THE JAPANESE POLITICAL ECONOMY
https://doi.org/10.1080/2329194X.2026.2688199

Greening the energy mix: the role of environmental policies in reducing fossil fuel consumption in EU-23 countries

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ABSTRACT

This study examines the factors that influence fossil fuel consumption in European economies, with a specific emphasis on renewable energy, alternative technologies, foreign investment, and economic growth. The study explores the factors of fossil fuel consumption (FFC) in 23 EU countries over the period 2005–2022, by focusing on the roles of renewable energy output (REO), climate adaptation technologies (CTA), environmental taxation (TET), foreign direct investment (FDI), and economic growth (GDP per capita). We use annual panel data with dynamic panel estimators, such as the autoregressive distributed lag model, system generalized method of moments, and random effects models to incorporate both short-term and long-term dynamics. The Pedroni cointegration test demonstrates a long-run equilibrium relationship. The dynamic ARDL specification's results show a strong persistence of fossil fuel use, as indicated by a significant lagged dependence of FFC, which underscores the entrenched reliance of European economies on carbon-intensive energy sources. Fossil fuel consumption is found to be significantly reduced by renewable energy output across all models, thereby supporting the substitution hypothesis that the deployment of renewable energy directly reduces reliance on fossil fuels. Foreign direct investment and GDP per capita growth, however, are positively correlated with FFC, in line with environmental Kuznets curve dynamics and the "pollution haven" effect. Climate adaptation technologies exhibit varying effects, decreasing reliance on fossil fuels in the short term but increasing it over the long term, illustrating transitional energy expenses and rebound phenomena. Overall, the results imply that technological innovation and renewable expansion are crucial in driving decarbonization, but structural economic growth and investment patterns still perpetuate dependence on fossil energy. Emphasizing policy implications highlights the necessity for enhanced integration of renewables, adapted energy efficiency measures, and environmentally friendly investment strategies to ensure long-term sustainability goals are met.

ARTICLE HISTORY
Received 30 August 2025
Accepted 9 June 2026

KEYWORDS
Fossil fuels; renewable energy; environmental tax; decarbonization; GDP growth

JEL CLASSIFICATION
Q42; Q48; Q58; C33

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

Introduction

The world is facing significant and interconnected environmental problems, such as environmental decline, global warming, and air pollution, which are primarily driven by human activities, particularly the extensive burning of fossil fuels. An urgent situation has led to a global consensus, as seen in significant agreements like the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), which stress the importance of substantial and immediate emission cuts to prevent rising global temperatures and promote sustainable living conditions for current and future populations (Holechek et al. 2022; Martins et al. 2019). Consistent warnings from projections highlight the urgent need for prompt and decisive action to alter the current trajectory of escalating carbon emissions. Transitioning from fossil fuels to renewable energy sources is widely regarded as a significant undertaking, but it is viewed as the most feasible route to achieving climate balance when weighing physical, financial, political, and environmental considerations (Mohsin et al. 2021; Pisani-Ferry, Tagliapietra, and Zachmann 2023).

The European Union has taken a proactive stance to tackle climate change, committing to an ambitious path toward achieving climate neutrality. This commitment is embedded in cornerstone initiatives like the European Green Deal and the REPowerEU plan, which outline specific and ambitious goals: to decrease the emission of GHG (Greenhouse Gases), increase the use of renewable energy sources considerably, and enhance energy efficiency (Proedrou 2023). These policies aim to transform the EU into a modern, environmentally sustainable, and competitive economy by shifting from a linear "take-make-dispose" economic model to a more circular economy framework. The shift aims to reduce reliance on external supplies, decrease waste production, and limit resource extraction, ultimately promoting more environmentally friendly production and consumption methods within the region. The EU's climate policy is becoming more integrated into European affairs, while energy policy decisions continue to be primarily a matter for individual member states, highlighting the need for a careful balance between shared objectives and national sovereignty to decide on energy compositions (Fatur Šikić and Hodžić 2023; Kılıç Depren et al. 2022).

Several European countries, notably those within the EU-23, which are often distinguished by unique economic and political conditions compared to other, more established EU members, continue to rely heavily on fossil fuels for their energy requirements despite existing comprehensive policy frameworks and evidence of decarbonization efforts. The continued dependence is troublesome on several counts. Firstly, fossil fuels are finite resources, and their rapid depletion is a major concern, with projections indicating that by 2050, around 14% of oil, 72% of coal, and 18% of gas proven reserves may remain globally under certain scenarios. For European countries, which typically have limited domestic reserves, this implies a swift depletion if current usage persists (Pleßmann and Blechinger 2017; Sgaravatti, Tagliapietra, and Trasi 2024). These fuels' extraction, processing, and combustion are major contributors to severe environmental and health issues, such as global warming, air pollution (e.g., CO2, SO2, PM10 emissions), and the degradation of natural habitats. In 2020, fossil fuels accounted for 83.1% of global energy consumption. The EU-27, despite being a smaller global extractor of materials, retains a considerable material footprint and ranks among the primary users, underscoring its substantial demand and reliance on global supply chains. Countries in the EU, specifically 22 of them, show significant reliance on imports for critical categories such as fossil fuels and metal ores, with many exhibiting reliance levels above 65%, frequently surpassing 80%. A heavy reliance on external sources creates substantial risks, such as geopolitical vulnerabilities and economic instability, which are worsened by global supply chain disruptions and rising geopolitical tensions (Frédéric Gonand et al. 2024).

Achieving ambitious sustainability goals requires a comprehensive and coordinated approach that involves both supply-side and demand-side measures, encourages technological progress, and promotes changes in behavior to reduce material usage and meet sustainability objectives effectively. Effective policy coordination at both national and EU levels is necessary to remove connector limitations in energy networks, maximize the efficient use of cross-border transmission, and resolve strategic dependencies on crucial materials. Education and public awareness play a crucial role; effective communication and education programs are vital to secure public backing for policies that involve initial expenses and disturbances during the energy transition, guaranteeing that citizens comprehend the long-term advantages and the higher costs of inaction (Brodny and Tutak 2025; Ciski and Rząsa 2025; Zhu et al. 2021). The 23 countries in the EU frequently require more stringent regulations and reforms, and they face significant challenges in striking a balance between rapid decarbonization, energy security, and industrial competitiveness, all while navigating geopolitical changes and unstable energy markets. This study aims to offer a comprehensive evaluation of how environmental policies specifically affect the decrease in fossil fuel consumption and the increase in renewable energy sources within 23 EU countries, thus contributing to a deeper understanding of achieving environmental sustainability objectives in the complex European context (Kılıç Depren et al. 2022; Zafar et al. 2020).

This research paper explores the vital link between energy consumption, economic growth, and environmental quality, focusing on the significant role that environmental policies play in driving a shift from nonrenewable to renewable energy sources in the 23 EU member countries. The study focuses on EU-23 countries for two major reasons. First, the EU-23 countries share a similar institutional, policy, and regulatory framework concerning the governance of energy markets and environmental regulation, which makes the region a unique domain for cross-country comparability. Second, the EU-23, which encompasses both emerging and developed economies, shares a collective commitment to the EU Green Deal, the green energy transition process, and climate neutrality. This makes EU-23 a unique empirical setting for analyzing the influence of environmental policies, technological adaptation, renewable energy, and economic growth on the dynamics of fossil fuel consumption over time.

Environmental policies, which involve various tools like environmental taxes, regulations, and subsidies, are regarded as crucial instruments to encourage a decrease in the use of fossil fuels and support the adoption of cleaner energy technologies, ultimately resulting in a more environmentally friendly energy mix. Environmental taxes have been demonstrated to have a negative long-term effect on ultimate energy consumption in both older and more recent EU countries, with this effect being notably less pronounced in the latter group. Policymakers are advised to introduce dynamic mitigation targets and help through tax breaks and subsidies for low-emitting power sources, such as biomass, to boost green energy production and usage. The effectiveness of these policies can differ substantially across various countries, primarily due to their distinct economic development stages, existing technological infrastructures, and distinct institutional frameworks.

Within the contemporary global discourse, this research holds substantial significance both academically and in terms of policy, particularly in relation to the transition to renewable energy sources. The study provides a detailed understanding of the intricate relationship between environmental policies, the adoption of renewable energy, and the ongoing use of fossil fuels. Econometric methods with robustness are applied, encompassing panel GMM, ARDL, and Random Effects Models, which are well-established in the literature for their analytical capabilities in examining these relationships.

The urgency of this investigation is emphasized by the critical need to balance ongoing economic expansion with environmental stewardship. This challenge is especially relevant within the European Union, which has set ambitious goals, primarily targeting complete climate neutrality by 2050 under initiatives such as the European Green Deal and the REPowerEU plan. Although EU countries have made these commitments and are continuing to move toward decarbonization, many countries within the EU-23 are still heavily reliant on fossil fuels for their energy needs, which requires more stringent regulations and reforms. This paper adds significant value to both academic research and policy discussions by presenting concrete data. The report explains how different financial and regulatory tools, including environmental levies, can efficiently encourage a transition away from burning fossil fuels and promote the inclusion of cleaner energy sources in the energy supply. The EU's prominent position in global climate governance, serving as a "role model" for other countries, makes the findings crucial not only for regional decision-makers in guiding the EU-23 toward its environmental sustainability targets but also offers valuable guidance for other economies worldwide striving to synchronize their energy policies with international climate objectives, such as those specified in the Paris Agreement and the Sustainable Development Goals.

Literature review

Achieving a sustainable energy mix has become a top priority in both academic discourse and policy-making spheres. Despite the general agreement on the need to decrease the usage of fossil fuels, the methods for accomplishing this goal are still being debated. The literature examines two interconnected issues: (i) the effects of consuming renewable energy on environmental conditions, and (ii) the structural and institutional factors that influence the effectiveness of environmental regulations. This review critically examines these lines of research, noting both areas of agreement and disagreement, and positions the current study within existing debates.

Renewable energy consumption and environmental quality

Extensive research has been conducted on the significance of renewable energy in reversing environmental deterioration, with results showing a range of positive outlooks. Bilgili, Koçak, and Bulut (2016) reexamined the Environmental Kuznets Curve (EKC) theory by explicitly incorporating renewable energy usage into the relationship between emissions and economic growth across 17 OECD countries. Their study confirms the Environmental Kuznets Curve, demonstrating that renewable energy causes a significant decrease in CO_2 emissions, whereas economic growth at first worsens environmental damage but improves it at higher income levels. Notably, their research contradicts previous Environmental Kuznets Curve studies that mainly overlooked renewable energy, focusing instead on total or fossil fuel energy consumption. This refinement further supports the argument that adopting clean energy can hasten the turning point of the EKC, thereby facilitating earlier decoupling of growth from emissions. The EKC framework remains a subject of debate, as it presumes that economic growth inevitably results in environmental betterment, a notion that opponents claim neglects systemic disparities, entrenched patterns of behavior, and policy shortcomings.

Evidence for the positive impact of renewables is also demonstrated by Zafar et al. (2020), who studied OECD countries, including the effects of education, foreign direct investment (FDI), and natural resource abundance. Their research shows that renewable energy and education improve environmental quality, whereas FDI inflows and resource abundance worsen emissions. The straightforward "renewables reduce emissions" narrative is complicated by its placement within broader economic dynamics. Investment inflows can bring in cleaner technologies, but they also tend to increase extractive activities, based on host-country regulations. Countries with abundant resources frequently experience the "resource curse," where reliance on fossil fuel income discourages efforts to diversify their energy investments.

Despite this, countervailing evidence is also present. Studies have discovered that the integration of renewable energy sources, which has a positive effect on lowering emissions, may not be enough to compensate for the increasing demand for energy in countries with high energy consumption. Shafiei and Salim (2014) found that in OECD countries, renewable energy sources lower emissions, yet nonrenewable energy consumption remains a substantial factor in environmental outcomes. The data indicates that relying on renewable energy by itself is insufficient to ensure a decrease in carbon emissions, necessitating the implementation of complementary strategies such as demand management, energy conservation, and industrial restructuring. While the literature generally concurs on the emissions-reducing effects of renewable energy sources, it also cautions against overly optimistic expectations.

Structural, institutional, and policy determinants

Institutional and structural factors are key in determining the relationship between energy and the environment beyond the immediate impacts of the green energy sources. Education plays a catalytic role in promoting environmental awareness and policy support, as highlighted by Shehad, Afzal, and Anwar (2023) and Piran, Sharifi, and Safari (2023). Education plays a crucial role in promoting the social acceptance of renewable energy sources as well as augmenting the dissemination of clean technologies through research, innovation, and the supply of skilled workers. The research shows that countries with higher levels of educational achievement have a greater ability to convert renewable energy usage into environmental benefits. This discovery corresponds with more general evidence on the significance of institutional capacity in environmental management.

Simultaneously, material and geopolitical obstacles complicate the policy landscape. Di Stefano et al. (2024) examined the European Union's material footprint and import dependency, revealing that it remains heavily dependent on external suppliers for both fossil fuels and critical minerals required for renewable technologies.

Pleßmann and Blechinger (2017) show that the dependence of the EU on imports of fossil fuels is over 90%, with a metal ores dependency rate of more than 80%, thus eroding the EU's strategic independence in its shift toward a sustainable future. The EU's adoption of circular economy principles and the Critical Raw Materials Act is hindered by these policies' inability to adequately address systemic weaknesses linked to international supply networks. A structural constraint is therefore evident in import dependency, which cannot be resolved solely through domestic environmental policies, underscoring the necessity for coordinated international strategies and diversification of supply. Import dependency thus emerges as a structural constraint that cannot be resolved solely through domestic environmental policies, highlighting the need for coordinated international strategies and diversification of supply.

The literature also highlights contradictions in the effectiveness of policy. On one hand, fiscal incentives, carbon pricing, and renewable energy subsidies have been demonstrated to promote clean energy investment (Polzin et al. 2015; Sadorsky 2009; Zhu et al. 2021). Conversely, policies that are poorly designed or inadequately enforced frequently lead to rebound effects, in which efficiency improvements or an increase in renewable energy production are countered by higher overall energy consumption. The Russia–Ukraine conflict has highlighted the vulnerability of the EU's energy infrastructure, with short-term measures to ensure energy stability sometimes leading to increased reliance on fossil fuels, which ultimately jeopardizes the EU's long-term climate goals (Holechek et al. 2022; Martins et al. 2019).

The table representing the key literature is as follows.

Authors	Year published	Methodology	Period	Findings and link
Apergis, Nicholas, and James E. Payne	2010	The authors employed the error correction and panel co-integration model.	1985–2005	The findings of the research reveal that the consumption of renewable energy has a positive impact on the economic growth of OECD countries. Link: https://doi.org/10.1016/j.enpol.2009.09.002
Bilgili, Faik, Emrah Kocak, and Umit Bulut	2016	Panel data analysis for the Environmental Kuznet curve	1977–2010	The findings of the study reveals that the consumption of renewable energies play a pivotal role in the reduction of CO2 emissions and thus supports the environmental Kuznet curve in OECD countries. Link: https://doi.org/10.1016/j.rser.2015.10.080

Authors	Year published	Methodology	Period	Findings and link
Mohsin et al.	2021	The authors used panel econometric analysis	1990–2015	The findings of the study reveal that the transition from the nonrenewable to renewable energies reduces the CO2 emission and positively impact the economic growth in developing Asian Economies. Link: https://doi.org/10.1016/j.jenvman.2021.111999
Holechek et al.	2022	The authors employed scenario analysis with energy demand and supply projections	2009–2050	The findings of the study reveals that by 2050, renewable energies will replace fossil fuels if the developed increased by six-fold. But the management of this demand requires changes in life style and character. Link: https://doi.org/10.3390/su14084792
John Stone, Nick, Ivan Hascic, and David Popp	2010	The author used panel data regression no Patent counts	1978–2003	The findings of the study reveals that public policies play a key role in influencing innovation in the renewable technologies with broad-based instruments such as renewable energy certificates. The findings also reveals that the Government based R&D also positively impacts patenting. Link: https://doi.org/10.1007/s10640-009-9309-1
Sadorsky, Perry	2009	The author used Panel co-integration estimation	1980–2005	The findings of the study reveal that the increase in the CO2 emission per capita and real GDP per capita also increases the renewable energy consumption per capita. Moreover, the findings also reveal that oil prices have a negative impact across the G7 countries. Link: https://doi.org/10.1016/j.eneco.2008.12.010

The existing literature offers significant insights into the relationship between energy use, growth, and environmental quality, yet significant gaps still exist. Most studies center on carbon emissions as the primary dependent variable (Bilgili, Koçak, and Bulut 2016; Ciski and Rząsa 2025; Kılıç Depren et al. 2022; Proedrou 2023), frequently disregarding fossil fuel consumption itself, which is the direct driver of emissions and a more immediate policy target for the EU. Despite their increasing importance under the European Green Deal and associated policy initiatives, relatively undermined the important role of environmental taxes and climate adaptation technologies. Studies on the EU have often highlighted the adoption of renewable energy but have not fully explored how a combination of fiscal tools and technological advancements contributes to the reduction of fossil fuel use. This study advances the literature by modeling fossil fuel consumption as the dependent variable and incorporating renewable energy production, environmental taxation, GDP per capita, adaptation technologies, and other macroeconomic factors. It initially alters the emphasis from outcomes (emissions) to inputs (fossil fuel use), thereby enabling a more precise examination of policy effectiveness. It uses dynamic econometric methods, including panel GMM, ARDL, and Random Effects Models, to measure both short-term adjustments and long-term equilibrium effects, while accounting for endogeneity and heterogeneity across 23 EU countries. The study presents new and policy-applicable findings on how environmental regulations and technological advancements can successfully incorporate renewable energy sources into Europe's energy supply.

Data and methodology

This study examines how population aging and macroeconomic fundamentals shape labor productivity across 23 EU countries over 2005–2022 using annual data. The study uses Panel GMM, REM and ARDL to investigate the short-run and long-run relationship between the dependent and independent variables. The dependent variable is fossil fuel consumption as percentage of total consumption (FFC). Explanatory variables are renewable energy output (REO), total environmental tax (TET), natural log of GDP per capita (LNGDPPC), climate change adaptation technologies (CTA), foreign direct investment (FDI), and alternative and nuclear energy usage (A&NEU).

The analysis uses variables defined as flows or ratios based on flows, observed annually, to prevent the combination of stock and flow ideas. Fossil fuel consumption, renewable energy production, usage of alternative and nuclear energy, GDP per capita growth, and foreign direct investment are measured as annual flows (or growth rates), whereas environmental taxes represent annual fiscal revenues collected by governments. Energy variables are expressed as shares of total energy consumption or output to ensure comparability across countries and to account for scale effects associated with economic size or population. This normalization transforms energy usage into flow measures based on intensity, a format commonly used in energy transition and decarbonization studies, enabling the analysis to concentrate on structural shifts in the energy mix rather than changes caused by overall demand fluctuations. This approach is designed to separate the dynamic substitution between fossil and non-fossil energy sources and maintain internal consistency across the variables utilized in empirical models.

The dynamic panel data model can be represented as:

$$\begin{aligned} FFC_{it} = \alpha\, FFC_{i,t-1} + \beta_1\, REO_{i,t} + \beta_2\, TET_{\ i,t} + \beta_3\, LNGDPPC_{\ i,t} + \beta_4\, CTA_{i,t} \\ + \beta_5\, FDI_{i,t} + \beta_6 A\,\&\, NEU_{i,t} + \mu_i + \varepsilon_{i,t} \ldots. \end{aligned} \tag{1}$$

Including $FFC_{i,t-1}$ captures persistence in productivity but makes the within estimators biased in short-to-moderate T panels. We therefore estimate the model with Generalized Method of Moments (GMM), one-step, using both Arellano–Bond difference GMM and (for persistence/ weak instruments concerns) Blundell–Bond system GMM.

To eliminate μ_i, we first-difference:

$$\begin{aligned}\Delta FFC_{it} &= \alpha\,\Delta \mathrm{FFC}_{i,t-1} + \beta_1\,\Delta REO_{i,t} + \beta_2\,\Delta TET_{\,i,t} + \beta_3\,\Delta LNGDPPC_{\,i,t} \\ &\quad + \beta_4\,\Delta CTA_{i,t} + \beta_5\,\Delta FDI_{i,t} + \beta_6 \Delta A\,\&\,NEU_{i,t} + \Delta\varepsilon_{i,t} \ldots.\end{aligned} \tag{2}$$

Endogeneity is addressed with internal instruments. We treat $FFC_{i,t-1}$, $LNGDPPC_{\,i,t}$, and $FDI_{i,t}$ as endogenous $REO_{i,t}$,$\Delta CTA_{i,t}$ and $TET_{\,i,t}$ as pre-determined as exogenous. In the difference GMM, lagged levels (e.g., t-2,t-3) instrument the differenced endogenous/predetermined regressors. In system GMM, we add the levels equation and use lagged differences as instruments, improving efficiency when regressors are persistent.

To curb instrument proliferation, we collapse the instrument matrix and restrict lag depth (e.g., use t-2:t-3 for endogenous/predetermined variables). Instrument validity is assessed with the Hansen J test of overidentifying restrictions (reported for the robust one-step estimator). Serial correlation is checked using Arellano–Bond AR(1) and AR(2) tests on differenced residuals; we expect significant AR(1) and no AR(2). We report the instrument count and ensure it is modest relative to the number of cross-sectional units.

The general panel ARDL (1,1) model is specified as:

$$Y_{i,t} = \alpha_i + \rho_i Y_{i,t-1} + \delta 0_i\, X_{i,t} + \delta 1_i\, X_{i,t-1} + u_{i,t}$$

Where Y is the vector of dependent variable FFC, and X is the vector of regressors, i.e., REO, TET, LNGDPPC, CTA, A&NEU, and FDI.

Re-parameterizing into the error-correction form yields:

$$\Delta Y_{i,t} = \varphi_i \left(Y_{i,t-1} - \theta_i X_{i,t-1}\right) + \gamma_i \Delta X_{i,t} + \varepsilon_{i,t}$$

Here, φ_i is the error-correction coefficient, expected to be negative and statistically significant.

The panel ARDL framework is well-suited for this analysis because it accommodates variables integrated of order zero, I(0), and order one, I(1), while excluding I(2). Estimation is carried out using the Pooled Mean Group (PMG) approach of Pesaran, Shin, and Smith (1999), which allows heterogeneity in short-run coefficients and adjustment speeds across countries.

As a complementary, static benchmark that exploits both within- and between-country variation, we estimate a Random Effects (RE) model without the lagged dependent variable:

$$\begin{aligned}FFC_{it} &= \delta_i + \beta_1\,REO_{i,t} + \beta_2\,TET_{\,i,t} + \beta_3\,LNGDPPC_{\,i,t} + \beta_4\,CTA_{i,t} + \beta_5\,FDI_{i,t} \\ &\quad + \beta_6 A\,\&\,NEU_{i,t} + \mu_i + \varepsilon_{i,t}.\end{aligned}$$

Table 1. Variables and sources.

Variable	Description	Source
FFC	Fossil Fuel Consumption as Percentage of Total Energy Consumption	Eurostat
REO	Renewable Energy Output as Percentage of Total Output	Eurostat
GDPPC	Growth of Per Capita GDP (Current USD)	WDI
TET	Total Environmental Tax in Percentage	Eurostat
CTA	Climate Adaptation Technologies as Percentage of Total Technologies	Eurostat
FDI	Foreign Direct Investment as Percentage of GDP	WDI
A&NEU	Alternative and Nuclear Energy Usage as a Percentage of Total Energy	Eurostat

Table 2. Descriptive statistics.

Statistics	A&NEU	REO	TET	CTA	FFC	LNGDPPC	FDI (% GDP)
Mean	17.35	34.44	4.12	2.13	66.26	1.83	4.59
Median	13.78	27.75	3.16	1.62	70.13	2.12	2.94
Std. Dev	13.97	24.62	2.52	1.74	19.14	3.70	28.90
Min	0.11	1.09	0.07	0.29	7.08	−16.04	−440.13
Max	51.30	99.47	12.30	16.44	95.99	12.83	234.25
Observations	414	414	414	414	414	414	414

Table 3. IPS panel unit root test.

Variable	T-statistics (t-bar)	*p*-value	Order of Integration
FFC	−3.5194	0.0000	I(1)
REO	−3.7000	0.0000	I(1)
GDPPC	−3.8663	0.0000	I(0)
TET	−2.8604	0.0000	I(0)
CTA	−3.6264	0.0000	I(0)
FDI	−3.1588	0.0000	I(0)
A&NEU	−3.5723	0.0000	I(1)

Where μ_i is the random country effect assumed to be uncorrelated with regressors. Estimation uses feasible GLS with cluster-robust standard errors by country. We perform a Hausman test (RE vs. FE) on the static specification to test for the presence of random effects. The RE results are interpreted as descriptive/robustness evidence; causal interpretation relies on the dynamic one-step GMM framework and ARDL model.

Table 1 below exhibits the description of the regressand and regressors, and Table 2 shows the descriptive statistics of each variable.

Estimation and results

To ensure the stationarity of the variables, we employed the IM-Pesaran-Shin Panel unit root test. The widely used Im–Pesaran–Shin (IPS) panel unit root test is preferred because it accommodates heterogeneity in autoregressive coefficients across cross-sectional units, in contrast to more restrictive tests such as the Levin–Lin–Chu. This hypothesis assumes that all series are non-stationary, whereas the alternative hypothesis allows that at least some series are stationary, providing greater flexibility in practical applications. In comparison to single time-series unit root tests, the IPS test exhibits superior power in small samples, which makes it particularly useful in scenarios with limited panel dimensions (Tables 3 and 4).

Table 4. Pedroni panel cointegration test.

	Statistic	*p*-value
Modified Phillips-Perron t	5.7781	0.0000
Phillips-Perron t	−6.3431	0.0000
Augmented Dickey-Fuller t	−6.4940	0.0000

Table 5. ARDL, GMM, and REM estimates.

	(1) ARDL	(3) GMM	(2) REM
main			
L.REO	0.00350		
	(0.54)		
REO		−0.0121**	−0.214***
		(−2.17)	(−13.03)
L.TET	−0.00621**		
	(−2.41)		
TET		−0.0624	0.0720
		(−1.28)	(0.97)
L.CTA	−0.00666***		
	(−2.94)		
CTA		0.0968	−0.466***
		(1.40)	(−3.77)
L.LNGDPPC	0.00398*		
	(1.95)		
LNGDPPC		0.0469*	−0.00980
		(1.75)	(−0.23)
L.FDI	0.00740***		
	(5.62)		
FDI		0.000233	0.00386
		(0.07)	(0.71)
A&NEU		−0.0716***	−0.975***
		(−3.05)	(−20.66)
L.FFC		0.910***	
		(26.81)	
_cons		6.950**	91.26***
		(2.38)	(24.23)
N	414	391	414
AR(1)		0.000	***Hausman***
AR(2)		0.274	***Chi-Square (χ^2) = 2.98***
Hansen P-Value		0.635	***p-value = 0.8112***

The panel unit root test shows that our dependent variable FFC is stationary at first difference, followed by REO and A&NEU also stationary at first difference. Variables GDPPC, TET, CTA, and FDI are stationary at the level. The mixture of stationarities at first difference and at level makes the use of panel dynamic models (GMM and ARDL) suitable for a robust and efficient analysis of the relationship between dependent and independent variables, both in the short-run and long-run.

Table 5 presents the outcomes from the ARDL, GMM, and REM estimations, where fossil fuel consumption (FFC) is the dependent variable. The dynamic GMM model verifies that there is strong persistence in energy consumption patterns, indicated by a positive and highly significant coefficient of 0.910 ($p < 0.01$) for lagged FFC, which shows the entrenched dependence of European economies on fossil fuels. Several policy and technology variables show significant impacts, nonetheless. In the short

Table 6. Short-run ARDL estimates.

Short run	ARDL
Ec	−1.741
	(−1.07)
A&NEU	−0.148
	(−0.15)
REO	−0.334***
	(−2.24)
TET	0.943
	(1.14)
CTA	0.262
	(0.91)
LNGDPPC	0.0196
	(0.80)
FDI	0.0513
	(1.58)
_cons	88.17***
	(13.48)
N	414

term, renewable energy output (REO) has a considerable negative impact on fossil fuel consumption (−0.334, $p < 0.05$), which supports the substitution hypothesis that increased renewable generation directly replaces reliance on fossil fuels. Results from this study align with earlier research showing that renewable energy deployment can cause a sudden decrease in demand for conventional energy sources (Apergis and Payne 2010; Sadorsky 2009). Despite the presence of cointegration as confirmed by the Pedroni test, the error-correction term in the ARDL model is negative but statistically insignificant (−1.741, t = 1.07), suggesting weak convergence back to the long-run equilibrium. It implies that while renewable energy can decrease reliance on fossil fuels in the short term, structural inflexibilities hinder transition toward a long-term equilibrium (Table 6).

The GMM Model estimates provide stronger evidence of the long-run drivers of energy transition. Renewable energy production continues to show a significant decrease (−0.214, $p < 0.01$), with alternative and nuclear energy usage (−0.975, $p < 0.01$) and the implementation of climate adaptation technologies (−0.466, $p < 0.01$) also contributing to a reduction in the use of fossil fuels. The results underscore the importance of technological innovation and expanding the energy mix in reducing dependence on fossil fuels. Post-estimation diagnostics, including the absence of second-order autocorrelation (AR(2) $p = 0.274$) and a non-rejected Hansen J-test ($p = 0.635$), support the validity of the instruments and confirm that certain endogeneity concerns inherent in energy–growth models have been addressed (Arellano & Bond, 1991; Blundell and Bond 1998). Variables such as GDP per capita growth and foreign direct investment are statistically significant and positive.

The REM estimates selected over fixed effects due to the non-significant results from the Hausman test (χ^2=2.98, $p = 0.8112$), also demonstrate the effectiveness of modeling unit-specific heterogeneity under the assumption that country-effects and regressors are independent (Baltagi 2021; Hausman 1978). The magnitudes of the coefficients may differ, but the REM shows that renewable and alternative energy development reduces fossil fuel consumption, in line with the GMM findings.

The consistency across ARDL, GMM, and REM estimations clearly suggests that increasing renewable and alternative energy supply and developing climate adaptation technologies are crucial tools for decreasing fossil fuel reliance in European economies. The evidence supports this alignment, which is in line with broader empirical evidence showing a link between the expansion of renewable energy and sustainable growth pathways and lower carbon intensity (Apergis and Payne 2010; Sadorsky 2009).

Discussion

The strong persistence of fossil fuel consumption observed in the GMM results is consistent with existing literature that highlights the path-dependent nature of energy systems, where sunk investments in fossil-fuel-based infrastructure create carbon lock-in. Transitions to renewables occur slowly due to the high capital costs and long planning horizons required for technological substitution (Fouquet 2016; Unruh 2000). Moreover, the structural dependence of industrial production and transport on fossil fuels reinforces this persistence, as energy use remains closely tied to economic activity. Policy and regulatory inertia, coupled with the influence of vested interests, further delay rapid reductions in fossil fuel reliance. In addition, consumer behaviors and lifestyles, shaped by existing infrastructure such as cars and heating systems, exhibit strong inertia that slows down energy transitions. Together, these factors explain why lagged fossil fuel consumption significantly predicts current usage, underscoring the entrenched dependence of European economies on fossil energy (Cherp et al. 2017; Stern 2011; Szulecki and Overland 2020).

Consistently, the results show that renewable energy output has a considerable negative effect on fossil fuel consumption across the ARDL, GMM, and REM models, directly supporting the substitution hypothesis. Increases in renewable energy generation instead of supporting fossil fuel usage are replacing their reliance, a dynamic also observed in long-run GMM and REM results, where the impact of REO remains significantly negative. Previous empirical research supports the conclusion that the deployment of renewable energy sources decreases dependence on fossil fuels and promotes energy diversification in OECD and EU regions (Apergis and Payne 2010; Sadorsky 2009). The robustness of this effect across three different econometric frameworks bolsters confidence in the conclusion that renewable energy acts as a structural substitute for fossil fuels, underscoring the role of renewable expansion as a key driver of decarbonization.

The results indicate that variables such as GDP per capita growth and foreign direct investment (FDI) are statistically significant and positive, suggesting that higher levels of economic growth and increased capital inflows tend to raise fossil fuel consumption. This outcome is consistent with the environmental Kuznets curve (EKC) literature, which shows that in the early stages of development, growth is often accompanied by higher energy use and greater environmental pressure. Economic expansion increases industrial output, transport demand, and household consumption, all of which are energy-intensive and still largely fossil-fuel dependent in many European economies. Similarly, FDI inflows often stimulate industrialization and infrastructure development, which initially rely heavily on fossil energy (Shahbaz and Lean 2012; Stern 2011). While some studies highlight the potential for "pollution halo" effects where FDI facilitates cleaner technologies, the empirical evidence frequently points to a "pollution haven" dynamic in which capital inflows increase energy intensity and carbon emissions, particularly in the short run (Pao and Tsai 2011; Zhu et al. 2021). Thus, the positive association of GDP per capita growth and FDI with fossil fuel consumption reflects the structural energy dependence of growth and investment processes, reinforcing the need for targeted policies to decouple economic expansion from carbon-intensive energy use.

Results from ARDL and REM indicates that climate adaptation technologies have a positive correlation with fossil fuel consumption over an extended period, yet a negative relationship in the short term. The long-run positive effect suggests that, despite their intended role in facilitating sustainable transitions, adaptation technologies may indirectly increase fossil fuel use by reinforcing existing energy systems or creating rebound effects. The deployment of adaptation infrastructure often necessitates substantial material and energy inputs, potentially entrenching economies in carbon-intensive pathways if the supporting energy mix continues to be dominated by fossil fuels (Brodny and Tutak 2025; Fatur Šikić and Hodžić 2023). Supporting the "rebound" or "backfire" hypothesis in energy economics, efficiency and adaptation measures can sometimes lead to an increase in total energy demand over time. In contrast, the initial implementation of adaptation technologies may lead to a short-term decrease in fossil fuel use, as indicated by the REM estimates, which can be partially attributed to policy incentives, targeted efficiency programs, or substitution effects during the early deployment phases (Johnstone, Haščič, and Popp 2010; Sorrell 2009; York 2012). In the long term, these initial benefits are largely counterbalanced by the substantial structural and indirect energy needs associated with the widespread implementation of adaptation measures, thereby accounting for the positive long-run association. These findings reveal the intricate patterns of technological uptake, as climate adaptation technologies could decrease reliance on fossil fuels in the short term but may increase energy demand and dependence on fossil fuels in the long term unless complemented by a significant transition toward cleaner energy sources.

Conclusion and recommendations

This study aimed to investigate the factors underlying fossil fuel consumption in European economies, employing panel econometric methods that enable the identification of both short- and long-term dynamics. The analysis, utilizing ARDL, GMM, and REM estimators, offers consistent evidence that renewable energy deployment, alternative energy sources, technological advancements, and macroeconomic variables interact in complex ways to influence fossil fuel dependence. The findings offer several significant contributions to the existing body of knowledge on energy transitions and sustainability.

The dynamic ARDL results validate the long-lasting persistence of fossil fuel consumption, as evidenced by the highly significant coefficient on lagged FFC. This persistence is a result of structural path dependence, where sunk investments in fossil-based infrastructure, regulatory stagnation, and consumer habits keep economies locked into carbon-intensive routes. These discoveries align with the concept of "carbon lock-in," supporting the idea that decarbonization efforts are hindered by significant resistance, even in the most developed European economies. Consistently, renewable energy output cuts down on fossil fuel consumption across all specifications. This supports the substitution hypothesis, which suggests that expanding renewable energy sources displaces our reliance on fossil fuels, rather than just augmenting the overall energy supply. The consistency of this outcome across ARDL, GMM, and REM estimations highlights the pivotal position of renewable energy growth in Europe's shift to cleaner energy systems.

In addition, GDP per capita growth and foreign direct investment (FDI) have positive effects, suggesting that continued economic growth and capital inflows are leading to increased fossil fuel consumption. The dynamic in question mirrors the initial stages of the Environmental Kuznets Curve, wherein economic growth leads to increased energy consumption, and the "pollution haven" phenomenon related to foreign direct investment influxes. The implication is that growth and investment will continue to be linked to fossil energy in developed economies unless structural decoupling takes place. On the other hand, climate adaptation technologies show a mix of positive and negative effects. In the short term, CTA reduces fossil fuel use, which may be due to initial efficiency gains and encouragement of substitution. In the long term, CTA appears to be positively linked to reliance on fossil fuels, possibly due to rebound effects or the energy-intensive process of deploying adaptation infrastructure. These findings illustrate the dual nature of technological innovation; it can initially reduce energy intensity but may increase fossil fuel reliance unless accompanied by concurrent investment in clean energy provision.

The findings paint a nuanced picture of Europe's energy transition: while renewables and technological innovation are key drivers of decarbonization, structural fossil fuel dependence persists due to economic growth pressures, investment patterns, and the long-term energy costs of adaptation technologies. Achieving climate neutrality, therefore requires not only accelerating renewable integration through subsidies, grid investments, and market incentives, but also strategically directing economic growth and FDI toward green industries, coupling adaptation technologies with clean energy policies to prevent rebound effects, and implementing regulatory reforms that phase out fossil fuel subsidies and reduce carbon lock-in.

Disclosure statement

No potential conflict of interest was reported by the authors.

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