of new raw materials that are mined and refined. Between 1970 and 2017, global annual raw material extraction tripled [34–36], while only 12% of the materials used in industry come from recycling [37–39]. The European Green Deal will support the EU industry's transition toward a sustainable growth model. The Circular Economy Action Plan will include a "sustainable products" policy. Reducing material consumption and promoting reuse over recycling have been identified as priorities. The Commission aims to ensure that by 2030, all packaging placed on the EU market is reusable or recyclable.

The Action Plan for a Circular Economy will also include measures to encourage companies to offer reusable products. To this end, the following research questions have been formulated:

RQ1: To what extent do the available Eurostat indicators document progress across EU Member States toward selected climate and energy objectives associated with the "3 × 20" package and the European Green Deal over 2010–2024?
RQ2: What is the relationship between the level of economic development, as measured by GDP per capita, and the level of greenhouse gas emissions in EU member states, and is this relationship nonlinear?
RQ3: Which internally and externally determined factors emerge from the qualitative SWOT assessment, and how do they relate to specific EU climate and energy policy instruments?

The above research questions attempt to address issues related to the broadly understood climate and energy transition. Given the strategic and regulatory context, there is a need to assess the extent to which EU member states are achieving the climate and energy goals associated with this transition, as well as identify the factors determining its pace and effectiveness.

The remainder of the article is organised as follows. Section 2 describes the Eurostat indicators, the 2024 cross-sectional regression samples, and the qualitative SWOT methodology. Section 3 presents descriptive country comparisons, the existing linear and polynomial estimations, previously conducted specification and sensitivity checks, and the policy-linked SWOT assessment. Section 4 summarises the findings while distinguishing cross-sectional associations from changes over time and from causal policy effects.

2. Materials and Methods

Eurostat country series were used to describe developments across the EU-27 over 2010–2024. All reported regression estimations, however, are cross-sectional analyses for the reference year 2024: each selected country contributes one observation (rather than 15 annual observations or a 2010–2024 country average). Consequently, the regressions describe between-country associations in 2024 and cannot identify changes over time or

causal policy effects. The full EU-27 coverage applies to the descriptive country comparisons; the regression subsets are listed separately below. The Eurostat export files used for cross-checking were sdg_13_10 (domestic net greenhouse gas emissions), sdg_07_10 (primary energy consumption), sdg_07_40 (renewable-energy share), and tec00001 (GDP per capita).

The development strategy formulated within the EU throughout this period was based on three main aspects: strengthening the foundations of a knowledge-based economy, accelerating the transition toward a low-carbon economy, and increasing the participation of citizens in each country in measures promoting employment and equal opportunities. This approach was intended to ensure a balance between the modernisation of the EU economy as a whole, environmental protection, and social cohesion.

The variables used in the estimations are as follows: domestic net greenhouse gas emissions (DNGGE; index, base year 1990 = 100, including the net-emissions accounting convention in the supplied Eurostat export); primary energy consumption (PEC; million tonnes of oil equivalent, Mtoe); and GDP per capita (GDP_pc; current euro per resident). Renewable energy is measured as a percentage of gross final energy consumption and is discussed descriptively. Results are estimated on individual country observations for 2024. EU-level reported aggregates are distinguished from the simple (unweighted) arithmetic means of the 27 country observations. To avoid inconsistencies in the terminology, the same notation DNGGE, PEC, and GDP_pc is used throughout.

The analysis carried out above was based on a set of specific indicators used to monitor EU climate and energy policies, among other things. Changes in greenhouse gas emissions, trends in the use of renewable energy sources, and, consequently, energy efficiency in relation to the size of the economy were considered. Consequently, the use of data from Eurostat enabled a comparative assessment of the progress made by individual EU member states in their efforts to maintain cohesion.

Country subsamples were selected purposively to illustrate heterogeneity rather than through a prespecified random sampling design. The greenhouse-gas model is calculated for 10 countries (Belgium, Bulgaria, France, Ireland, the Netherlands, Germany, Czechia, Slovakia, Hungary, and Italy), and separately for 14 countries (Belgium, Bulgaria, Denmark, France, Spain, Ireland, the Netherlands, Germany, Poland, Hungary, Italy, Czechia, Slovakia, and Romania). The PEC–GDP comparison uses two distinct seven-country groups specified in Section 3. Since the membership and economic scale of these groups differ, their regression estimates should be treated as exploratory and must not be interpreted as representative high-income versus low-income EU-wide effects.

The study examines changes in selected indicators relevant to the EU climate and energy frameworks, placing their definitions and target years in context. It also investigates exploratory associations of GDP per capita with greenhouse-gas emissions and primary energy consumption and uses a qualitative SWOT framework to examine implementation constraints. It does not constitute an exhaustive country-by-country compliance test for every component of the 2020 climate and energy package.

For RQ1, progress is operationalised descriptively using the 2010 and 2024 country-level domestic net-GHG index (1990 = 100), renewable-energy share in gross final energy consumption, and national primary energy consumption. These indicators cover selected dimensions of the climate–energy transition, not formal compliance with each original 2020 target. In particular, the 20% energy-efficiency objective was defined relative to a projected baseline, and the transport-sector renewable-energy objective requires a separate sector-specific indicator; neither compliance test is undertaken here. The 2024 observations also postdate the "3 × 20" target year of 2020, while the European Green Deal was launched in 2019. Accordingly, the findings describe developments in a changing policy context rather than verified achievement of every policy target [9].

The study combines a qualitative review of EU policy documents and academic literature, descriptive statistics for the EU-27 during 2010–2024, and exploratory 2024 cross-sectional ordinary least squares (OLS) regressions. Linear, quadratic, and cubic GDP_pc specifications are compared using identical samples within each model group, nested F-tests, AIC, and BIC. The two seven-country PEC–GDP_pc slopes are also evaluated in a pooled interaction specification. Leave-one-country-out and extreme-observation exclusion analyses assess model sensitivity. Country-pairs resampling (5000 attempted bootstrap draws, fixed random seed) is used to characterise fitted-value uncertainty; a separately labelled empirical predictive distribution additionally samples centred regression residuals within each bootstrap replication. Resamples lacking full model rank are excluded. These exploratory predictive distributions are conditional on the selected 2024 countries and are not independently validated forecasts.

For the seven-country PEC–DNGGE quadratic specification, the same country-pairs resampling approach was implemented with 5000 attempted draws (fixed seed 4596289), excluding resamples with fewer than three distinct DNGGE values or rank-deficient fits. Percentile intervals were constructed for the fitted conditional mean at the observed median DNGGE index (73) and for the quadratic coefficient; an illustrative predictive interval was formed by adding a randomly sampled centred residual within each valid bootstrap replication. Additional sensitivity checks omit one country at a time and jointly exclude observations at the extremes of either DNGGE or PEC. These small-sample procedures are exploratory and do not constitute external forecast validation.

Data preparation and initial regression analyses were performed using Microsoft Excel for Microsoft 365 (Microsoft Corporation, Redmond, WA, USA). Additional statistical analyses and graphical visualisations were performed using R (R Foundation for Statistical Computing, Vienna, Austria).

3. Results and Discussion

The "3 × 20" Climate and Energy Package is one of the European Commission's most important documents regulating issues related to air protection and combating adverse climate change. It constitutes a set of instruments whose implementation has been entrusted to the governments of individual EU member states. The "3 × 20" Climate and Energy Package addresses key issues related to greenhouse gas emissions into the atmosphere, as well as the promotion of renewable energy sources, including matters concerning the energy independence of the entire Union.

The European Commission's initial proposals and recommendations focused on the Union's commitment to combatting the greenhouse effect. Combating global warming and mitigating its effects became one of the top priorities. This stemmed from the EU's decision to intensify efforts aimed at combating climate change. As experts emphasise, these were among the most ambitious goals adopted to date.

Several thematic areas were proposed as an introduction to the discussion on the scope of the "3 × 20" climate and energy package, including greenhouse gas emissions, which are the main cause of global warming; renewable energy sources as an alternative to conventional sources; and the need to strengthen the Union's energy independence from external suppliers. Proposed solutions aimed at combating climate change also focused on increasing the share of biofuels as a feedstock used in transportation within the European Union [40–42].

The main recommendations and observations regarding air quality protection and climate change mitigation formed the basis for formulating key objectives and legal provisions in this area under EU law. The originally set targets concerned the following issues:

- A 20 percent reduction in greenhouse gas emissions compared to 1990 levels;

- Increasing the share of energy from renewable sources to at least 20%;
- A 20 percent improvement in energy efficiency compared to projections for 2020;
- Increasing the share of biofuels to at least 10 percent of total fuel consumption in transportation.

The position initially developed covered all types of measures and plans through 2020. As experts emphasise, the proposed solutions represented an important and decisive step toward significant changes in EU law. A key aspect of the "3 × 20" climate and energy package was the assumption that the planned environmental and climate goals would be expanded in the long term. There were many arguments in favour of this direction, based on various reports presented within the European Union. The adopted positions introduced new proposals, including:

- Reducing greenhouse gas emissions by up to 80%;
- Increasing the share of energy generated from renewable sources to 35%.

All of these goals were to be achieved by 2050. Following the European Council's announcement of the climate package's objectives in January 2008, the European Commission presented new measures aimed at combating climate change. Among these measures were the following:

- Reducing CO_2 emissions from transportation;
- Measures to support the development of modern technologies for storing and "capturing" carbon dioxide emitted into the atmosphere (carbon capture and storage);
- Introducing measures and incentives for EU member states to reduce greenhouse gas emissions, including carbon dioxide;
- Restructuring the European Union Emissions Trading System (EU ETS) by expanding its scope beyond carbon dioxide emissions to include other greenhouse gases.

In this way, the "3 × 20" climate and energy package was expanded to include the above-mentioned issues. The main instruments for its implementation were directives concerning the following:

- Reducing greenhouse gas emissions;
- The promotion of renewable energy sources;
- Improving and expanding the greenhouse gas emissions trading system;
- State aid rules related to the provision of public support for environmental protection;
- Geological storage of carbon dioxide.

The proposals presented by the European Commission regarding the expansion of the "3 × 20" climate and energy package were aimed, in the long term, at strengthening the European Union's position as a key leader "in the race to create the low-carbon economy that our planet so urgently needs." This represents the second most important objective of the package, alongside environmental benefits, namely, economic benefits.

The ‘3 × 20’ policy framework, adopted in December 2008, set EU-wide objectives for 2020 relating to greenhouse gas emissions, renewable energy and efficiency [9]. The achievement of individual targets should be evaluated against each indicator's official reference year and definition. In particular, country-level net-emissions indices with 1990 = 100 cannot automatically be interpreted as changes relative to 2010 or as evidence of the effect of the EU ETS.

Figure 1 juxtaposes the country-level domestic net greenhouse-gas emissions indices for 2010 and 2024, both expressed relative to 1990. Comparisons are descriptive and should not be described as year-on-year changes in 2020 or 2024. A consistent appraisal of the transition requires checking the country, reference year, indicator definition and treatment of net emissions against the underlying Eurostat series.

The two-period comparison in Figure 1 does not establish how many states reduced emissions specifically between 2023 and 2024. Based on the two supplied reference years alone, the chart shows differences in national indices between 2010 and 2024. Such variation may reflect differences in sectoral composition, energy mix, land-use accounting and broader structural factors; the figure does not identify the effect of any individual EU or domestic policy measure.

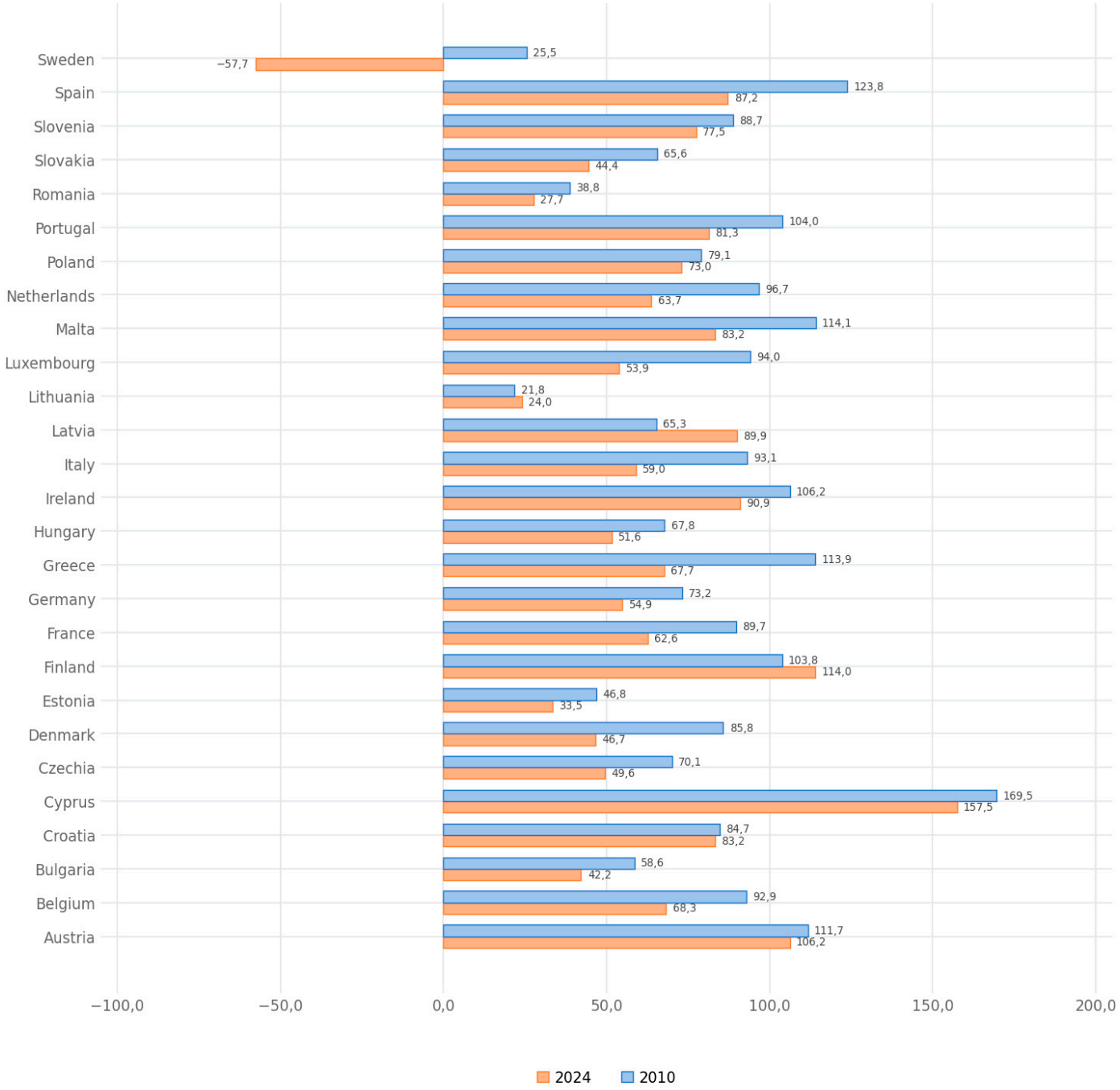


Figure 1. Domestic net greenhouse-gas emissions index (1990 = 100), EU-27, 2010 and 2024. Grouped horizontal bars compare national observations for the two reference years; the index is not a year-on-year change. Source: authors' calculations from Eurostat sdg_13_10 [43,44].

The first greenhouse-gas regression uses Belgium, Bulgaria, France, Ireland, the Netherlands, Germany, Czechia, Slovakia, Hungary, and Italy (n = 10; 2024). DNGGE is the dependent variable, and GDP $_{pc}$ is the explanatory variable. A cubic polynomial was

initially fitted for descriptive comparison with lower-degree specifications; the displayed cubic equation is therefore considered a candidate specification, not an automatically preferred model (Figure 2).

$$DNGGE = 1.6274 \times 10^{-13}\, GDP_{pc}{}^{3} - 2.8294 \times 10^{-8}\, GDP_{pc}{}^{2} + 0.0018772\, GDP_{pc} + 18.1197 \quad (1)$$

where:

GDP $_{pc}$: gross domestic product per capita;

DNGGE: national net greenhouse gas emissions.

The cubic fit for the 10 selected countries gives $R^2 = 0.9126$, indicating that it reproduces approximately 91.3% of the observed cross-country variation within this specific 2024 sample. This result must not be generalised to the EU-27. Although the fitted curve may display curvature, the formal comparisons reported below do not establish that a cubic model is warranted. The observed shape therefore does not confirm an environmental Kuznets Curve (EKC) or a causal effect of GDP per capita on emissions.

For the 10-country cubic specification, the fitted terms are not individually significant at the 5% level (linear term $p = 0.2116$; squared term $p = 0.3357$; cubic term $p = 0.3297$). The overall fit is $R^2 = 0.9126$, with $F = 20.8748$ ($p = 0.0014$), but these results do not validate the cubic shape. In particular, a high R^2 in a small, selected sample does not by itself establish an environmental Kuznets relationship.

Although the 10-country cubic regression is significant overall ($F = 20.8748$; $p = 0.0014$), the individual polynomial terms are not significant at the 5% level. Model-level significance does not establish that curvature is needed. The nested comparisons and information criteria below favour the simpler linear functional form for this selected sample.

Comparing candidate models for the same 10 countries, the linear, quadratic and cubic models produce R^2 values of 0.8959, 0.8962 and 0.9126, respectively. Nevertheless, AIC values are 61.65, 63.62 and 63.90, and BIC values are 62.25, 64.53 and 65.12, respectively. Adding the quadratic term to the linear specification does not improve fit significantly ($F = 0.0168$, $p = 0.9005$); adding the cubic term to the quadratic specification also fails a nested test ($F = 1.1250$, $p = 0.3297$). Accordingly, the linear specification is preferred on parsimony grounds for this subset, notwithstanding the apparently high cubic R^2. The cubic curve in Figure 2 is retained only as an exploratory visualisation.

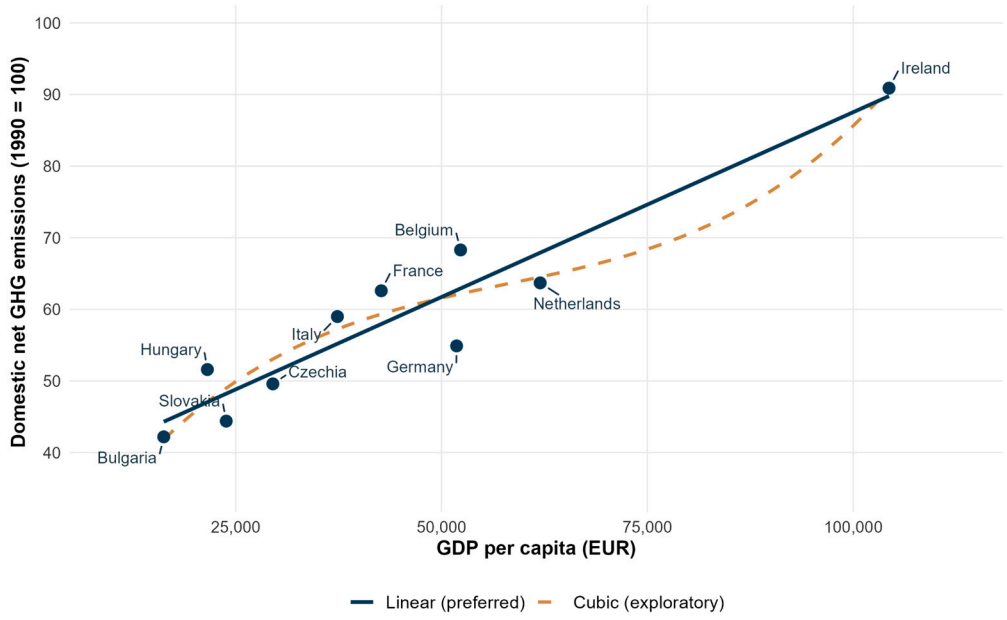


Figure 2. Relationship between GDP per capita and domestic net greenhouse-gas emissions (DNGGE) in 10 selected EU Member States in 2024. The solid line denotes the statistically preferred linear specification; the dashed curve illustrates the original cubic specification as an exploratory comparison. Source: authors' calculations from Eurostat [43,44].

The expanded greenhouse-gas model (n = 14; 2024) includes Belgium, Bulgaria, Denmark, France, Spain, Ireland, the Netherlands, Germany, Poland, Hungary, Italy, Czechia, Slovakia, and Romania. This list corresponds to the observations used in the supplied data file and the model underlying Figure 3. The group contains both Western European and Central and Eastern European economies and must not be described as a low-development-country sample. Compared with the initial 10-country subset, this larger sample includes Denmark, Spain, Poland and Romania; all country comparisons remain descriptive owing to the purposive inclusion criteria.

The 14-country set includes both large and smaller EU economies with heterogeneous production structures, industrial activity and energy profiles. Countries not included in the model should not be characterised as having a particular emission value without verifying that value in the relevant Eurostat series. Because countries were included purposively, this subset does not represent a formally defined class of less-developed EU economies. A third-order polynomial was fitted as one candidate description of the 2024 GDP $_{pc}$–DNGGE relationship (Figure 3), alongside the lower-degree alternatives discussed below:

$$DNGGE = 7.08 \times 10^{-13}\, GDP_{pc}{}^{3} - 1.2439 \times 10^{-7}\, GDP_{pc}{}^{2} + 0.0065162\, GDP_{pc} - 39.5708 \quad (2)$$

For the 14-country subset, the cubic specification yields R^2 = 0.5592 (adjusted R^2 = 0.4270; F = 4.2289; p = 0.0358). This estimate refers solely to these 14 countries and not to the entire EU-27. The linear, quadratic, and cubic alternatives yield R^2 = 0.2978, 0.2996, and 0.5592, with corresponding AIC values of 117.65, 119.62 and 115.13 and BIC values of 118.93, 121.53 and 117.69. Unlike the 10-country case, information criteria favour the cubic model here, although the small sample warrants careful interpretation.

Formal nested tests provide additional information on the 14-country specification. Adding a squared GDP $_{pc}$ term to the linear model is not supported (F = 0.0293; p = 0.8672), whereas the additional cubic term improves fit relative to the quadratic specification (F = 5.8891; p = 0.0356). These tests compare models fitted to the identical 14 observations. The fitted coefficients should not be interpreted as causal marginal effects of income on emissions; the shape and any implied turning points remain conditional on the selected countries and the 2024 cross-section.

The 14-country cubic specification describes a sample-dependent nonlinear pattern in the 2024 cross-section. Energy efficiency, industrial composition, renewable-energy deployment and environmental policy are plausible contextual mechanisms, but their separate effects are not estimated by this GDP $_{pc}$-only regression [45–47]. Consequently, neither the fitted turning points nor the polynomial coefficients should be interpreted as causal effects, development thresholds or evidence that a particular policy produced the observed emission levels.

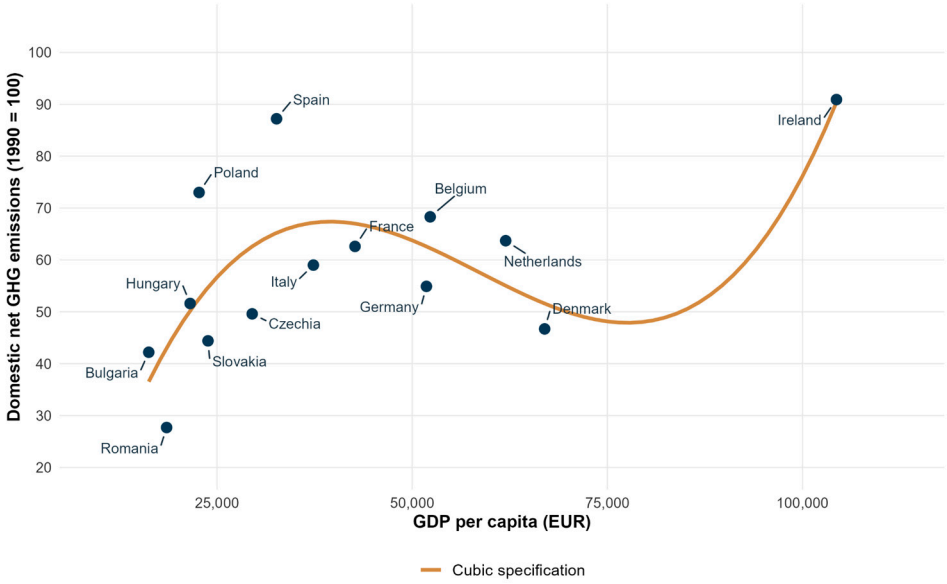


Figure 3. GDP per capita and domestic net greenhouse-gas emissions (DNGGE) in 14 selected EU Member States in 2024. The curve presents the cubic specification favoured by within-sample model comparisons; the findings are exploratory and not EU-wide causal effects. Source: authors' calculations from Eurostat [43,44].

The renewable-energy share is defined as energy from renewable sources divided by gross final energy consumption (percentage). In the supplied Eurostat country extract (sdg_07_40), the unweighted mean of the 27 Member-State shares increases from 16.35% (2010) to 28.02% (2024). This simple cross-country mean is not the official consumption-weighted EU aggregate: Eurostat reports an EU-wide share of 25.2% in 2024. The highest 2024 national shares in the supplied dataset are Sweden (62.85%), Finland (52.12%), and Denmark (46.46%); the lowest are Belgium (14.34%), Luxembourg (14.74%), and Ireland (16.06%). Malta records 17.21% and Poland 17.77% in the same dataset. No country in this series exceeds 100%. Differences between country averages and EU aggregates must be maintained when presenting Figure 4 and evaluating progress toward EU targets.

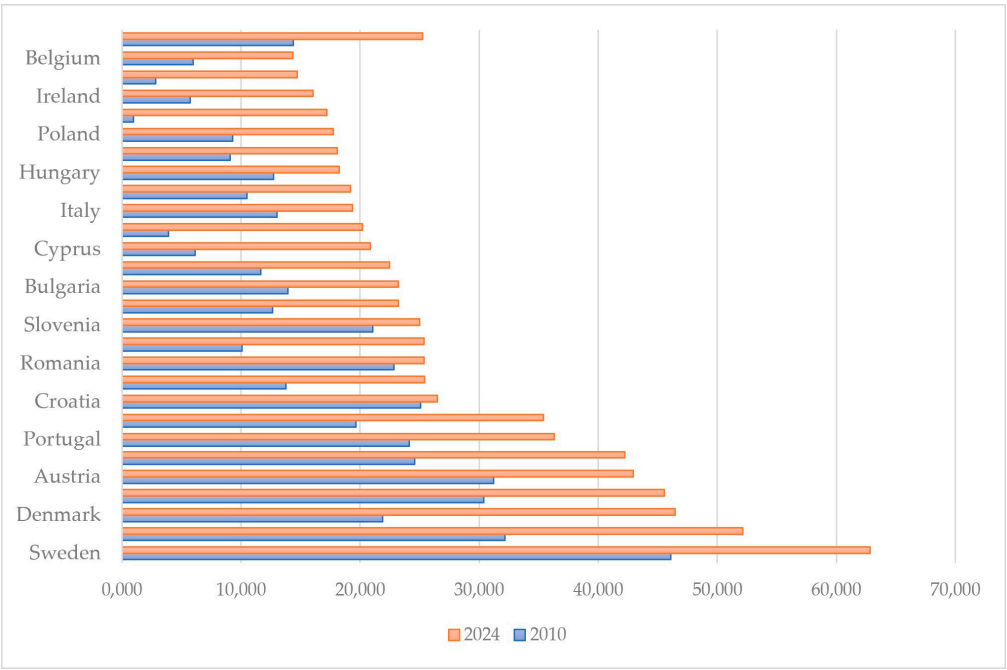
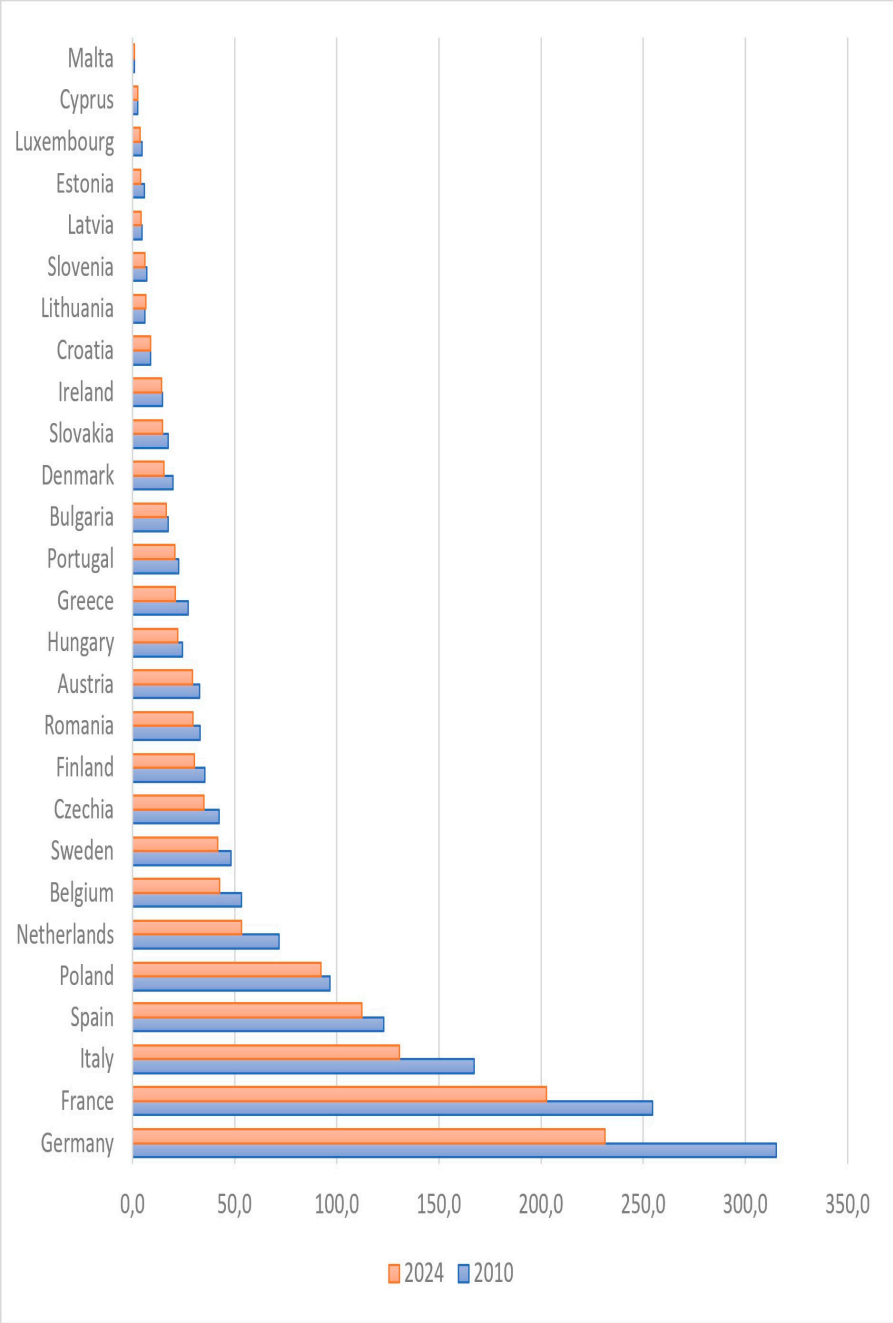


Figure 4. Renewable energy as a share of gross final energy consumption, EU-27, 2010 and 2024 (%). Grouped horizontal bars show the national observations and the separately labelled official EU-27 aggregate, not an unweighted country mean. Source: Eurostat sdg_07_40 [44,48].

Primary energy consumption (PEC) is measured in million tonnes of oil equivalent (Mtoe) as a national total, not Mtoe per 100,000 residents. In the supplied Eurostat series (sdg_07_10), the 2024 totals are 231.3 Mtoe for Germany, 202.6 Mtoe for France, 130.8 Mtoe for Italy, 29.6 Mtoe for Romania and 0.9 Mtoe for Malta [44]. The unweighted average of the 27 national totals is 44.21 Mtoe; it is not the aggregate EU consumption figure. Country size, industrial structure, and the distinction between totals and rates must be considered when interpreting Figure 5 and the later regressions.



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Figure 5. Primary energy consumption by EU Member State, 2010 and 2024 (Mtoe, national totals). Grouped horizontal bars report absolute national consumption, not per-capita measures. Source: Eurostat sdg_07_10 [44].

PEC is an absolute national energy-consumption total, whereas GDP per capita is a resident-level income indicator. The seven countries in this first sample—Bulgaria, France, Spain, Germany, Poland, Romania and Italy—differ markedly in population and economic scale (Figure 6). Their positive cross-sectional association may therefore partly reflect economic size and structure. The estimated linear model for the seven 2024 observations is as follows:

$$\mathrm{PEC} = -71.7225 + 0.005935\,\mathrm{GDP_{pc}} \quad (3)$$

where:

PEC: primary energy consumption;

GDP_pc: GDP per capita.

The coefficient of 0.005935 Mtoe per euro implies that an increase of EUR 1000 in GDP per capita is associated with approximately 5.94 Mtoe higher national PEC within this selected 2024 sample. The OLS regression yields $R^2 = 0.9507$ (adjusted $R^2 = 0.9408$) and a residual standard error of 19.5917 Mtoe for $n = 7$. This is an in-sample association involving a national total and a per-capita predictor, not an estimate of the causal effect of income on energy demand.

The model as a whole is statistically significant ($F = 96.4257$; $p = 0.00019$), indicating a statistically significant relationship between GDP per capita and primary energy consumption. The coefficient for GDP is also statistically significant: 0.005935 (standard error = 0.000604; t = 9.8197; $p = 0.00019$). Its 95% confidence interval is [0.004381; 0.007489] and thus does not include zero. This means that the positive relationship between GDP per capita and primary energy consumption is confirmed by the estimation results.

The intercept is −71.7225, with a standard error of 20.5499 (t = −3.4902; $p = 0.0175$), and its 95% confidence interval is [−124.5477; −18.8972]. It is therefore also statistically significant at the $\alpha = 0.05$ level.

The results indicate that the level of economic development in this group of countries is strongly and positively correlated with the scale of primary energy consumption. The high R^2 value and the statistical significance of the coefficient for GDP indicate a very good fit of the model to the analysed data. At the same time, due to the small number of observations ($n = 7$), the results should be interpreted with caution. A good model fit does not imply a causal relationship as energy consumption may also be influenced by other factors, such as economic structure, industrialisation, the energy mix, or energy efficiency.

The country-deletion check for this seven-observation linear regression yields leave-one-out R^2 values ranging from 0.9204 to 0.9785. Such in-sample R^2 statistics should not be treated as proof of good out-of-sample prediction, especially because PEC is a national total whereas GDP_pc is measured per resident.

For this purposively selected seven-country sample, a positive GDP_pc–PEC association is observed in the previously estimated linear model. However, differences in country population, economic structure and energy requirements make absolute PEC totals difficult to compare with per capita GDP. High within-sample R^2 must not be interpreted as evidence of causal income effects or reliable out-of-sample predictions.

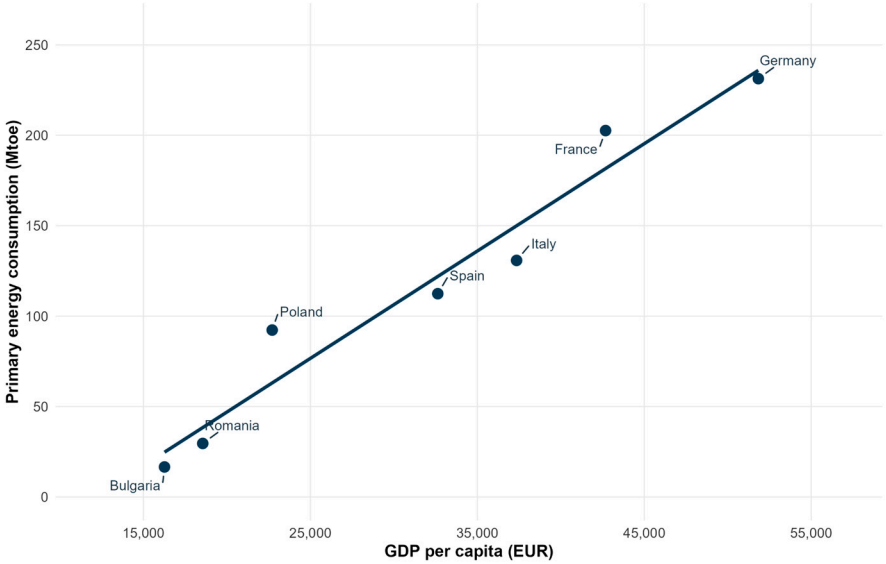


Figure 6. GDP per capita and national primary energy consumption in seven selected EU Member States in 2024 (Bulgaria, France, Spain, Germany, Poland, Romania and Italy). The solid line denotes the original linear regression. Source: authors' calculations from Eurostat [44].

The second PEC–GDP_pc sample comprises Cyprus, Greece, Lithuania, Malta, Slovakia, Slovenia and Hungary ($n = 7$; 2024). Its estimated simple linear specification exhibits a negative association between GDP per capita and the national total of primary energy consumption (Figure 7). Results in this subsection correspond exclusively to the stated seven-country linear specification.

$$\mathrm{PEC} = 42.68818 - 0.00110507\,\mathrm{GDP_{pc}} \quad (4)$$

For the second seven-country linear regression, the GDP_pc coefficient is −0.00110507 Mtoe per euro, equivalent to approximately −1.105 Mtoe per additional EUR 1000 of GDP per capita within the sample. The model yields $R^2 = 0.8449$ (adjusted $R^2 = 0.8139$), $F(1, 5) = 27.2421$ and $p = 0.00341$. The coefficient and corresponding significance tests refer to this simple linear specification and must not be combined with results from a different polynomial model.

The first seven-country PEC–GDP_pc model has a positive slope of +0.005935 Mtoe per euro ($R^2 = 0.9507$; $p = 0.00019$), while the second has a negative slope of −0.001105 Mtoe per euro ($R^2 = 0.8449$; $p = 0.00341$). A pooled group–dummy interaction regression, using the same 14 observations, gives a between-group slope difference of −7.0402 Mtoe per EUR 1000 (conventional 95% confidence interval −9.0601 to −5.0203; $p = 0.0000153$). Stratified country-pairs bootstrap resampling (5000 full-rank replicates, fixed random seed) yields an illustrative percentile interval of −8.42 to −5.76 Mtoe per EUR 1000. The contrast is conditional on the selected country groups and should not be interpreted as a general EU-wide structural relationship.

Leave-one-country-out re-estimation yields R^2 ranges of 0.9204–0.9785 for the first PEC–GDP_pc linear model and 0.8161–0.9313 for the second. As the sample sizes are only seven in each group, any comparison is sensitive to sample construction, to national economic scale, and to omitted determinants such as population, industry structure and energy mix. The groups should not be labelled categorically as "highly developed" and "least developed" countries; descriptive differences may reflect their composition.

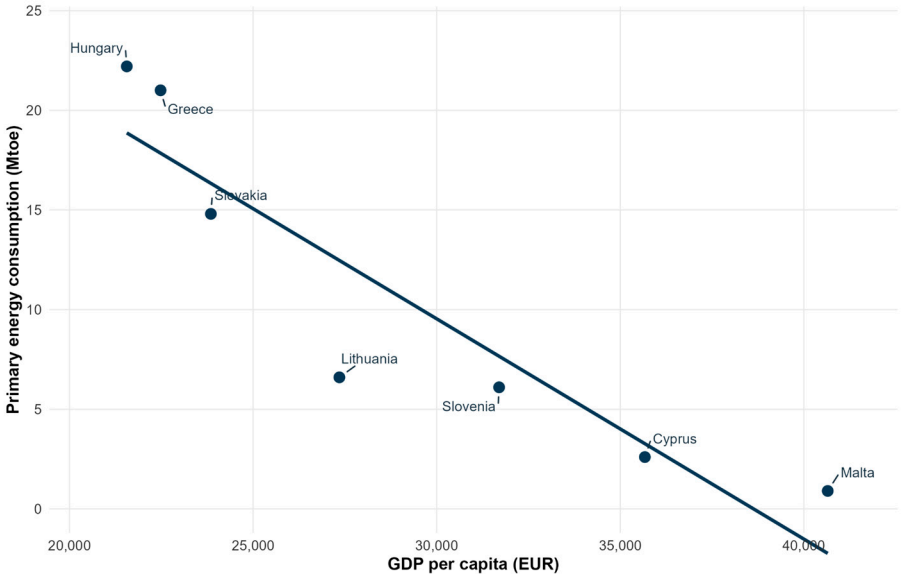


Figure 7. GDP per capita and national primary energy consumption in the second selected seven-country subgroup (2024; Cyprus, Greece, Lithuania, Malta, Slovakia, Slovenia and Hungary). The solid line denotes the estimated linear association; the unconstrained line may extrapolate below zero, which is not a physically plausible PEC prediction. Source: authors' calculations from Eurostat [44].

The final empirical relationship concerns domestic net greenhouse-gas emissions (DNGGE) and primary energy consumption (PEC), illustrated in Figure 8. The seven selected countries are Austria, France, Spain, Germany, Poland, Italy and Finland. These observations differ substantially in national energy needs, production structures and energy mix; their inclusion does not make them a statistically representative or uniformly developed group [49,50]. Both national PEC totals and the emissions index must be read in their stated units. The quadratic specification reproduced below is retained as an exploratory model already present in the authors' working files, rather than as a confirmed nonlinear mechanism.

A polynomial model was used with the assumption that the relationship between the analysed variables may be nonlinear. An increase in energy consumption does not necessarily lead to a proportional increase in emissions as this relationship is influenced by factors such as energy transition, improvements in energy efficiency, and structural changes in the economy. Based on the estimation, the following regression equation was obtained:

$$\mathrm{PEC} = 0.0309516\,\mathrm{DNGGE}^2 - 8.15822\,\mathrm{DNGGE} + 556.90917 \quad (5)$$

For the selected seven-country sample (Austria, France, Spain, Germany, Poland, Italy and Finland), a quadratic PEC–DNGGE regression gives $R^2 = 0.8053$ (adjusted $R^2 = 0.7080$; overall $F = 8.2723$, $p = 0.0379$). A linear specification fitted to the same observations gives $R^2 = 0.7874$, with AIC = 72.92 versus AIC = 74.31 for the quadratic model. The additional squared term does not improve fit in a nested test ($F = 0.3675$; $p = 0.5771$).

The quadratic equation is presented to document the original exploratory specification; it is not favoured over the simpler linear form by the model comparison. The association may also reflect country size and structural characteristics, since PEC is measured in national totals and DNGGE is an index. The leave-one-out R^2 of this seven-country quadratic model ranges from 0.7410 to 0.9132, and the squared term is not individually significant. This sensitivity, together with the very small sample, precludes a strong claim of a stable nonlinear PEC–emissions association.

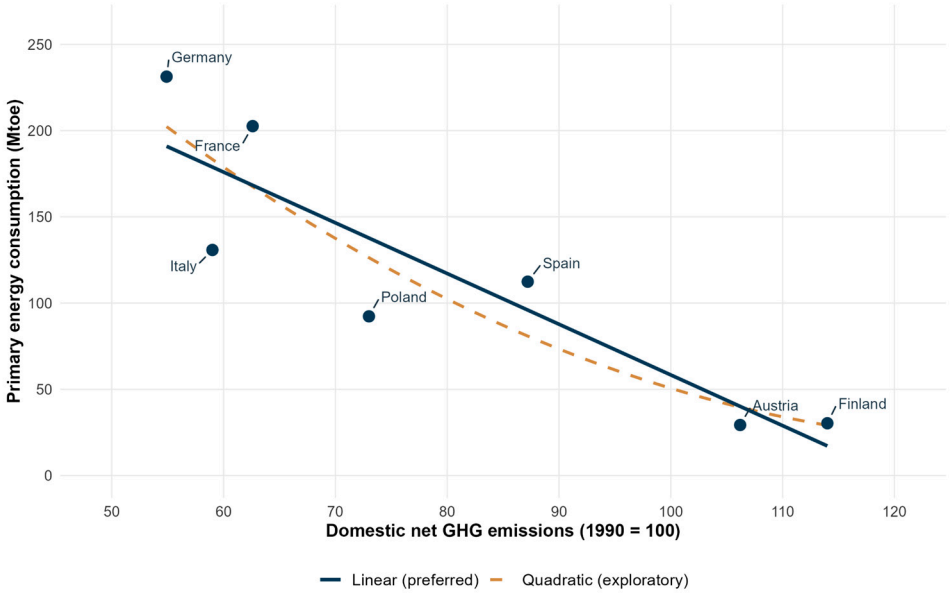


Figure 8. Domestic net greenhouse-gas emissions (1990 = 100 index) and national primary energy consumption (Mtoe) in seven selected EU Member States in 2024. Source: authors' calculations from Eurostat [43,44].

3.1. Model Comparison and Sensitivity Checks

Model comparison was performed on the same country observations within each subset. For DNGGE versus GDP_pc in the 10-country subset, the cubic extension is not supported relative to a quadratic model ($p = 0.3297$), and both AIC and BIC favour a linear specification. For the 14-country subset, the cubic term improves fit relative to the quadratic ($p = 0.0356$), but $R^2 = 0.5592$ and the purposive sample design limit generalizability. For PEC versus DNGGE in seven countries, the quadratic extension is not supported ($p = 0.5771$); its AIC is higher than that of a linear model. These results show why the highest in-sample R^2 should not be treated as the sole specification-selection rule.

A leave-one-out sensitivity assessment produced R^2 ranges of 0.7658–0.9491 for the 10-country DNGGE cubic regression and 0.3834–0.6641 for the 14-country DNGGE cubic regression. For the first and second seven-country PEC–GDP_pc linear groups, the ranges were 0.9204–0.9785 and 0.8161–0.9313, respectively. The seven-country PEC–DNGGE quadratic model yielded 0.7410–0.9132. These variations indicate that individual countries, notably Ireland in the DNGGE subsamples, can exert considerable leverage on small-sample fit. The analysis is exploratory and should not be read as an out-of-sample validation exercise.

Predictive uncertainty was additionally assessed through nonparametric country-pairs bootstrap resampling with 5000 attempted draws (fixed seed 4596289), fitting the original cubic or linear specification on each valid resample. At the specified reference GDP_pc values (EUR 40,015 for DNGGE $n = 10$; EUR 34,990 for DNGGE $n = 14$; EUR 32,630 for PEC group A; and EUR 27,350 for PEC group B), the respective 95% percentile intervals for the fitted conditional mean were 51.9–62.5 and 55.3–80.6 DNGGE index points, and 109.2–137.7 and 6.8–14.6 Mtoe. To distinguish fitted-mean uncertainty from predictive dispersion, each bootstrap fitted value was combined with one draw from the corresponding centred empirical regression residuals. The resulting illustrative 95% predictive intervals were 49.7–65.6 and 48.2–89.5 index points, and 100.6–153.4 and 6.6–16.5 Mtoe, respectively. The 10-country cubic model had three rank-deficient resamples excluded (4997 valid); the other three models had 5000 valid resamples. These bootstrap distributions are

sensitive to country selection and residual assumptions; they are exploratory, not externally validated forecasts.

For the seven-country quadratic PEC–DNGGE model, 4982 of 5000 attempted country-pairs bootstrap resamples produced full-rank fits (18 excluded). At the observed median DNGGE index of 73, the fitted PEC estimate was 126.30 Mtoe, with a 95% percentile bootstrap interval of 71.95–166.90 Mtoe for the conditional mean. The residual-augmented illustrative 95% predictive interval was 46.08–185.56 Mtoe. The quadratic coefficient was 0.030952, with a 95% bootstrap percentile interval from −0.088455 to 0.257681, which includes zero and is consistent with the nested model-comparison test ($p = 0.5771$). The percentile interval for bootstrap R^2 was 0.5814–1.0000; its upper limit partly reflects resamples with only three distinct predictor values and should not be interpreted as evidence of strong out-of-sample predictive performance.

Figure 9 visualises the bootstrap 95% confidence interval for the fitted conditional mean and the residual-augmented illustrative 95% predictive interval for the quadratic PEC–DNGGE model at DNGGE = 73.

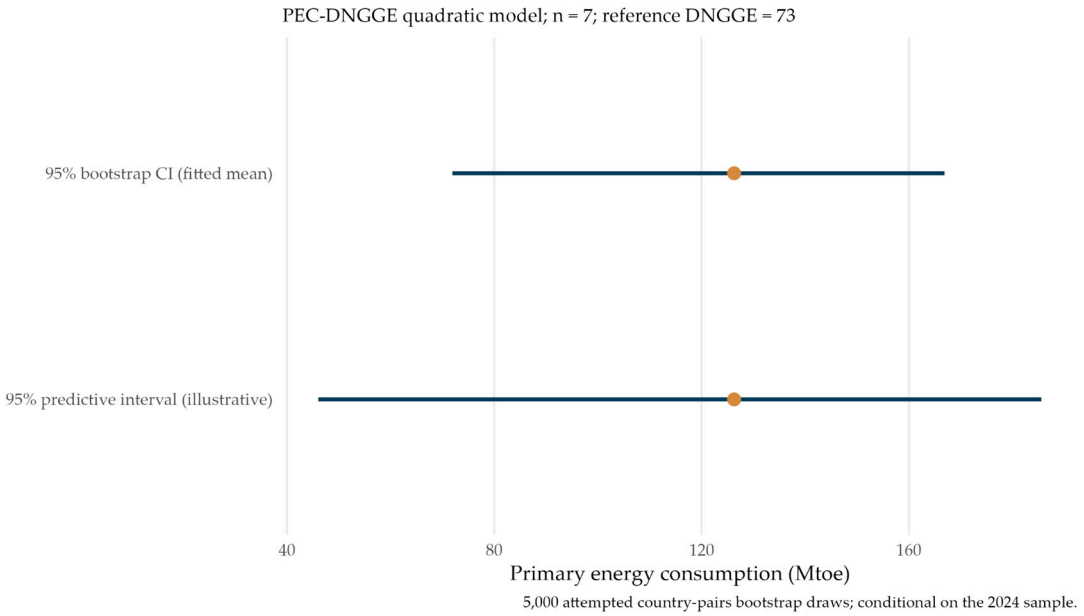


Figure 9. Bootstrap confidence and predictive intervals for the quadratic relationship between domestic net greenhouse-gas emissions (DNGGE) and primary energy consumption (PEC) in seven selected EU Member States in 2024. Source: Authors' calculations based on Eurostat data [44], using 5000 attempted country-pairs bootstrap resamples (4982 valid estimations.

Figure 9 shows bootstrap confidence and illustrative predictive intervals for the quadratic PEC–DNGGE model in seven selected EU Member States (2024), evaluated at DNGGE = 73. The upper interval shows the 95% percentile bootstrap interval for the fitted conditional mean; the lower interval shows the residual-augmented illustrative 95% predictive interval, based on 5000 attempted country-pairs bootstrap draws, of which 4982 produced full-rank fits.

The seven-country quadratic PEC–DNGGE model is also sensitive to extreme observations. Excluding Germany and Finland, respectively, the lowest and highest DNGGE-index observations, reduces R^2 from 0.8053 ($n = 7$) to 0.6749 ($n = 5$) and changes the quadratic coefficient from +0.030952 to −0.020387. Excluding Austria and Germany, the PEC extremes, gives $R^2 = 0.6796$ ($n = 5$) and a quadratic coefficient of −0.004219. The leave-one-country-out R^2 values range from 0.7410 to 0.9132; omitting Germany alone reverses the

quadratic coefficient to −0.002062. These findings reinforce the sample dependence of the fitted curvature and the preference for the simpler linear specification rather than a robust nonlinear interpretation.

When the lowest- and highest-outcome observations are jointly excluded, cubic-model R^2 falls to 0.6737 for the 10-country DNGGE subsample (excluding Bulgaria and Ireland) and to 0.2678 for the 14-country DNGGE subsample (excluding Romania and Ireland). Equivalent low-/high-PEC exclusion reduces linear-model R^2 to 0.8857 in the first PEC–GDP_pc group and 0.8276 in the second. These country-exclusion exercises underscore the sensitivity of small, selected samples and the need to avoid interpreting in-sample correlations as causal evidence.

The SWOT assessment examines the institutional and operational environment of EU climate and energy policy. Its strengths concern the EU-wide legal framework, monitoring mechanisms and established climate-policy instruments, while weaknesses concern implementation capacity, inherited fossil-fuel dependence, network bottlenecks and unequal access to finance [43,48,51–61]. The analysis remains qualitative: it neither measures the causal effectiveness of EU instruments nor provides a statistical ranking of the listed factors. Table 1 distinguishes policy-system characteristics from external opportunities and threats and relates them to illustrative implementation mechanisms.

Table 1. SWOT analysis of EU climate policy.

Strengths	Weaknesses
EU-wide legislative climate framework—common targets and monitoring help coordination.	Uneven administrative capacity—local implementation and permitting may be delayed.
EU ETS—an annually declining emissions cap gives a price-based decarbonisation signal [60].	Continued fossil-fuel lock-in—legacy heat and industrial assets raise adjustment costs.
Renewable-energy framework—the EU target for 2030 guides investment [61].	Grid and storage bottlenecks—constrained connections reduce project deployment.
Monitoring through Eurostat and national plans—comparable indicators aid transparency.	Regional disparities in financing and skills—transition capacity is unequal.
EU cooperation and common funding rules—scope for cross-border learning.	Uneven access to implementation finance—vulnerable regions and smaller administrations may face project-development and co-financing barriers.
Opportunities	**Threats**
Just Transition Fund—place-based diversification and reskilling support for exposed territories [62,63].	Energy-price volatility—affordability and energy-poverty concerns may weaken acceptance.
Investment in renewables and storage—reduces fossil dependence if infrastructure is aligned.	Exposure of carbon-intensive regions—concentrated employment and investment losses.
Digital innovation—firm-level capabilities may support emissions reductions [59].	Financing and cost-of-capital gaps—risk of uneven, clean-technology investment.
Regional cooperation and grid integration—possible economies of scale.	Supply-chain and critical-material constraints—potential delays to implementation.
Targeted cohesion-policy assistance—potential to strengthen investment and implementation capacity in less-resourced territories [62].	Regulatory or implementation delays—uncertain delivery of 2030 milestones.

3.2. SWOT Assessment of the EU Climate and Energy Transition

The SWOT framework distinguishes strengths and weaknesses arising from the existing policy and implementation environment from external opportunities and threats facing the transition. Entries have been consolidated to avoid listing general policy objectives as weaknesses or threats. Table 1 links each item to a mechanism and an illustrative policy response; the assessment is qualitative and does not rank causal impacts. In particular, higher carbon costs under the EU Emissions Trading System (EU ETS), renewable-energy support mechanisms, and place-based investment assistance through the Just Transition Fund provide concrete pathways for differentiated action [60–62].

Policy implications should reflect differences in transition exposure, regional financing capacity, inherited energy systems and administrative implementation capacity, rather than be inferred mechanically from any polynomial turning point. Under the current EU ETS framework, the collective target is a 62% reduction in covered emissions by 2030 compared with 2005 [60]. The European Environment Agency reports that stationary-installation emissions in the ETS fell by 51% between 2005 and 2024 and by approximately 7% in 2024 relative to 2023 [64]. These are monitoring statistics for ETS-covered installations, not coefficients derived from the current cross-sectional regressions. The Renewable Energy Directive sets a collective EU 2030 target of at least 42.5% renewables in gross final energy consumption [61]. The Just Transition Fund supports the diversification and reconversion of territories facing concentrated transition costs [62]. Planned financing and observed disbursements are distinct: neither is measured in the present regressions.

The regression results suggest heterogeneous country-level outcomes, but they do not identify the effect of specific EU policies. In the ten-country DNGGE–GDP_pc sample a parsimonious linear specification is preferred, whereas cubic curvature in the 14-country sample remains sensitive to membership; neither result measures EU ETS stringency nor does it determine an income threshold for policy intervention. Similarly, the contrasting PEC–GDP_pc slopes describe selected national energy-consumption totals, not responses to renewable-energy subsidies. As a qualitative interpretation of these findings, the SWOT strengths of common regulation and monitoring provide the institutional context for the EU ETS [60], implementation weaknesses such as grid bottlenecks and uneven administrative capacity may constrain renewable deployment [61], and JTF assistance offers place-based opportunities for territories exposed to industrial adjustment, while energy-price volatility and financing constraints remain threats [44,62,63]. These mechanisms motivate differentiated support but are not causal effects estimated by the regressions.

For scale, the European Commission's published gross JTF allocations for 2021–2027 (current-price EUR million; before technical-assistance transfers) include Poland 3864 (20.0% of EU-27 allocations), Germany 2489 (12.9%), Romania 2149 (11.1%), and France 1034 (5.4%), compared with EU-27 planned allocations of 19,321 [63]. These are multiannual programmed allocations, not observed expenditure or country-specific ETS subsidy intensities. Their unequal distribution illustrates exposure-sensitive programme design; it does not identify the effect of the JTF on any of the article's emissions or energy outcomes.

Figure 10 illustrates the Just Transition Fund allocations for 2021–2027 (EUR million, current prices; planned gross allocations). Source: European Commission, Just Transition Fund allocations per Member State [63].

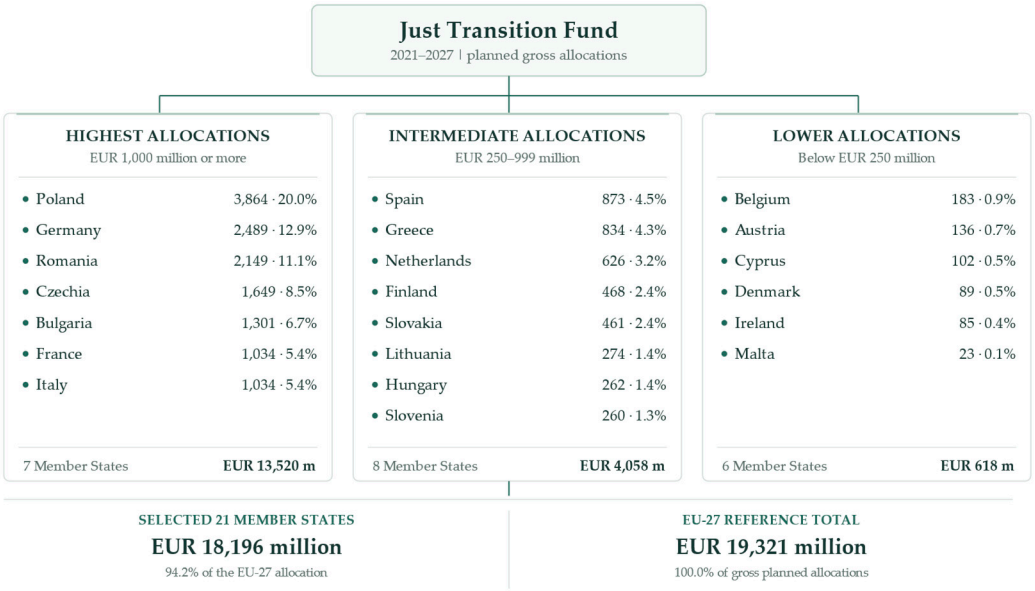


Figure 10. Planned Just Transition Fund allocations across 21 selected EU Member States (2021–2027). Source: Authors' elaboration based on European Commission, *Just Transition Fund—Allocations per Member State (Current Prices)* [63].

The documented ETS emissions series is not equivalent to the domestic net-GHG index used in Figures 1–3: it covers specified installations, changes in ETS scope and a 2005 reference year. Likewise, JTF allocations refer to 2021–2027 planned support rather than energy-sector outcomes in the 2024 cross-section. Direct comparisons of coefficients and policy performance would therefore be inappropriate without harmonising scope, denominators, exposure and timing [63,64].

A quantitative policy-effectiveness test would require country- or region-year measures of ETS exposure and allowance-price incentives, the intensity of national renewable-energy support, and actual JTF or cohesion-policy disbursements rather than only planned allocations, with consistent timing, population and industrial-structure controls. These variables are not included in the present 2024 OLS models; Figure 10 therefore illustrates planned support and must not be read as a regression-based ranking of policy performance [60–64].

Digital adoption is a plausible microeconomic mechanism connecting economic transformation and carbon performance, but its effects are conditional rather than uniform. Lin et al. [59] discuss the role of dynamic capabilities and boundary conditions in firm-level carbon performance. Their findings complement, without validating, the present cross-country associations. This distinction between enterprise-level mechanisms and national-level indicators is important when formulating policy recommendations.

The SWOT analysis identifies external threats such as energy-price volatility, the concentrated exposure of carbon-intensive regions, financing constraints, supply-chain vulnerability, and regulatory delays. These factors may undermine the implementation of climate and energy policies; however, they do not constitute direct estimates of policy effectiveness. A comprehensive causal assessment would require additional country- or region-level data on policy instruments and funding.

The descriptive country series indicate variation in the speed of energy transition across Member States. Because the reported indicators differ in scale and calculation, country-by-country comparisons should be tied to the same Eurostat series, reference year and units. The 2024 cross-sectional regressions are separate from the descriptive 2010–2024 trends.

The observed cross-country differences in greenhouse-gas emissions and energy consumption highlight the importance of considering variations in EU ETS exposure, national renewable-energy support intensity, and Just Transition Fund financing needs, although these policy dimensions are not directly measured in the present regressions and their effects cannot be established from the estimated relationships.

4. Conclusions

This study brings together descriptive Eurostat country indicators for 2010–2024, exploratory 2024 cross-sectional OLS regressions on purposively selected country samples, and a qualitative SWOT assessment of the EU policy implementation context. The analysis documents differences in outcomes and sample-conditional associations, but cannot identify causal effects of EU ETS rules, renewable-energy support, or just-transition allocations.

The descriptive Eurostat evidence indicates variation across EU Member States in renewable-energy shares, emissions indices and national energy consumption. The 2024 renewable-energy share reported for the EU aggregate is 25.2%, whereas the unweighted mean of national renewable shares in the supplied dataset is 28.02%; these are different statistics and must not be substituted for one another [44,48]. The dataset does not by itself demonstrate that every country achieved each of the separate ‘3 × 20’ targets, which have distinct measurement definitions and reference years.

With regard to RQ1, the analysed indicators provide descriptive evidence of changes in emissions indices, renewable-energy shares and primary energy consumption, but do not support a comprehensive verdict on whether individual Member States met all “3 × 20” obligations by 2020 or achieved the broader European Green Deal objectives by 2024. The energy-efficiency target relative to projected consumption and the transport-specific renewable target are outside the tested indicator set, and the 2024 regression cross-section cannot identify policy-driven progress between years. Thus, conclusions about target attainment must be confined to each observed indicator, its reference year and official definition [9,43,44,48].

The existence of common EU objectives, regulatory instruments and financing mechanisms offers a coordinated framework for climate action. Nevertheless, the scale and effectiveness of interventions differ by implementation conditions and cannot be determined from the present GDP_pc–DNGGE and GDP_pc–PEC correlations. The policy discussion therefore identifies possible mechanisms and differentiated support needs rather than treating the EU institutional framework as an empirically identified cause of the observed cross-country patterns [60–62].

The 2024 regressions reveal statistical associations within selected country groups, not a measured policy-treatment effect. High in-sample R^2 values do not establish that the climate and energy transition has been highly effective or quantify the contribution of national, regional and local instruments. Evaluating those contributions would require explicit policy-exposure measures, credible comparison designs and appropriately harmonised longitudinal observations.

The ‘3 × 20’ framework was adopted in December 2008 with targets for 2020, not introduced as a new package by the European Parliament in 2010 [9]. The subsequent European Green Deal and legislative measures, including the EU ETS and the Renewable Energy Directive, operate within an evolving policy framework [60,61]. The current analysis provides background context for these instruments but does not estimate their individual effects on emissions or energy consumption.

The 2024 cross-sectional estimates identify associations between GDP per capita and greenhouse-gas emissions that depend on sample definition and polynomial specification. The 10-country cubic R^2 of 0.913 does not imply a confirmed Kuznets curve, because

nested tests and information criteria favour the linear specification. In the mixed 14-country subset, the cubic extension improves fit, but explanatory power is lower and the results remain sample-sensitive. Therefore, the study does not provide a causal test or an EU-wide confirmation of the environmental Kuznets curve.

Descriptive Eurostat evidence points to progress in the climate–energy transition, but comparisons require a consistent year, definition and indicator. For renewable energy, the official EU aggregate was 25.2% of gross final energy consumption in 2024 [48], distinct from the unweighted average of Member-State shares (28.02%) calculated from the supplied dataset. These descriptive indicators should not be conflated with the 2024 regression results or interpreted as direct estimates of the effectiveness of individual policy instruments.

The qualitative SWOT assessment highlights the implementation environment, including governance capacity, cost exposure, financing gaps, infrastructure and just-transition needs. It does not quantify which factor has the largest causal effect. In particular, policy instruments such as the EU ETS and the Just Transition Fund require separate data on their stringency, allocation and implementation if effects are to be evaluated empirically.

Policy implications therefore remain conditional. Regions with high dependence on carbon-intensive activities or limited administrative and investment capacity may benefit from differentiated implementation assistance; the JTF allocation examples discussed above illustrate planned funding priorities rather than realised spending or established causal effects. The 2024 correlations cannot estimate the amount of intervention needed or its expected impact.

The additional PEC–DNGGE bootstrap exercise reinforces this limitation: its 95% percentile interval for the quadratic coefficient includes zero and country-exclusion analyses reduce R^2 to approximately 0.675–0.680 in the five-country subsamples. Accordingly, these results provide no reliable basis for claiming a stable nonlinear energy–emissions mechanism or for attributing country differences to the EU ETS, the Just Transition Fund, or renewable-energy support.

The relationship between national income levels and emissions is not uniform across the examined subsets, and the best-supported functional form varies. Furthermore, the seven-country PEC–GDP_pc groups exhibit statistically different fitted slopes in a pooled interaction regression, but this comparison is based on purposively chosen samples and an absolute PEC outcome. Causal interpretations, representative EU-wide group contrasts and strong predictions are therefore not supported.

The contribution of this exploratory study lies in bringing together comparative EU descriptive statistics, explicit specification checks and a policy-linked qualitative SWOT assessment. Rather than empirically confirming a single Kuznets-type path, the results demonstrate how dependent cross-sectional patterns can be on country inclusion and polynomial choice.

The results are subject to important limitations: the regressions use a single year (2024), despite the longer descriptive series; country groups are small (n = 7, 10 and 14) and purposively selected; leverage from high-income or extreme-emissions observations can be substantial; national PEC totals and GDP per capita have different scale interpretations; and omitted factors include population, sectoral composition and energy mix. Leave-one-out and extreme-country exclusion demonstrate sensitivity, while bootstrap fitted-value and empirical predictive distributions quantify selected forms of sampling and residual dispersion but do not provide external predictive validation or resolve selection bias.

Further research should exploit comparable EU-27 country-year panel observations and consider size-standardised energy/emissions outcomes, transparent country selection, and pre-specified functional-form comparisons. To assess instruments rather than policy context, future analyses should include EU ETS coverage and intensity, renewable support expenditure, and verified commitments, allocations and disbursements under JTF and cohesion-policy programmes. Individual-level forecasts should be tested against genuinely held-out countries or future observations before being used in policy decisions.

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Conflicts of Interest: The authors declare no conflicts of interest.

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