4 AN ECONOMIC AND STRATEGIC PERSPECTIVE ON THE EUROPEAN ENERGY SECTOR

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Abstract

*The New Normal following the outbreak of the war in Ukraine highlights a new dimension of the energy sector: its strategic importance for economic stability and energy security. This study assesses the socio-economic determinants of renewable electricity production in 27 European Union member states over the period 2000–2024. More specifically, it examines whether innovation capacity, research and development expenditure, energy-use efficiency, and selected macroeconomic and demographic factors are associated with annual renewable-production growth at different points of its distribution. The dependent variable is renewable electricity production, while the main determinants capture innovative capacity, research and development (R&D) expenditure, and energy-use efficiency, complemented by macroeconomic and demographic controls. Using the panel dataset, we estimate two-way fixed-effects recentered-influence-function regressions and a pooled Common Correlated Effects specification, with Driscoll–Kraay inference as a robustness exercise. The Two-Way Fixed Effects (TWFE) and Driscoll–Kraay results indicate positive associations of energy-use efficiency at several middle quantiles, alongside negative consumption associations, while population growth is positive at Q90. These findings suggest that efficiency improvements may facilitate renewable-production growth, whereas rapid increases in household demand may temporarily outpace additions to renewable capacity. The positive population-growth coefficient at Q90 also indicates that demographic expansion may support renewable growth when accompanied by adequate infrastructure and urban planning. The CCE-RIF coefficients are not statistically significant at conventional levels, indicating that the conclusions are sensitive to allowing for heterogeneous responses to common shocks. From a policy perspective, the findings support an integrated approach combining energy-efficiency measures, demand-side management, grid modernization, storage investment, and the coordination of demographic development with renewable-energy infrastructure***.**

Keywords: *energy sector, Europe, production, panel data, strategic, security, quantile regression*

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1. Introduction

In recent decades, political conflicts have often generated significant energy crises. The oil crisis of 1973–1974, triggered by the Yom Kippur War and the Arab states' embargo on oil supplies to the United States and Western Europe, created a profound energy crisis. At the time, Western countries, dependent on cheap oil, had no viable alternatives to replace these resources. However, each such crisis brought about changes in energy policies. For example, the embargo of 1973–1974 led to initiatives such as the "Messmer Plan" in France, which aimed to increase the share of nuclear energy, diversify energy sources, and conserve energy.

These episodes demonstrated that energy and energy resources can become essential political tools. On the other hand, energy crises have shown that social and political aspects significantly impact the development of renewable energy. The Ukrainian-Russian crisis 2014 forced a rethinking of energy policies, and the war in 2022 promises to have even wider consequences. This conflict raises questions about the future of energy policies: whether they will accelerate the transition to green energy sources or, on the contrary, delay this transition.

In Europe and elsewhere, the war in Ukraine has created two main paradigms of energy policy: national energy security and accelerating the energy transition. Sharp increases in energy and gas prices risk triggering deep social crises with major political implications. The Yellow Vests movement in France was a social protest that began in 2018, initially as a reaction to the increase in fuel taxes, which were perceived as a significant economic burden for middle- and working-class citizens, particularly those in rural areas. This movement highlighted the tension between government environmental policies, such as reducing carbon emissions through higher fuel prices, and the immediate economic needs of the population, like the cost of living and energy affordability. The Yellow Vests case illustrates how essential economic measures implemented by governments can trigger social resistance if not accompanied by strategies to mitigate their impact on vulnerable populations. Thus, managing the energy crisis becomes necessary for preventing further social and political tensions.

In this context, energy security has been redefined as an element of national security. Many states emphasize the continuity of energy supply, considering it a pillar of economic and political stability. States significantly dependent on gas and oil imports from Russia, such as Germany, Poland, or Italy, face significant costs to replace these resources, making the transition even more difficult.

Security is a key element in the economics of the energy sectors. However, unlike other economic sectors, in addition to the standard functions of profitability, viability, and reliability, the national security represents a key function for the energy sectors. Within the current geopolitical context, characterized by ongoing military conflicts, uncertainty, and multipolar influences, energy security is an immediate goal for Europe. Moreover, the European Commission's agenda on climate change includes an important security component. Although the initiative to ensure energy security was taken nearly 20 years ago, as mentioned in the Green Paper, "A European strategy for sustainable, competitive and secure energy", concrete steps in this direction were not taken, as shown by the situation following the outbreak of the war in Ukraine in 2022.

Bahgat (2006) discusses in detail the steps that member states should follow according to the Green Paper. A detailed discussion about how Europe can diversify its energy sources to reduce dependence on Russia can be found in Heshmati and Abolhosseini (2017). It is interesting to compare the solutions underlined by Bahgat (2006) with those in Heshmati and Abolhosseini (2017) in order to see how the Annexation of Crimea by the Russian Federation in 2014 has changed the policymakers' perceptions on the Europe's energy security.

Regarding the transition to a green economy and energy security, at the intersection of these two concepts, a third one has emerged: sustainability. The war in Ukraine has highlighted that finding alternative corridors for securing the energy supplies must be accompanied by sustainability. A crucial pivot within the transition process to a green economy, concomitant with ensuring energy security in a sustainable manner refers to directing FDI towards an adequate development of the energy infrastructure, as highlighted in a recent study by Mauro (2024). In this regard, the National Recovery and Resilience Plan for Romania includes a significant component for the energy sector.

This paper investigates the factors influencing electricity production across the 27 EU countries from 2000 to 2024. The study adopts quantile regression as its analytical framework, offering robust insights into the relationships between the electricity production and some relevant explanatory variables such as: foreign direct investments or FDI (expressed as the change in its share of GDP), household consumption (expressed as a share of GDP), economic growth (rate of change in real GDP), inflation (percent change in the Consumer Price Index), unemployment rate and population size (expressed in millions). From the outset, we must consider several special characteristics of the energy market in Europe. The internal energy production in the EU does not fully cover domestic consumption, which is why European countries are dependent on energy imports, and at the overall level, the EU is a net energy importer. Therefore, internal energy production in the EU and energy consumption are closely linked.

The rest of the paper is structured as follows: Section 2 develops the hypotheses, Section 3 describes the data, Section 4 presents the econometric approach, Section 5 reports the results, and Section 6 concludes the paper.

2. Hypotheses development

The specialized literature on the determinants of renewable energy production, and more specifically of energy production at the national level, highlights a very wide range of factors, such as economic, technological, institutional, and geopolitical ones.

A first important group of determinants concerns the technological dimension. Bamati and Raoofi (2020) show that technological factors, especially high-technology exports, significantly influence renewable energy production in developed countries, but less so in emerging ones. Tee *et al*. (2021) focus on intellectual property rights and show that a strong protection regime for these rights stimulates investment and production from renewable sources. Khan and Wyrwa (2025) identify R&D expenditures at the macroeconomic level as one of the most important positive factors for renewable energy production in Europe, suggesting that technological innovation plays an essential role in the energy transition. In the same technological-innovation logic, Michalak & Wolniak (2023) moves beyond single proxies and argues that broader country innovativeness is linked to renewable-energy-oriented outcomes, suggesting that the overall innovation ecosystem can matter for the capacity to scale renewables.

A second set of determinants consists of macroeconomic and structural variables. Several studies highlight the role of GDP and income per capita (Bamati & Raoofi, 2020; Bayale, et al., 2021; Elmassah, 2023), economic growth (Dilanchiev, et al., 2023; Przychodzen & Przychodzen, 2020), and the structure of energy investments or final energy consumption. The price of oil and CO_2 emissions frequently appear as relevant determinants (Bamati & Raoofi, 2020; Bayale, et al., 2021; Elmassah, 2023), while financial development and public debt are associated with either stimulating or constraining renewable energy production in emerging economies (Przychodzen & Przychodzen, 2020; Petrovic & Ostojic, 2025). Recent OECD evidence further nuances the “R&D automatically increases renewable output” view: Opoku, *et al*. (2024) finds that energy innovation R&D generally does not increase total renewable energy generation in OECD countries, implying that the impact of R&D may depend on complementary factors (e.g., policy design, diffusion/absorption capacity, investment structure) rather than being uniformly positive.

The demographic dimension and urbanization also play an important role. Dilanchiev *et al*. (2023) show that urbanization, CO_2 emissions, and economic growth are closely correlated with renewable energy production in BSEC member countries, highlighting the pressure on energy infrastructure in the context of population growth and the expansion of urban areas. Bayale *et al*. (2021) also find significant effects of urbanization and unemployment on renewable energy production in WAEMU countries, indicating that labor market dynamics and the spatial structure of the economy influence the energy profile.

Other recently published academic articles highlight institutional and governance determinants. Ozturk *et al*. (2025) introduce into the analysis digital governance, the circular economy, and the stringency of environmental regulations, and show that digitalization and circular economy practices significantly support renewable energy production, while overly strict regulations can have adverse effects. Marra and Colantonio (2022) analyze, for the EU, the role of environmental policy stringency, public awareness, lobbying, and education, highlighting heterogeneous effects depending on the degree of energy security and dependence on imports. Khan and Wyrwa (2025) add factors such as political instability and the rule of law, which hinder the energy transition in the absence of stable governance.

Another important pillar of the literature concerns policy uncertainty and geopolitical risk. Petrovic and Ostojic (2025) investigate the impact of policy-induced uncertainty and geopolitical risk on renewable energy production, using a robust panel cointegration framework for 42 countries. Their results indicate an absence of long-term effects, but highlight short-term positive and negative effects, heterogeneous across countries, of geopolitical risk and policy uncertainty. These findings suggest that geopolitical and policy shocks can temporarily alter the trajectory of energy production, without necessarily changing the long-term structural trend. Complementary evidence focused on the investment channel shows that uncertainty can still matter for the energy transition: Pata, *et al*. (2023), analyzing G7 countries, find that higher economic policy uncertainty and geopolitical risk are associated with weaker renewable energy investment, implying that uncertainty may slow capacity expansion even if long-run production effects are not always detected in cross-country settings.

The reviewed literature also addresses aspects such as model uncertainty (Bayale, et al., 2021), the role of competition in the energy market, and international climate policies such as the Kyoto Protocol (Przychodzen & Przychodzen, 2020). In addition, recent integrations with machine learning methods (Khan & Wyrwa, 2025) show that the macroeconomic structure (GDP, inflation, population, financial development) and the quality of institutions can be combined with advanced prediction techniques to obtain a better understanding of the factors that determine renewable energy production.

Despite this rich literature, several important gaps can still be identified. Although some studies take into account technological components (high-tech exports, intellectual property rights) or aggregate R&D expenditures, none of these articles uses a country-level innovation index that would capture innovative capacity (human capital, research system, digitalization, collaborations, etc.). In addition, only one study explicitly treats R&D expenditures as a determinant of energy production, and the role of foreign direct investment (FDI) as a direct determinant of energy production is not addressed at all, even though FDI can finance both energy infrastructure and technology transfer.

Building on these gaps in the literature, we formulate the following working hypotheses:

H1: A higher level of innovation, measured through a composite country-level innovation index, is positively associated with energy production, suggesting that more innovative economies succeed in developing and exploiting energy production capacities more efficiently.

H2: Research and development (R&D) expenditures, especially those targeted at the energy sectors and green technologies, have a significantly positive impact on energy production, with the effect being more pronounced in economies located in the upper quantiles of the energy production distribution.

H3: Foreign direct investment (FDI) contributes positively to the growth of energy production through the financing of infrastructure, technology transfer, and the import of managerial know-how, and this relationship remains robust after controlling for the macroeconomic, institutional, and demographic factors discussed in the existing literature.

3. Data description

For this quantitative study we will use a data set for the 27-Member States of the European Union (EU) for the considered period 2000 – 2024. The dependent variable is the quantity of electrical energy from renewable sources (gigawatt-hour), that express the effective measurement of energy transition at national level. The key explanatory variables are those that express innovation capacity and the efficiency of the resources' use – innovation index, research and development expenditures (as a percentage of GDP) and GDP per unit of energy used – because they reflect the structural potential of an economy to adopt green technologies and to produce more energy from renewable sources, with a given level of energy consumption. The other variables are to be considered control variables: economic growth, household consumption, inflation, unemployment rate, trade openness and population size, all these charecterizing the macroeconomic and social environment, in which energy production takes place and allowing for a clearer isolation of the effect of structural factors on renewable energy.

The level sample contains 675 country-year observations for 27 EU countries. For estimation, renewable electricity production is expressed as annual growth, nonstationary regressors are entered in first differences, and variables already measured as annual rates retain their original form, resulting in 648 observations. Missing predictor values are addressed through 20 predictive-mean-matching imputations, while observed Eurostat renewable-production values are not imputed.

Table 1. Data description

Variable	Definition	Source
Gross elecricity production (Electricity)	Electricity production from renewable sources, expressed in GWh	Eurostat
Economic growth (*Growth*)	Real GDP growth rate (the annual rate of change of GDP real)	The Global Economy
Household consumption (*Consumption*)	Final household expenditures, as a percentage of GDP	The Global Economy
Inflation	Annual inflation rate, measured as the percentage change of the price consumer index.	The Global Economy
Unemployment rate (*Unemployment*)	Unemployment rate, expressed as percentage of labor force	AMECO
Trade openness (*Oppeness*)	The percentage of a country's GDP derived from exports and imports of goods and services	World Bank
GDP per unit of energy used (*Conversion*)	GDP generated per unit of energy used (energy efficiency indicator at economy level)	The Global Economy

Foreign Direct Investments (*FDI*)	Are the net inflows of investment to acquire a lasting management interest (10 percent or more of voting stock) in an enterprise operating in an economy other than that of the investor. Reported as % GDP.	The Global Economy
Innovations index (*Innovation*)	An innovation index, with values between 0 and 100, which reflects an economy's innovation capacity	The Global Economy
Research and development expenditure (*R&D*)	Expenditures for research and development, expressed as a percentage of GDP	The Global Economy
Population size (Pop)	The size of population, expressed in millions of citizens	World Bank

As a first step of the empirical analysis, we examne cross-sectional dependence using Pesaran's CD test. The null hypothesis of cross-sectional independence is strongly rejected (CD = 8.664, p < 0.001), confirming that common shocks or other unobserved factors generate dependence across EU member states. We therefore apply the second-generation CIPS test, which allows for cross-sectional dependence. In levels, the CIPS test does not reject the unit-root null for renewable electricity production, household consumption, trade openness, R&D expenditure, or population growth. These variables are transformed into the estimation forms described above. The CIPS test subsequently rejects the unit-root null at the 5% level for annual renewable-production growth and all regressors entering the transformed RIF models. The empirical models are therefore estimated using the stationary transformed specification. The results of CIPS tests are presented in Table 2.

Table 2. CIPS tests for transformed model variables

Variable name	CIPS statistic	p-value	Decision at 5%
Electricity	-4.310	0.010	Stationarity
Growth	-3.090	0.010	Stationarity
Consumption	-3.115	0.010	Stationarity
Inflation	-2.969	0.010	Stationarity
Unemployment	-2.797	0.024	Stationarity
Openness	-2.996	0.010	Stationarity
FDI	-2.936	0.010	Stationarity
Conversion	-3.427	0.010	Stationarity
Innovation	-2.964	0.010	Stationarity
R&D	-2.762	0.033	Stationarity
Population	-3.321	0.010	Stationarity

Notes: The null hypothesis is that the panel series contains a unit root. The CIPS decisions are based on the transformed variables used in the RIF estimations; Δ denotes a first difference.

As a further diagnostic step, we assess the potential presence of multicollinearity among the explanatory variables. Multicollinearity can inflate standard errors, reduce the precision of coefficient estimates, and complicate the interpretation of marginal effects, particularly in models that include several macroeconomic, structural, and innovation-related indicators. This issue is especially relevant in panel settings where economic variables may co-move over time due to common shocks or structural trends.

To evaluate multicollinearity, we first inspect the pairwise correlation matrix of the main regressors. As a rule of thumb, absolute correlation coefficients above 0.80–0.90 may signal severe multicollinearity, while values below this threshold are generally considered acceptable. The results presented in Appndix 1 indicate that, with a few moderate correlations, the explanatory variables do not exhibit problematic levels of multicollinearity. The highest correlation is observed between Innovation and R&D, which is expected from an economic perspective, as both variables capture closely related dimensions of innovative capacity. Importantly, even in this case, the correlation remains below commonly used critical thresholds.

4. Econometric approach

One way to assess a heterogeneous distributional effect relies on the Conditional Quantile Regression (CQR). At any level τ, across the distribution of y, which is the dependent variable, given a set of explanatory factors x, the conditional quantile $Q_y(\tau|x)$ shows $inf\{k: T(k|x) \geq \tau\}$ where $T(* \,|x)$ represents the conditional distribution function. In a panel data framework, the most common approach is the CQR with fixed effects (Koenker, 2004):

$$Q_{y_{i,t}}(\tau|x_{i,t}) = \alpha_i + x_{i,t}^T \beta^{CQR}(\tau). \qquad (1)$$

In Eq. (1), $i = \overline{1,N}$ and $t = \overline{1,T}$, represent countries and years, $y_{i,t}$ is the dependent variable, $x_{i,t}$ denotes the covariates, $\beta^{CQR}(\tau)$ is the common slope coefficient while α_i is a location shift parameter.

In order to better capture the impact of the covariates on electricity production, including explanatory variables in CQR renders coefficients which fail to reflect the impact of these covariates across quantiles. Consequently, Firpo *et al*. (2009) proposed the UQR by computing a recentred influence function (RIF) designed without reference to covariates, which is regressed subsequently on the explanatories:

$$RIF\left(y_{i,t}; v\left(F_{y_{i,t}}\right)\right) = v\left(F_{y_{i,t}}\right) + IF\left(y_{i,t}; v\left(F_{y_{i,t}}\right)\right). \qquad (2)$$

In Eq. (2), $F_{y_{i,t}}$ represents the CDF of $y_{i,t}$ while $v(F_{y_{i,t}})$ quantifies the marginal impact on the parameter of distribution $F_{y_{i,t}}$ when removing or adding a variable. The influences function (IF) measures the impact of a particular variable on a distributional statistic:

$$IF\left(y_{i,t}; v\left(F_{y_{i,t}}\right)\right) = \lim_{\varepsilon \to 0}\left(\frac{v\left[(1-\varepsilon)F_{y_{i,t}} + \varepsilon G_{y_{i,t}}\right] - v\left(F_{y_{i,t}}\right)}{\varepsilon}\right). \qquad (3)$$

In Eq. (3), $0 \leq \varepsilon \leq 1$ and $G_{y_{i,t}}$ denotes the distribution that puts mass at the value $y_{i,t}$. The expected value of the RIF is $v(F_{y_{i,t}})$, as the expected value of the $IF\left(y_{i,t}; v(F_{y_{i,t}})\right)$ is zero. In addition, if we select the τ^{th} quantile as the statistic of interest and choose to estimate the density functions for each quantile, the RIF is given by:

$$RIF\left(y_{i,t}; q_\tau; F_{y_{i,t}}\right) = q_\tau + IF\left(y_{i,t}; q_\tau; F_{y_{i,t}}\right) = q_\tau + \frac{\tau - \mathbb{I}\{y_{i,t} \leq q_\tau\}}{f_{y_{i,t}}(q_\tau)}. \qquad (4)$$

In Eq. (4), q_τ is the τth quantile of the unconditional distribution of $y_{i,t}$, $f_{y_{i,t}}(q_\tau)$ represents the PDF of $y_{i,t}$ evaluated at the τth quantile using a Kernel-density estimation, while $\mathbb{I}\{y_{i,t} \leq q_\tau\}$ is an indicator function showing whether $y_{i,t}$ falls below the τth quantile or otherwise. Thus, the UQR estimator is:

$$RIF\left(y_{i,t}; q_\tau; F_{y_{i,t}}\right) = x_{i,t}^T \beta^{UQR}(\tau). \qquad (5)$$

Following Borgen (2016), we estimate the unconditional quantile regression in two stages: after computing the recentered influence function for each selected quantile, we regress it on the explanatory variables while absorbing country and year fixed effects. More specifically, for each quantile $\tau \in \{0.10, 0.25, 0.50, 0.75, 0.90\}$, we estimate:

$$RIF\left(g_{i,t}; q_\tau\right) = \alpha_i + \lambda_t + x_{it}^{'}\beta_\tau + \varepsilon_{it}. \qquad (6)$$

Here, $g_{i,t}$ denoted annual growth in renewable electricity production for country i in year t, q_τ is the τ-th unconditional quantile of $g_{i,t}$, α_i denotes country fixed effects, λ_t denotes year fixed effects, and x_{it}' contains the stationary explanatory variables. Quantile regression is particularly useful under heightened geopolitical and macrofinancial uncertainty because it captures asymmetric and heterogeneous responses across the distribution that mean-based estimators may conceal. Recent applications demonstrate its value for assessing the heterogeneous effects of green and climate-adaptation technologies on renewable-energy use and energy efficiency, the effects of geopolitical and macrofinancial shocks on the Northern European energy transition, and the distributional environmental effects of green finance and technological innovation (Muhammed *et al.*, 2025; Uluğ and Andrei, 2025; Song *et al.*, 2023).

The TWFE-RIF specification therefore controls for time-invariant country heterogeneity and uniform year shocks. The estimates use country-clustered standard errors. Because the Pesaran CD test indicates cross-sectional dependence that may reflect heterogeneous reactions to common shocks, we also estimate a pooled CCE-RIF model following the Common Correlated Effects framework introduced by Pesaran (2006), with the pooled estimator supported by the fixed-T results of Westerlund *et al.* (2019). This specification augments the RIF regression with cross-sectional averages and interprets the slope coefficients after accounting for common factors. The models are estimated across 20 predictive-mean-matching imputations.

5. Results

This section presents and interprets the empirical results obtained from the TWFE-RIF, CCE-RIF, and Driscoll–Kraay specifications. The quantiles represent different positions in the unconditional distribution of annual renewable-production growth, with Q10 and Q25 describing lower-growth outcomes and Q75 and Q90 describing higher-growth outcomes. Comparing the estimates across quantiles makes it possible to identify whether the associations between the explanatory variables and renewable-production growth vary across the distribution.

Table 3 reports the baseline TWFE-RIF results. No coefficient is statistically significant at Q10. At Q25, changes in household consumption have a negative effect, while inflation and changes in energy-use efficiency have positive effects. Changes in consumption remain negative at Q50 and Q75, and energy-use efficiency remains positive at these quantiles. At Q90, population growth has a positive coefficient. The year effects absorb shocks that shift all countries uniformly in a given year.

Table 3. Two-way fixed-effects RIF estimates

Variable	Q10	Q25	Q50	Q75	Q90
Growth	−0.281 (0.575)	−0.246 (0.235)	−0.083 (0.762)	−0.007 (0.979)	−0.197 (0.676)
Consumption	−1.119 (0.174)	−1.115** (0.012)	−1.016** (0.035)	−1.459*** (0.007)	−0.390 (0.763)
Inflation	0.407 (0.381)	0.647** (0.019)	−0.063 (0.808)	0.090 (0.768)	−0.374 (0.417)
Unemployment rate	0.264 (0.312)	0.254 (0.275)	0.052 (0.827)	−0.110 (0.713)	−0.629 (0.296)
Openness	−0.291 (0.450)	−0.284 (0.127)	−0.234* (0.080)	−0.127 (0.529)	0.063 (0.873)
FDI	0.003 (0.635)	−0.004 (0.513)	0.010 (0.192)	−0.020 (0.110)	−0.024 (0.710)
Energy-use efficiency	0.496 (0.133)	0.376*** (0.005)	0.394*** (0.004)	0.488*** (0.001)	0.536 (0.115)
Innovation index	0.680 (0.388)	−0.096 (0.822)	0.005 (0.991)	−0.053 (0.918)	0.575 (0.534)
R&D	0.026 (0.941)	0.058 (0.684)	−0.010 (0.949)	−0.074 (0.609)	0.080 (0.765)
Population	−1.837 (0.607)	−0.794 (0.660)	−1.062 (0.358)	−0.981 (0.513)	5.727** (0.034)

*Notes: Entries are coefficients, with p-values in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$. The dependent variable is annual renewable-production growth. Estimates use 648 transformed country-year observations across 27 EU countries and 20 predictive-mean-matching imputations.*

The clearest baseline results concern energy-use efficiency and household consumption. Changes in energy-use efficiency are positively associated with renewable-production growth at Q25, Q50, and Q75, with coeffcients increasing from 0.376 to 0.488. This pattern suggests that efficiency improvements may facilitate faster renewable-production growth, with the association becoming stronger toward the upper-middle part of the distribution. Greater energy efficiency can reduce pressure on the electricity system and improve its capacity to integrate additional renewable generation. In contrast, changes in household consumption are negatively associated with renewable-production growth at Q25, Q50, and Q75. A possible explanation is that rapid increases in household demand can outpace short-run additions to renewable capacity, requiring electricity systems to rely temporarily on dispatchable conventional generation or energy imports.

Table 4 presents the CCE-RIF estimates, which allow the observed variables to be evaluated after accounting for heterogeneous reactions to common shocks. None of the reported slope coefficients is statistically significant at the 10% level. Consequently, the TWFE findings should not be interpreted as invariant to the common-shock specification; under CCE, the evidence does not isolate a statistically significant domestic association for the included regressors.

Table 4. Pooled Common Correlated Effects RIF estimates

Variable	Q10	Q25	Q50	Q75	Q90
Growth	−0.209 (0.944)	−0.260 (0.915)	−0.140 (0.954)	0.947 (0.713)	0.851 (0.854)
Consumption	−0.135 (0.976)	−1.624 (0.653)	−1.625 (0.636)	−1.143 (0.768)	1.339 (0.852)
Inflation	2.216 (0.711)	1.447 (0.703)	0.734 (0.837)	0.500 (0.916)	−0.204 (0.975)
Unemployment rate	−0.120 (0.965)	0.400 (0.890)	0.377 (0.913)	0.400 (0.915)	−1.661 (0.756)
Openness	−0.393 (0.746)	−0.221 (0.866)	−0.400 (0.824)	−0.003 (0.998)	0.459 (0.831)
FDI	0.023 (0.988)	−0.010 (0.995)	0.033 (0.988)	−0.013 (0.995)	−0.021 (0.995)
Energy-use efficiency	0.442 (0.695)	0.605 (0.439)	0.541 (0.596)	0.564 (0.669)	0.771 (0.732)
Innovation index	0.620 (0.831)	0.087 (0.975)	0.129 (0.970)	0.197 (0.951)	0.784 (0.889)
R&D	−0.120 (0.942)	0.011 (0.995)	−0.160 (0.950)	−0.379 (0.837)	−0.159 (0.959)
Population	−1.128 (0.950)	−2.370 (0.885)	−2.491 (0.904)	−1.694 (0.928)	2.465 (0.934)

*Notes: Entries are coefficients, with p-values in parentheses. *** $p < 0.01$; ** $p < 0.05$; * $p < 0.10$. The dependent variable is annual renewable-production growth; Δ denotes a first difference. Estimates use 648 transformed country-year observations across 27 EU countries and 20 predictive-mean-matching imputations.*

Although the CCE coefficients generally preserve the positive sign of energy-use efficiency and the negative middle-quantile sign of household consumption, none is statstically significant. This loss of statistical significance indicates that the baseline associations are sensitive to explicitly controlling for heterogeneous exposure to common factors. EU-wide technological, policy, economic, or geopolitical developments may therefore account for part of the relationships identified in the TWFE specification. However, the CCE results do not establish that the baseline relationships are spurious; rather, they show that domestic effects cannot be estimated with sufficient precision once cross-sectional averages are included.

As a CSD-robust exercise, Table 5 re-estimates inference for the TWFE-RIF coefficients using Driscoll–Kraay standard errors with a maximum lag of two. The positive coefficient of changes in energy-use efficiency is significant at Q25, Q50, and Q75 and marginally significant at Q10 and Q90. Changes in household consumption are negative at Q25 and Q75 and marginally significant at Q50; trade openness is negative at Q25, inflation is positive at Q25, and population growth is positive at Q90.

Table 5. TWFE-RIF estimates with Driscoll–Kraay standard errors

Variable	Q10	Q25	Q50	Q75	Q90
Growth	−0.281 (0.700)	−0.246 (0.386)	−0.083 (0.805)	−0.007 (0.977)	−0.197 (0.616)
Consumption	−1.119 (0.339)	−1.115** (0.021)	−1.016* (0.069)	−1.459** (0.040)	−0.390 (0.739)
Inflation	0.407 (0.280)	0.647*** (0.008)	−0.063 (0.704)	0.090 (0.732)	−0.374 (0.240)
Unemployment rate	0.264 (0.553)	0.254 (0.206)	0.052 (0.872)	−0.110 (0.722)	−0.629 (0.256)
Openness	−0.291 (0.386)	−0.284** (0.017)	−0.234 (0.234)	−0.127 (0.443)	0.063 (0.869)
FDI	0.003 (0.700)	−0.004 (0.588)	0.010 (0.345)	−0.020 (0.165)	−0.024 (0.538)
Energy-use efficiency	0.496* (0.069)	0.376*** (0.002)	0.394** (0.013)	0.488** (0.011)	0.536* (0.091)
Innovation index	0.680 (0.383)	−0.096 (0.809)	0.005 (0.991)	−0.053 (0.905)	0.575 (0.518)
R&D	0.026 (0.930)	0.058 (0.663)	−0.010 (0.951)	−0.074 (0.603)	0.080 (0.731)
Population	−1.837 (0.693)	−0.794 (0.612)	−1.062 (0.302)	−0.981 (0.447)	5.727** (0.019)

*Notes: Entries are coefficients, with p-values in parentheses. *** p < 0.01; ** p < 0.05; * p < 0.10. The dependent variable is annual renewable-production growth; Δ denotes a first difference. Estimates use 648 transformed country-year observations across 27 EU countries and 20 predictive-mean-matching imputations.*

Taken together, the TWFE-RIF and Driscoll–Kraay results provide a distribution-specific view of renewable-production growth. Driscoll–Kraay inference preserves the TWFE coefficient estimates while adjusting the standard errors for cross-sectional dependence and temporal correlation, which is useful for the moderate transformed panel of 27 countries over 24 years. Three main patterns emerge. First, changes in energy-use efficiency are positively associated with renewable-production growth at Q25, Q50, and Q75 and are marginally significant at Q10 and Q90, indicating that efficiency improvements are relevant across much of the distribution. Second, changes in household consumption are negatively associated with growth at Q25 and Q75 and marginally at Q50, consistent with short-run increases in demand outpacing additions to renewable capacity. Third, population growth is positively associated with renewable-production growth at Q90, which may reflect the stronger investment incentives and scalability of renewable infrastructure in high-growth energy systems. Nevertheless, the absence of significant CCE-RIF coefficients shows that these findings remain sensitive to the treatment of heterogeneous common shocks and should be interpreted as associations rather than causal effects.

6. Conclusions

Access to a safe and reasonably priced energy supply is essential for energy-intensive industries like manufacturing, and foreign direct investments can move into nations that can offer it. However, in our empirical models, foreign direct investment does not emerge as a robust determinant of renewable electricity production once structural drivers (innovation capacity, R&D, and energy-use efficiency) and macro controls are included.

By promoting the variety of energy sources, FDI can help to advance energy security. For instance, foreign investments in renewable energy projects can reduce its reliance on a single energy source. FDI frequently contributes significantly to the construction of energy infrastructure, including distribution networks, pipelines, and power plants. By modernising and growing a nation's energy infrastructure, this can improve energy security. That said, the central contribution of this paper is to explain cross-country differences in renewable electricity production, showing that energy-use efficiency is the most consistent correlate in the TWFE and Driscoll–Kraay specifications, while CCE results require a more cautious interpretation of domestic drivers.

The revised distributional results show that changes in energy-use efficiency are positively associated with renewable-production growth at Q25, Q50, and Q75 in the TWFE specification, while changes in household consumption are negatively associated with growth at the same parts of the distribution. Population growth is positive at Q90. These results remain visible under Driscoll–Kraay inference, although the specific significance pattern varies across quantiles.

The pooled CCE-RIF estimates are not statistically significant at conventional levels. This result qualifies the TWFE and Driscoll–Kraay evidence and indicates that the estimated domestic associations are sensitive to heterogeneous common shocks. Therefore, policy implications may continue to consider energy-use efficiency, but they should remain cautious about the stability and causal interpretation of the coefficients across alternative CSD treatments.

Our empirical results suggest that the expansion of renewable energy on the supply side is associated with demand and demographic management. Because efficiency gains favor the development of renewable energy particularly at Q25, Q50 and Q75, governments should promote stricter standards for energy efficiency in buildings, the use of efficient household appliances, and the modernization of energy infrastructure. Decreasing unnecessary energy consumption may reduce pressure on electricity grids and facilitate the integration of a higher share of renewables without disproportionate investments in additional generation capacity.

On the other hand, to prevent sudden changes in consumption from overloading the energy system, policymakers should use smart pricing mechanisms, demand response programs, and digital demand management technologies. These tools may increase system flexibility and reduce the costs of integrating renewable energy.

The results suggest that investments in energy transmission and distribution infrastructure need to accompany the expansion of renewable capacities. Without grid modernization and the development of energy storage solutions, the benefits of investments in green energy production may be limited by infrastructure constraints and grid congestion.

Public policies should stimulate private investment in storage technologies, digitalization and smart grids through predictable fiscal schemes, public-private partnerships, and stable financing mechanisms. A stable regulatory framework is essential to reduce investment risk and accelerate the energy transition.

In economies characterized by an accelerated development of green energy (Q90), population growth appears as a favorable factor when accompanied by effective urban planning. Authorities should link the development of urban areas with investments in electric public transport, energy-efficient buildings, and green infrastructure, so that demographic expansion can generate economies of scale and more efficient energy use.

The results highlight the need for an integrated approach between energy, climate, and demographic policies. The energy transition cannot be treated exclusively as a supply-side issue; its success depends on the coordination of infrastructure investments, energy efficiency policies, urban planning, and demand-side management measures.

Finally, the findings of the study suggest that national renewable energy strategies should be tailored to the level of economic development and structural characteristics of each economy. A “one-size-fits-all” approach is unlikely to be optimal, as the determinants of renewable energy deployment vary between economies at different stages of the energy transition.

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Appendix 1. Correlation matrix of the explanatory variables

Variable	Growth	Consumption	Inflation	Openness	Conversion	FDI	Innovation	R&D	Pop
Growth	1.0000	-0.0566	0.1271	0.1847	0.0389	0.0575	-0.0678	-0.2091	-0.1423
Consumption	-0.0566	1.0000	0.1377	-0.6148	-0.3550	0.0392	-0.6699	-0.4714	0.1005
Inflation	0.1271	0.1377	1.0000	-0.0055	-0.0237	-0.0606	-0.2651	-0.1826	-0.0618
Openness	0.1847	-0.6148	-0.0055	1.0000	0.3646	0.1351	0.1968	-0.1348	-0.4766
Conversion	0.0389	-0.3550	-0.0237	0.3646	1.0000	0.1494	0.0962	0.0080	0.0100
FDI	0.0575	0.0392	-0.0606	0.1351	0.1494	1.0000	0.0755	-0.1688	-0.1277
Innovation	-0.0678	-0.6699	-0.2651	0.1968	0.0962	0.0755	1.0000	0.7134	0.0680
R&D	-0.2091	-0.4714	-0.1826	-0.1348	0.0080	-0.1688	0.7134	1.0000	0.2057
Pop	-0.1423	0.1005	-0.0618	-0.4766	0.0100	-0.1277	0.0680	0.2057	1.0000