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GLOBAL BUSINESS AND POLICY DRIVERS SHAPING SUSTAINABLE ENERGY EFFICIENCY IN THE EUROPEAN UNION THROUGH THE ODEX LENS

Ramona VASILAS PIRVU [1✉], Roxana Maria BĂDÎRCEA [1], Elena JIANU [1,2], Laura Mariana CISMAȘ [3], Sorin TUDOR [1], Maria Eliza ANTONIU [2]

[1]*Faculty of Economics and Business Administration, University of Craiova, Craiova, Romania*
[2]*Faculty of Economic Sciences and Law, Pitești University Center, National University of Science and Technology Politehnica, Bucharest, Romania*
[3]*Faculty of Economics and Business Administration, West University of Timisoara, Timisoara, Romania*

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Abstract. This study explores the global business and policy determinants of sustainable energy efficiency across the 27 European Union member states from 2013 to 2023, using the ODEX index to measure aggregate progress in reducing energy intensity in industry, transport, and households. Based on balanced panel data from Eurostat, the World Bank, WIPO, and the Worldwide Governance Indicators, we apply fixed-effects and System GMM estimations to assess the contributions of foreign direct investment (FDI), per capita GDP growth, government effectiveness (GE), and the Global Innovation Index (GII), while controlling for the 2022 energy crisis. The results reveal strong persistence in energy efficiency patterns, a robust positive influence of the Global Innovation Index (GII), and a negative effect of GDP per capita growth through rebound mechanisms, which becomes statistically significant in the dynamic specification. Government effectiveness exerts a strong structural effect in the static model. These findings underscore the strategic role of innovation and governance in improving energy performance and inform EU policymakers on aligning investment, innovation, and institutional frameworks with the Union's 2030 energy efficiency and 2050 carbon-neutrality objectives.

Keywords: sustainable energy efficiency, ODEX index, foreign direct investment, economic growth, government effectiveness, global innovation index, European Union.

JEL Classification: O44, O33, F21.

✉Corresponding author. E-mail: ***ramona.pirvu@edu.ucv.ro***

1. Introduction

The European Union's transition to a low-carbon economy raises a fundamental question for international affairs and public policy research: what are the determinants of sustainable energy efficiency in member states, and to what extent do international capital flows, innovation capacity, and institutional quality act together to improve energy performance? Although recent literature has separately analyzed the role of foreign direct investment (FDI), economic growth, institutional quality, and innovation in relation to energy efficiency, an empirical integration of these factors into a unified framework, specifically applied to the 27 EU member states and measured by the ODEX indicator, remains absent. This study aims to fill this gap by empirically analyzing the relationships between FDI, GDP per capita growth, government effectiveness (GE) and the Global Innovation Index (GII) as determinants of sustainable energy efficiency in the EU-27 for the period 2013–2023, while providing practical insights for policymakers and managers in the context of the European Green Deal objectives, which aims to reduce primary energy consumption by at least 55% by 2030 and achieve climate neutrality by 2050 (Karasek et al., 2023).

From a *global business and policy perspective*, the European Union's transition toward sustainable energy efficiency reshapes *investment patterns*, *industrial competitiveness*, *and governance frameworks*. Understanding how international capital flows, innovation capacity, and institutional quality interact to influence energy outcomes is essential for aligning business strategies with the EU's Green Deal objectives. This dynamic requires a nuanced examination of the factors shaping sustainable energy efficiency, defined through the lens of the ODEX indicator – an energy efficiency index developed for monitoring energy efficiency and the implementation of EU policies, an aggregate tool that captures progress in dissipating energy intensity in sectors such as industry, transport, and housing (ODYSSEE-MURE, 2024). These factors highlight the pivotal role of foreign direct investments (FDI) in facilitating the transfer of clean technologies, the expansion of GDP per capita as a source of resources for green innovations, governmental effectiveness as an institutional anchor for policy implementation, and the Global Innovation Index (GII) as a catalyst for discoveries that diminish dependence on conventional resources. Recent studies, such as those by Osuma and Bonga-Bonga (2025), underscore the ambiguity of FDI effects on renewable consumption in EU member states, where capital inflows can initially accentuate dependence on traditional productive models before generating efficiency gains, suggesting the need for strict regulatory frameworks to direct investments toward projects with high potential for reducing energy intensity, while Török's analyses (2025) illustrate how economic growth, measured by GDP per capita, structurally supports the share of renewables through increased financial allocations, although intra-national temporal effects remain subtle, highlighting differentiation between states in absorbing these benefits.

This interconnection is not merely a matter of economic aggregation, but a profound one, in which FDI acts as a vehicle for technological spillovers, enabling the adoption of advanced managerial practices that optimize industrial processes and reduce losses in infrastructure, as highlighted in recent reports of the European Investment Bank (2026), which document the significant increase in financing for renewable energy and green infrastructure projects – a trend that can be further strengthened in the EU through alignment with energy efficiency directives. However, the duality of FDI – evidenced by Fang et al. (2024) in low-income countries, where investments aggravate structural transitions toward clean sources by perpetuating energy-intensive models – requires moderation through institutional quality, represented here by Government Effectiveness (GE) from the Worldwide Governance Indicators. According to Vatamanu et al. (2025), higher institutional quality enhances energy efficiency by promoting green investments and reducing aggregate inefficiencies. In parallel, the Global Innovation Index (GII) introduces an innovative dimension, capturing the capacity to generate solar patents or smart storage solutions. Alofaysan et al. (2024) show that a 1% increase in green patents improves energy efficiency by 0.0374 units, accelerating the integration of renewables into European networks, especially in the post-crisis period, where innovation proved essential for resilience (Eichhammer, 2024; World Intellectual Property Organization, 2024).

The central objective of our analysis is to examine the relationships between these factors in the EU-27 over the period 2013–2023, using balanced panel data from Eurostat, the World Bank, WIPO, and the Worldwide Governance Indicators. The study provides empirical insights into the direct and indirect effects of foreign direct investment (FDI), per capita GDP growth, government effectiveness (GE), and the Global Innovation Index (GII) on sustainable energy efficiency as measured by the ODEX index, while controlling for the 2022 energy crisis. Particular attention is given to the potential moderating role of institutional quality (GE) and to the risk of rebound effects associated with economic growth, thereby offering lessons for Green Deal policies that avoid rebound effects through integrated decarbonization strategies, as also emphasized by Lu et al. (2025) in their analysis of technology, resource efficiency, and innovation in Europe's low-carbon transition (European Commission, 2024a).

Unlike studies focused on BRICS, where Yan et al. (2024) emphasize FDI's role in adopting sustainable technologies under evolving institutions, adaptation to the EU context highlights intra-bloc heterogeneity, with states like Germany benefiting from superior innovative capacities compared to Eastern European ones, where deficiencies in GE slow progress, according to Hu et al. (2024). The innovative contribution lies in integrating GII as a distinct variable, rarely explored in the EU energy nexus, and using GE as a specific proxy for institutional quality, surpassing generic aggregates and capturing essential non-economic barriers, such as accountability in implementing directives, which allows a more granular perspective on persistent east-west disparities. Furthermore, this methodological approach – based on fixed-effects and System GMM estimations with robust Driscoll-Kraay standard errors – allows us to account for unobserved heterogeneity, persistence, and potential endogeneity, while providing a more nuanced understanding of the structural role of innovation (GII) and institutional quality (GE) in the EU energy efficiency nexus.

From the perspective of theoretical and international contributions, the present study brings several novel elements to the existing literature. First, it is the first empirical study that integrates the Global Innovation Index (GII) – as a distinct variable of innovation capacity – together with the ODEX indicator and government effectiveness (GE), in a dynamic panel framework applied to the EU-27. Previous studies, focused on BRICS contexts (Yan et al., 2024) or on global economies (Van Tran et al., 2025), do not capture the specificity of the European space, characterized by deep institutional integration and common decarbonization objectives. Second, the use of ODEX as a measure of energy efficiency is rare in the international panel literature, most studies resorting to more generic indicators such as energy intensity or the share of renewable sources – indicators that do not capture the multisectoral progress (industry, transport, households) that ODEX quantifies. Third, by combining static (fixed effects) and dynamic (System GMM) estimates and explicitly testing the moderating effect of GE, the study provides evidence on the structural versus dynamic role of governance – a distinction with direct implications for the design of European public policies.

Essentially, through the lens of ODEX, the study illuminates mechanisms that can transform the EU's energy challenges into opportunities for sustainable convergence, where economic expansion does not erode but potentiates resource resilience, contributing to a trajectory that aligns regional competitiveness with global environmental objectives, without sacrificing innovative potential or institutional stability.

The article's structure will follow a literature review, methodology detailing, results presentation, and implications for decision-makers, culminating in a synthesis that underscores the urgency of targeted interventions to accelerate the green transition in the Union's economic diversity. However, while the existing literature has separately analyzed FDI, economic growth, institutional quality and innovation in relation to energy efficiency, most studies focus on bilateral relations or examine these factors in isolation, often in global contexts or in BRICS countries. What is still missing is an integrated analysis of how these factors act together on sustainable energy efficiency in the specific space of the European Union with 27 Member States, especially when efficiency is measured by the ODEX index over the period 2013–2023, which also includes the impact of the 2022 energy crisis. In this study, we aim to address exactly this gap by integrating the Global Innovation Index (GII) as a distinct variable, reflecting the capacity to diffuse green technologies, and by examining Government Effectiveness (GE) not only as an independent factor but also as a potential moderator of the relationships. We believe that this integrated approach allows us to better understand intra-European heterogeneity, in particular the persistent differences between Western and Eastern states. Thus, we hope that our results will provide useful practical information for European policymakers, contributing to better aligning investment, innovation and public policies with the Green Deal objectives, avoiding rebound effects and supporting a more balanced convergence in energy performance across the Union.

2. Literature review

The interaction between foreign direct investment, economic growth, institutional quality, and the Global Innovation Index—examined through the ODEX indicator—offers valuable insight into how these factors shape the European Union's shift toward a low-emission economy. This perspective helps identify mechanisms that can improve energy resource efficiency and support the EU's 2030 emission-reduction and 2050 climate-neutrality goals, while accounting for the economic and institutional differences among member states.

The Role of FDI in Advancing Sustainable Energy Efficiency in the European Union

Foreign direct investment (FDI) contributes significantly to strengthening sustainable energy efficiency within the European Union by promoting the spread of cleaner technologies and modern management approaches that curb energy use across key industries. In doing so, FDI supports the modernization of production systems and infrastructure, though its outcomes vary among member states depending on their capacity to absorb external capital and align investments with sustainability objectives (United Nations Conference on Trade and Development [UNCTAD], 2025). Recent studies indicate a U-shaped nonlinear relationship between foreign direct investments (FDI) and renewable energy consumption globally, suggesting that FDI can initially increase dependence on conventional sources before favoring the transition to energy efficiency, with implications for EU states where interaction with economic growth amplifies these effects (Van Tran et al., 2025). In the context of EU policies, energy efficiency is integrated into decarbonization efforts, where the "energy efficiency first" principle contributes to CO_2 emission reductions by prioritizing efficient measures, although globalization can increase emissions through intensive trade, requiring adjustments in national strategies (von Malmborg, 2025).

This duality of FDI is also highlighted by empirical analyses examining their effects on renewable energy consumption in 20 EU countries over the period 2013–2023, where the use of multiple mobile quantile regression methods demonstrates a negative impact of FDI on the share of renewables in total energy consumption (Osuma & Bonga-Bonga, 2025). In parallel, recent evaluations of FDI's influence on energy consumption structure reveal a more pronounced negative effect in low-income EU countries, where foreign investments aggravate the structural transition toward renewables by accentuating dependence on traditional productive models, suggesting that, to counteract these trends, member states should prioritize institutional capacities that filter capital inflows in favor of projects with high potential for energy efficiency (Fang et al., 2024).

Furthermore, research integrating FDI into the optimal energy mix for the EU underscores the absence of a significant impact of foreign investments on diversifying renewable sources, highlighting the gap between capital flows and sustainability objectives, which imposes strategic adjustments such as incentivizing investments in storage infrastructure and smart grids to transform FDI into effective drivers of energy intensity reduction (Osuma & Yusuf, 2025).

The Role of Economic Growth in the EU's Energy Efficiency

Economic growth in the EU interacts with sustainable energy efficiency by providing resources for investments in green infrastructures, such as energy distribution networks that reduce losses, although uncontrolled growth can increase energy consumption if not accompanied by efficiency policies (EU DSO Entity, 2025). National energy and climate plans, which integrate economic growth with efficiency targets, highlight the need for substantial investments to achieve reductions in energy consumption through balanced financial allocations between public and private sources (European Commission, 2025). Economic growth supports energy efficiency through the expansion of clean electricity production, which has reached record shares in the EU, reducing emissions and optimizing consumption, although stagnant demand underscores the need for electrification to maximize benefits (Ember, 2025).

In the EU context, Soto and Martinez-Cobas (2025), through an examination of the 2004-2022 period on outbound foreign direct investments, reveal that these do not favor renewable energy penetration, explainable by the relocation of domestic capital and filtering of energy-intensive investments, which implies a need for progressive taxes based on dependency levels and investment periods to prevent declines in energy productivity and support sustainable economic growth. Džogan et al. (2025) show that in lower-income EU countries, FDI efficiency increased during the early pandemic period (2019–2020), attributed to managerial improvements and expansionary policies that maintained capital flows despite economic shocks, enabling resilience that links economic growth to more efficient use of energy resources, unlike in more developed states where market saturation slowed such benefits. Török (2025) finds that economic growth, expressed through GDP per capita, is structurally linked to the expansion of renewable energy in the European Union, as higher income levels create the financial space for investments in efficient infrastructure. However, the effects within individual countries remain modest in the short run, suggesting that growth differentiates states rather than directly driving energy efficiency. Similarly, Jóźwik et al. (2024) show that, between 1995 and 2021, both renewable and non-renewable energy use are connected to economic growth in EU economies, with renewables displaying a weaker yet positive association, while fossil-based consumption maintains a stronger two-way relationship with GDP. Positive shocks in the circular economy index demonstrate amplified benefits in economies with high performance in clean energy, with elasticity coefficients increasing across quantiles, indicating that nations with established renewable infrastructure optimally capitalize on circular economy improvements through synergistic effects (Bergougui & Ben-Salha, 2025).

Institutional Quality and Sustainable Energy Efficiency

In the context of the transition to a green economy at the European Union level, the relationship between institutional quality (Institutional Quality – IQ) and sustainable energy efficiency (Sustainable Energy Efficiency – SEE) has attracted the attention of researchers in recent years, especially in light of the objectives of the European Green Deal. Recent empirical studies demonstrate a positive and significant relationship between IQ and energy efficiency in EU countries. For example, Vatamanu et al. (2025) analyze panel data from 27 EU countries for the period 2000–2020 and show that improvements in IQ, combined with renewable energy consumption, lead to an increase in energy efficiency by promoting investments in green technologies and reducing inefficient consumption. Similarly, a panel analysis for the period 1996–2014 in 14 European countries (Barra et al., 2025) highlights that IQ reduces aggregate economic inefficiency, including in energy sectors, through the key role of regulation quality and accountability, which facilitates the implementation of EU energy efficiency directives. This relationship is explained by the mechanism of "institutional spillover": efficient governments ensure the application of EU directives (e.g., Energy Efficiency Directive 2012/27/EU), facilitating the transfer of knowledge and resources to economic sectors.

The literature underscores IQ's role as a moderator in the energy-environment nexus. A recent study on EU countries (Ayoungman et al., 2025) demonstrates that IQ enhances the impact of human capital and financial development on SEE, by reducing corruption risks that divert funds intended for energy efficiency projects, with non-linear effects observed in countries with moderate IQ. In the EU context, where east-west disparities persist, countries such as Romania or Bulgaria, with lower GE scores, record slower progress in SEE compared to Germany or Sweden, where IQ supports the rapid implementation of targets to reduce energy consumption by 32.5% by 2030 (Hu et al., 2024). This dynamic is amplified by interaction with economic growth: a rising GDP per capita, moderated by high IQ, accelerates the transition to sustainable consumption models, avoiding the "rebound effect" (increase in consumption due to improved efficiency) (Li et al., 2020).

The Role of Innovation in Sustainable Energy Efficiency

Recent literature highlights a robust positive link between innovation – whether through green patents, R&D expenditures, or digital technologies – and energy efficiency, emphasizing how innovation drives technological advances that contribute to achieving the European Green Deal targets of improving energy efficiency by at least 32.5% by 2030 (European Commission, 2024b). Empirical studies from the 2023–2025 period consistently demonstrate that higher innovation scores correlate with improved SEE outcomes in EU member states (Alofaysan et al., 2024). Similarly, a quantile regression model at the provincial level in China indicates that technological innovation (TI) has a major impact on increasing renewable energy consumption (REC), by lowering technological costs and improving the performance of systems using renewable energy sources (Chu et al., 2025). In the context of the 2022 energy crisis, innovation's role in accelerating the integration of renewable sources – through advances in smart grids and energy storage – was essential, contributing to a better ranking of nations with high innovation, such as Germany (Eichhammer, 2024).

Hypotheses development

Based on the reviewed literature and analytical context, the following testable hypotheses are formulated, targeting the interactions between key variables and sustainable energy efficiency in EU-27:

H1: *Foreign direct investments* (*FDI*) *exert a significant positive impact on sustainable energy efficiency*, *measured by ODEX*. This hypothesis starts from the premise that FDI can facilitate the transfer of clean technologies and the modernization of managerial practices in energy-intensive industrial sectors. However, the empirical literature reveals ambiguous effects: some studies document a negative impact of FDI on renewable energy consumption in EU countries, especially in economies with low absorptive capacity (Osuma & Bonga-Bonga, 2025; Fang et al., 2024), while others emphasize the potential of FDI to generate positive technological spillover effects when directed towards sectors with high technological intensity (Yan et al., 2024; Van Tran et al., 2025). In the EU context, where the common regulatory framework and energy efficiency directives create structural incentives for green investments, we expect the net effect of FDI to be positive, albeit of moderate amplitude and conditional on the institutional quality of the host state.

H2: *GDP per capita growth positively influences ODEX*. The relationship between economic growth and energy efficiency is fundamentally dual. On the one hand, higher GDP per capita generates additional financial resources for investments in green infrastructure and efficient technologies, supporting the energy transition in the long term (Török, 2025; Jóźwik et al., 2024; Bergougui & Ben-Salha, 2025). On the other hand, rapid economic expansion tends to amplify energy demand, generating the rebound effect, whereby efficiency gains are partially or completely cancelled out by increased consumption (Li et al., 2020; Ma & Li, 2025). In the context of the EU-27, where energy efficiency policies are implemented unevenly across Member States, we expect the effect of GDP per capita growth on ODEX to be negative in the short term – dominated by the rebound effect – and positive in the long term, in the presence of institutional decoupling mechanisms.

H3: *Government Effectiveness* (*GE*) *has a positive effect on sustainable energy efficiency* (*ODEX*) *and may moderate the relationships between FDI*, *GDP growth and energy efficiency*. This hypothesis draws on studies showing that higher institutional quality facilitates the implementation of energy efficiency policies, promotes green investments, and reduces inefficiencies (Vatamanu et al., 2025; Barra et al., 2025; Hu et al., 2024). Effective governance is expected to create a more favorable environment for translating FDI and economic growth into energy efficiency gains, particularly in the heterogeneous EU context.

H4: *The Global Innovation Index* (*GII*) *has a positive effect on ODEX*. Recent studies indicate a strong link between innovation capacity and improving energy efficiency, through the development of green patents, smart storage solutions and the optimization of industrial processes (Alofaysan et al., 2024; Eichhammer, 2024; Chu et al., 2025). We believe that, in the European context, a higher GII score contributes significantly to accelerating the transition to a low-energy economy.

Although the existing literature provides a solid foundation, it also has some important limitations. Many studies report contradictory effects of FDI on energy efficiency – some highlight benefits through technology transfer, while others report negative or ambiguous effects, especially in countries with low institutional capacity. Similarly, the relationship between economic growth and efficiency remains controversial, with clear evidence of a rebound effect contradicting the hypothesis of an automatic positive impact. Most research focuses on bilateral relations or non-European contexts, leaving the complex interaction between innovation, governance and energy efficiency in the specific EU-27 framework unexplored. These gaps and contradictions justify the need for an integrated approach, as we propose in this study.

3. Methodology and data used

The empirical analysis of this study is based on a balanced panel dataset comprising 27 European Union member states (EU-27) for the period 2013–2023, totaling 296 observations. This design allows for the simultaneous capture of temporal and cross-sectional variations, providing a comparative perspective on energy efficiency dynamics and convergence across countries. A dummy variable (D2022) was constructed, taking the value 1 for the year 2022 and 0 for other years, to capture the effect of the energy crisis. The variables used are detailed in Table 1, which includes symbols, full names, sources, and descriptions.

Table 1. Variables description and data sources

Variable	Acronym	Definition	Variable Type	Source
ODEX Index	ODEX	Measures energy efficiency for each country, expressed as a percentage, with the year 2000 as the reference year.	Dependent	ODYSSEE-MURE Database
Foreign Direct Investment Stock	FDI	Stock of foreign direct investment as a percentage of GDP.	Independent	Eurostat
GDP per Capita Growth Rate	GDP_growth	Annual percentage variation in GDP per capita.	Independent	Eurostat
Government Effectiveness Index	GE	Reflects the quality of institutional performance and public governance.	Independent	Worldwide Governance Indicators
Global Innovation Index	GII	Measures a country's innovation capacity and performance.	Independent	World Intellectual Property Organization (WIPO)
Energy Crisis Dummy (2022)	D2022	Takes the value 1 for the year 2022 and 0 otherwise, capturing the effect of the energy crisis.	Dummy	Author's definition

Although the 27 Member States of the European Union form an economic and political union with common objectives set out in the European Green Deal, they present considerable differences in macroeconomic, institutional and structural-energy terms. These disparities are visible in the distribution of the variables used in the analysis: the ODEX index varies between 57.6 and 89.4, the Global Innovation Index (GII) between 34.1 and 64.2, government effectiveness (GE) between −0.29 and 2.18, GDP per capita growth between −11.39% and 23.44%, and the FDI stock between 10.1 and 6,729.5 billion euros (see Table 2). However, the comparability of the countries included in the analysis is justified from at least three perspectives. First, all Member States report the ODEX index through the same methodological protocol of the ODYSSEE-MURE database, which ensures the consistency of the measurement of the dependent variable. Second, all 27 economies are subject to the same European energy efficiency policy framework, including the Energy Efficiency Directive and the objectives of the European Green Deal, which creates a common institutional basis. Third, structural heterogeneity is controlled econometrically through the fixed effects estimator, robust Driscoll-Kraay standard errors and the System GMM model, which addresses both the persistence of energy efficiency and the potential endogeneity of the variables. Thus, the panel approach manages the existing heterogeneity rather than ignoring it.

The adopted methodology integrates advanced econometric tools for panel data analysis, capable of addressing cross-sectional dependence, autocorrelation, and endogeneity, following a sequential structure illustrated in Figure 1.

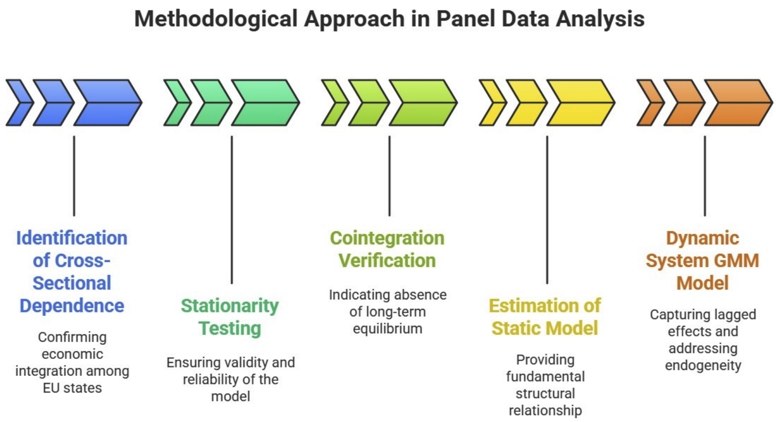

Figure 1. Representation of the methodological process

In the first stage, cross-sectional dependence is assessed using the Pesaran CD test, complemented by the Breusch–Pagan LM and Pesaran Scaled LM statistics, which are particularly suitable for panels with a large cross-sectional dimension and a relatively short time period (N = 27 > T = 11). Subsequently, the stationarity of the variables is examined through Pesaran's (2007) CIPS and CADF tests, which explicitly account for cross-sectional dependence effects. The pooled OLS estimator was not retained in the final analysis, as it does not account for unobserved country-specific heterogeneity, which represents a critical feature in the European Union context, where structural, institutional, and technological differences across member states play a fundamental role in shaping energy efficiency outcomes. To verify the existence of a long-run equilibrium relationship, the Pedroni (1999) cointegration test is employed, as it is robust to both heterogeneity and interdependence across cross-sections.

During the estimation phase, a static panel model with fixed effects is used to control for structural heterogeneity across countries and years, specified as follows:

$$ODEX_{it} = \beta_0 + \beta_1 FDI_{it} + \beta_2 GDP_{it} + \beta_3 GE_{it} + \beta_4 GII_{it} + \beta_5 D2022_t + \mu_i + \tau_t + \varepsilon_{it}, \quad (1)$$

where μ_i represents country-specific effects, τ_t captures year-specific effects, and ε_{it} denotes the idiosyncratic error term.

To capture persistence and correct for potential endogeneity, a dynamic System GMM model (Arellano–Bover/Blundell–Bond, 1998) is subsequently estimated, expressed as:

$$\begin{aligned} ODEX_{it} = \alpha_0 + \alpha_1 ODEX_{i,t-1} + \alpha_2 ODEX_{i,t-2} + \beta_1 FDI_{it} + \\ \beta_2 GDP_{it} + \beta_3 GE_{it} + \beta_4 GII_{it} + \beta_5 D2022_t + \varepsilon_{it}. \end{aligned} \quad (2)$$

The instruments employed include lagged endogenous variables (@DYN(ODEX,−2)) and the levels of exogenous variables (@LEV(FDI, GDP, GE, GII, D2022)), with robust standard errors computed using the White period method. Instrument validity is evaluated through the J-statistic. All estimations were performed in EViews 12, with fully reproducible codes available upon request.

To test hypothesis H3 regarding the moderating role of Government Effectiveness (GE), we included interaction terms between the independent variables and GE in the additional analyses. Specifically, we estimated extended specifications of both fixed effects and System GMM models, in which we introduced the interaction terms FDI × GE and GDP_growth × GE. This approach allows us to assess whether higher institutional quality (GE) amplifies or attenuates the effect of foreign direct investment and economic growth on energy efficiency measured by ODEX. Interpreting the interaction coefficients helps us understand to what extent effective governance acts as a catalyst for energy efficiency policies in the heterogeneous context of the European Union.

The choice between the fixed-effects and random-effects specifications was formally assessed through the application of the Hausman test, whose results are presented and discussed in the empirical analysis section, thereby ensuring that the final model selection is grounded in both statistical rigor and the structural characteristics of the dataset. The results of which are presented in the empirical analysis section indicated correlation between country-specific effects and explanatory variables, making the random-effects estimator inconsistent. The System GMM estimator was used to deal with the persistence of energy efficiency and possible endogeneity issues. The Levin-Lin-Chu (LLC) and Im-Pesaran-Shin (IPS) stationarity tests showed a mixed order of integration for the variables. Although this situation may complicate the analysis, the combination of robust Driscoll-Kraay techniques with the Pedroni cointegration test ensures valid inferences in the integrated EU context.

The analyzed period 2013–2023 was chosen because it provides consistent and comparable data for the ODEX index across all EU member states, covers the implementation stage of the main European directives on energy efficiency, and allows the inclusion of the effect of the 2022 energy crisis through the dummy variable D2022.

The methodological structure, depicted in Figure 1, ensures the robustness and internal consistency of the analysis, providing a comprehensive and realistic understanding of the determinants of energy efficiency across the EU-27 by incorporating both cross-sectional dependence and short-term dynamics.

4. Empirical analysis and results

4.1. Descriptive statistics

The descriptive statistics presented in Table 2 provide an initial overview of the main variables included in the empirical analysis, capturing their central tendencies, variability, and distributional characteristics across the 27 EU member states over the 2013–2023 period. This statistical summary serves as the foundation for understanding the underlying patterns of energy efficiency, investment, innovation, and institutional quality in the European context, before proceeding to more advanced econometric estimations.

For the Global Innovation Index (GII), the mean value of 48.38 and the relatively high variability (Std. Dev. = 7.53) reveal important differences in innovation capacity and technological competitiveness within the EU. Northern economies such as Germany, Sweden, and Finland continue to lead in research and development, while the Government Effectiveness (GE) index, with a mean of 1.03, confirms generally strong institutional quality across the Union, albeit with persistent gaps between regions.

Table 2. Summary of descriptive statistics for the main variables (2013–2023, EU Panel) (source: author's computation based on EViews output)

Statistic	ODEX	GII	GE	GDP	FDI
Mean	73.90	48.38	1.03	2.22	386.82
Median	74.50	47.85	1.03	2.10	55.45
Maximum	89.40	64.20	2.18	23.44	6729.50
Minimum	57.60	34.10	–0.29	–11.39	10.10
Standard Deviation	7.04	7.53	0.55	3.79	1049.28
Skewness	–0.25	0.23	–0.24	0.29	4.10
Kurtosis	2.48	2.07	2.35	7.21	20.68
Jarque–Bera	6.42	13.16	8.00	222.52	4686.13
Probability (JB)	0.04	0.00	0.02	0.00	0.00
Observations	296	296	296	296	296

The GDP variable displays an average growth rate of 2.22%, yet its large range from –11.39 to 23.44 points to macroeconomic volatility caused by external shocks and crisis periods. In contrast, Foreign Direct Investment (FDI) shows extreme dispersion (mean = 386.82; Std. Dev. = 1049.28), indicating high concentration of capital flows in a few countries such as Luxembourg, Ireland, and the Netherlands. Overall, the Jarque–Bera probabilities below 0.05 suggest mild deviations from normality, which justifies the use of robust estimation techniques in the following econometric analysis.

4.2. Cross-sectional dependence test

Prior to estimating any econometric specification, it was imperative to assess whether the dataset exhibited cross-sectional dependence—reflecting the degree to which economic developments in one country are connected to those in others within the panel. Given the European Union's deep policy and market integration, assuming independence among member states would be both unrealistic and potentially misleading for the validity of results. To verify this, three complementary diagnostics were applied: the Breusch–Pagan LM, Pesaran scaled LM, and Pesaran CD tests, each capturing distinct forms of interdependence among countries.

Table 3. Residual cross-section dependence test (source: author's calculations based on EViews output, 2025)

Test	Statistic	d.f.	Prob.
Breusch-Pagan LM	2708.174	351	0.0000
Pesaran scaled LM	88.96582		0.0000
Pesaran CD	50.87143		0.0000

The results of Table 3 strongly reject the null hypothesis of independence, as all probability values are below 0.05 ($p = 0.0000$), confirming that the residuals across EU countries are highly correlated. This suggests that economic, institutional, and energy-related dynamics move together within the Union. Progress in energy reforms or increases in foreign investment within one member state often produce spillover effects through trade, regulatory, and innovation channels. Such interconnectedness is structural rather than incidental, rooted in the EU's shared policy environment and mechanisms like the Green Deal and cohesion funding. The presence of strong cross-sectional dependence justifies the use of second-generation panel techniques, such as the CIPS and CADF tests, which explicitly account for cross-country correlation and ensure consistent results in integrated economic systems. Ultimately, these findings confirm that the European Union operates as an interdependent network in which investment, governance, and innovation jointly drive sustainable energy efficiency.

4.3. Panel unit root tests

Assessing the stationarity of the variables represents a key step in ensuring the reliability of panel estimations. In this context, stationarity tests help distinguish between variables affected by persistent structural forces and those fluctuating around a stable mean. Given the interdependence of European Union economies, macroeconomic and institutional indicators are expected to evolve jointly rather than independently over time. Two complementary procedures were applied – Levin, Lin & Chu (LLC) and Im, Pesaran & Shin (IPS) – capturing both common trends and country-specific effects within the dataset.

The results (Table 4) reveal heterogeneous dynamics among variables. Energy efficiency (ODEX) appears non-stationary across both tests, suggesting that variations stem from gradual structural transformations – modernization of infrastructure, diffusion of renewables, and policy reforms – rather than cyclical fluctuations.

Table 4. Panel unit root tests (LLC and IPS) for the main variables, 2013–2023 (source: author's computation based on EViews output)

INDICATOR	LLC		IPS	
METHOD	STATISTIC	PROB.	STATISTIC	PROB.
ODEX	0.89387	0.8143	6.00561	1.0000
FDI	–3.91356	0.0000	0.02218	0.5088
GE	–1.79665	0.03624	0.32865	0.6288
GII	2.57137	0.9949	2.69880	0.9965
GDP	–11.5074	0.0000	–6.34564	0.0000

Foreign direct investment (FDI) exhibits clear stationarity under the LLC test ($p < 0.01$), indicating that investment flows stabilize over time as market integration and regulatory predictability reinforce investor confidence. The milder IPS result suggests adjustment differences across member states, with Western economies generally adapting faster than Eastern ones. Government effectiveness (GE) lies near the boundary of stationarity—significant in LLC but neutral in IPS—consistent with the slow evolution of institutional capacity shaped by administrative reforms and governance inertia. The Global Innovation Index (GII) remains non-stationary, following a long-term path influenced by cumulative R&D investment, human capital formation, and technological diffusion. Conversely, GDP shows firm stationarity under both tests, confirming that EU economic growth reverts to equilibrium after temporary shocks, supported by coordinated fiscal and monetary mechanisms. Overall, these results reveal a structural duality: some indicators, such as GDP and FDI, display short-term stabilization tendencies, while others, like ODEX and GII, evolve along persistent trajectories driven by long-term technological and institutional change. This heterogeneity provides the rationale for the subsequent cointegration analysis, aimed at identifying potential long-run equilibrium relationships among the core variables.

4.4. Panel cointegration test

After confirming the mixed stationarity of the variables, the next analytical step explores whether long-run equilibrium relationships exist among them. The Pedroni residual cointegration test was employed, as it accommodates heterogeneity and cross-sectional dependence across EU member states, making it appropriate for integrated macroeconomic panels. The test evaluates both the within-dimension (panel statistics) and between-dimension (group statistics) components to identify shared long-term dynamics among energy efficiency (ODEX), investment (FDI), growth (GDP), institutional quality (GE), and innovation (GII) (Table 5).

Table 5. Pedroni panel cointegration test results (2013–2023) (source: author's computation based on EViews output)

Pedroni residual cointegration test							
Alternative hypothesis: common AR coefs. (within-dimension)					Alternative hypothesis: individual AR coefs. (between-dimension)		
	Statistic	Probability	Weighted Statistic	Probability		Statistic	Probability
Panel v-Statistic	37.55	0.00	24.10	0.00	Group rho-Statistic	8.37	1.00
Panel rho-Statistic	6.52	1.00	6.03	1.00	Group PP-Statistic	3.77	0.99
Panel PP-Statistic	4.12	1.00	1.66	0.95	Group ADF-Statistic	4.46	1.00
Panel ADF-Statistic	3.35	0.99	4.47	1.00			

The results indicate no evidence of cointegration among the variables, as most statistics are insignificant and fail to reject the null hypothesis of no long-run relationship. This outcome suggests that movements in energy efficiency, innovation, and institutional quality do not converge toward a shared equilibrium during the 2013–2023 period. Such divergence may reflect asymmetric policy responses, varying levels of technological development, and heterogeneous investment absorption capacities across the European Union.

The absence of long-term cointegration does not imply the lack of interdependence but rather emphasizes the dynamic and adaptive nature of the European energy and economic landscape. Persistent differences in structural transformation, innovation capacity, and governance efficiency continue to shape each country's adjustment path. Consequently, short- and medium-term effects may dominate, justifying the subsequent use of dynamic estimation methods such as the System GMM, which capture lagged interactions and endogeneity within the EU context.

4.5. Correlation and covariance analysis

In order to explore the internal consistency and interdependence among the selected indicators, a covariance analysis was performed for all variables in the model: the overall Energy Efficiency Index (ODEX), the Global Innovation Index (GII), Government Effectiveness (GE), Gross Domestic Product growth (GDP), and Foreign Direct Investment (FDI). This diagnostic step helps identify the extent to which fluctuations in one variable correspond to changes in another, offering preliminary insight into potential linear associations before formal econometric testing. In the context of the European Union, where investment, innovation, and institutional performance are interconnected through shared policies and sustainability objectives, such relationships are particularly informative.

Table 6. Covariance analysis – all Indicators (2013–2023) (source: author's computation based on EViews output)

INDICATOR	ODEX	GII	GE	GDP	FDI
ODEX	49.37	26.16	1.96	–5.42	826.85
GII	26.16	56.54	3.55	–4.43	1325.94
GE	1.96	3.55	0.31	–0.39	125.05
GDP	–5.42	–4.43	–0.39	14.31	–212.94
FDI	826.85	1325.94	125.05	–212.94	1097266.15

In the Table 6 the covariance matrix highlights several notable relationships among the analyzed variables. The strong positive association between ODEX and GII (26.16) indicates that greater innovation capacity aligns with improvements in energy efficiency, confirming that sustained technological progress supports long-term sustainability performance. Likewise, the positive but modest covariance between ODEX and GE (1.96) implies that more effective governance fosters the stability and coherence necessary for implementing energy policies.

In contrast, GDP displays a negative covariance with both ODEX (−5.42) and GII (−4.43), suggesting that periods of rapid growth are often linked with increased energy consumption and higher resource intensity. This pattern underscores the structural challenge within EU economies, where industrial expansion continues to depend on energy demand despite ongoing decarbonization efforts.

The magnitude of covariance involving FDI—especially with GII (1325.94) and ODEX (826.85)—reveals substantial variability in foreign capital flows across the Union. Such dispersion likely reflects divergent investment priorities and the uneven presence of high-technology sectors. While volatility in FDI inflows may obscure short-term efficiency effects, targeted investment in innovation-driven industries could significantly enhance energy performance over time.

The covariance structure portrays a system where innovation and governance operate as stabilizing forces, while economic expansion and volatile FDI introduce asymmetry into energy efficiency outcomes. These preliminary findings validate the use of advanced estimation models—specifically the Fixed Effects and System GMM frameworks—to untangle causal links and correct for endogeneity among the examined variables.

4.6. Static panel estimation and model selection

The fixed-effects estimation captures the interplay between economic, institutional, and innovation-related drivers shaping the European Union's energy efficiency between 2013 and 2023. By controlling for unobserved country-specific effects, the model isolates the structural contribution of each determinant while preserving temporal consistency. With an R-squared (within) of approximately 0.90, the model explains a substantial portion of the variation in ODEX.

Table 7. Fixed effects panel estimation results (dependent variable: ODEX, 2013–2023) (source: author's computation based on EViews output)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	35.36098	3.642460	9.707993	0.0000
FDI	0.000550	0.000658	0.834792	0.4046
GDP	–0.040238	0.039194	–1.026635	0.3055
GE	4.940265	1.095810	4.508323	0.0000
GII	0.688850	0.076860	8.962435	0.0000

Note: R-squared (within): 0.900784. F-statistic: 80.19800 ($p < 0.01$).

To choose between fixed-effects and random-effects specifications, we applied the Hausman test. The test rejects the null hypothesis that the random-effects estimator is consistent (Chi-square = 15.501646, df = 4, Prob. = 0.0038). This result indicates that the unobserved country-specific effects are systematically correlated with the explanatory variables (particularly GE and GII), making the random-effects model inconsistent. Consequently, the fixed-effects specification is preferred, as it provides consistent estimates by controlling for time-invariant heterogeneity across EU member states.

In this specification, in the Table 7, Government Effectiveness (GE) and the Global Innovation Index (GII) have positive and highly significant coefficients, confirming their important structural role in improving energy efficiency. Conversely, FDI and GDP per capita growth are statistically insignificant. The negative sign on GDP_growth, although not significant, is consistent with the existence of a potential rebound effect documented in the literature (Li et al., 2020; Ma & Li, 2025). This result aligns with previous findings showing that FDI can have ambiguous or even negative effects on energy efficiency in certain contexts due to the heterogeneity of investment flows (Yang & Li, 2019; Awodumi, 2021; Wang & Shao, 2023). Although the static fixed-effects model highlights important structural relationships, it does not account for the persistence of energy efficiency or potential endogeneity. Hence, we proceed with a dynamic System GMM estimation.

4.7. Dynamic panel estimation – system GMM

To capture the dynamic nature of energy efficiency, its persistence, and to address potential endogeneity issues, we estimate a System Generalized Method of Moments (System GMM) model (Table 8). The model includes two lags of the dependent variable and employs internal instruments.

Table 8. System GMM estimation results (dependent variable: ODEX, 2013–2023) (source: author's computation based on EViews output)

Variable	Coefficient	Std. Error	t-Statistic	Prob.
ODEX(–1)	1.5732	0.0516	30.48	0.0000
ODEX(–2)	–0.6263	0.0400	–15.66	0.0000
FDI	0.0001	0.0004	0.34	0.7350
GDP	–0.0156	0.0027	–5.90	0.0000
GE	0.0241	0.2828	0.09	0.9329
GII	0.1160	0.0184	6.29	0.0000
D2022	0.7299	0.7984	0.91	0.3691

Note: J-statistic: 20.43 ($p = 0.43$), Number of instruments: 27, S.E. of regression: 0.55.

The results confirm strong persistence in energy efficiency. More importantly, GDP per capita growth now shows a statistically significant negative effect ($\beta = -0.0156$, $p < 0.01$). This finding, which was not significant in the static model, provides clearer evidence of rebound effects. By accounting for persistence in the dependent variable and potential endogeneity, the dynamic model reveals that short-term economic expansion tends to increase energy demand, partially offsetting efficiency gains. In contrast, Government Effectiveness (GE) loses statistical significance in the dynamic specification, suggesting that its influence is primarily structural and long-term, largely absorbed by country fixed effects. The Global Innovation Index (GII) remains positive and highly significant in both models, underscoring its central role as the key driver of sustainable energy efficiency through green technological spillovers.

5. Discussion

The results of this study provide a coherent picture of how innovation, governance and economic growth shape sustainable energy efficiency in the EU-27. The most robust result is the positive and strongly significant influence of the Global Innovation Index (GII) on ODEX, confirmed in both the static fixed-effects model and the dynamic System GMM specification. This consistency suggests that technological innovation – embodied in green patents, smart storage solutions and the diffusion of clean technologies – represents a structural, not just cyclical, driver of European energy performance. The result converges with the findings of Alofaysan et al. (2024) and Chu et al. (2025), who document a positive link between innovation capacity and energy efficiency, but extends this evidence beyond national or regional samples to the entire EU-27 space, capturing simultaneously the structural and dynamic dimensions of the relationship.

A second central result concerns the rebound effect associated with GDP per capita growth. While the static model shows a negative but insignificant coefficient for GDP_growth, the System GMM specification reveals a negative and strongly significant effect ($\beta = -0.0156$, $p < 0.01$). This change from insignificant to significant when controlling for persistence and endogeneity constitutes an important empirical contribution: it shows that the rebound effect is not visible in simple static analyses, but becomes evident only when the dynamics of energy efficiency are correctly modeled. The result confirms the mechanism theoretically described by Li et al. (2020) and Ma and Li (2025), but documents it empirically, with recent data (2013–2023), at the level of the entire Union – an aspect rarely captured in the existing literature, which is mainly focused on the BRICS context or on individual economies.

Regarding government effectiveness (GE), the results reveal an interesting dissociation between the short and the structural time horizon: GE has a positive and strongly significant effect in the static fixed-effects model, but loses its statistical significance in the dynamic specification. This finding does not contradict the literature emphasizing the role of institutional quality (Vatamanu et al., 2025; Barra et al., 2025; Hu et al., 2024), but rather qualifies it: the effects of governance seem to be largely absorbed by country fixed effects, suggesting that GE acts more as a structural factor, institutionally "frozen" in the long term, than as a determinant with a dynamic impact year by year. This distinction between the structural and the dynamic role of governance represents one of the original contributions of the study, as most previous research does not explicitly separate the two components.

Regarding foreign direct investment (FDI), the results indicate a statistically insignificant effect in both specifications, which is consistent with the literature documenting ambiguous or conditional effects of FDI on energy efficiency (Osuma & Bonga-Bonga, 2025; Fang et al., 2024; Yang & Li, 2019). The absence of a significant effect in the EU-27 context suggests that, unlike in other regions of the world, the common institutional framework and European energy efficiency directives may sufficiently level the playing field that the mere presence of foreign capital is no longer, in itself, a differentiating factor—FDI flows seem to be "neutralized" by the common regulatory context, rather than directly transformed into efficiency gains. Taken together, these results support the novelty of the study: it is the first research that simultaneously integrates GII, ODEX and GE – both as a direct factor and as a possible moderator – in a dynamic panel framework applied exclusively to the EU-27, compared to previous studies focused on BRICS (Yan et al., 2024) or on heterogeneous global economic samples (Van Tran et al., 2025). Combining static and dynamic estimates allows the separation of structural effects (GE) from dynamic and persistent ones (GII, the rebound effect), providing a more faithful picture of how governance, innovation and economic growth interact concretely in the European space.

6. Conclusions and implications

This study examined the global business and policy drivers shaping sustainable energy efficiency across the 27 European Union member states from 2013 to 2023, using the ODEX index as a comprehensive multisectoral measure. The results demonstrate that technological innovation capacity, captured by the Global Innovation Index, is the most reliable and consistent driver of energy efficiency improvements. Institutional quality plays an important structural role, while economic growth exhibits a clear rebound effect that becomes evident when persistence is accounted for. Foreign direct investment does not exert a significant direct influence, pointing to the need for better alignment with sustainability objectives. From a theoretical perspective, the study contributes to the energy economics and sustainability literature by integrating the Global Innovation Index into a unified dynamic panel framework applied specifically to the EU-27. It advances understanding of the rebound effect in developed, highly integrated economies and illustrates the value of distinguishing between structural (long-term) and dynamic (short-term) effects of governance and growth. The use of the ODEX index, rather than more generic energy-intensity or renewable-share indicators, offers a more granular view of multisectoral progress.

From a practical perspective, the findings carry direct implications for EU policymakers and businesses. To counteract rebound effects associated with economic growth, authorities should strengthen decoupling mechanisms through carbon pricing, stricter energy-efficiency standards, targeted fiscal incentives for green investments, and the promotion of circular business models. Accelerating innovation ecosystems via instruments such as Horizon Europe and public-private partnerships remains essential to sustain the positive impact of the Global Innovation Index. Enhancing government effectiveness, especially in Central and Eastern European member states, is critical for the effective transposition and enforcement of the European Green Deal directives and for directing foreign investment towards energy-efficient projects. For companies operating in the EU, aligning strategies with high-innovation sectors and green technologies can improve long-term competitiveness and regulatory compliance.

The study has several limitations. The relatively short time dimension (T = 11) constrains the analysis of very long-term dynamics. Although interaction terms were conceptually considered to test the moderating role of Government Effectiveness, they were not included in the main reported specifications. The aggregate character of the ODEX index limits detailed sectoral insights, and potential spatial spillovers across member states were not modelled. Future research could usefully extend the time span beyond 2023 to evaluate the effects of REPowerEU and subsequent policy initiatives, incorporate spatial econometric techniques to capture cross-border spillovers, apply quantile regression to explore heterogeneous effects across countries with different income or innovation levels, and explicitly test interaction effects between institutional quality and other drivers. Such extensions would provide further refinement for policies aimed at achieving a balanced and effective green transition across the diverse economies of the European Union. In summary, sustainable energy efficiency in the European Union is driven primarily by technological innovation and supported by strong institutions, rather than by economic growth or foreign capital inflows alone. These insights can help align investment, innovation, and governance strategies with the Union's 2030 energy-efficiency targets and 2050 climate-neutrality objectives.

Author contributions

RPV and EJ conceived the study and were responsible for the design and development of the data analysis. ST and MEA were responsible for data collection and analysis. RMB and LMC were responsible for data interpretation. RPV wrote the first draft of the article.

Disclosure statement

The authors declare no conflict of interest.

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