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Navigating Energy Transition: Driving Energy Efficiency Improvement in EU Industry

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Abstract

This study examines the primary determinants of energy efficiency improvements within the European Union's (EU) industrial sector from 2004 to 2023. The analysis is situated within the strategic framework of the European Green Deal and the "Fit for 55" package, which addresses the challenge of accelerating the industrial energy transition while maintaining global competitiveness. Utilizing a Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model, this research accounts for cross-sectional dependence and heterogeneous short-run dynamics across Member States. Empirical results reveal that economic growth and rising energy prices act as significant drivers of industrial energy efficiency in both the short and long run. Conversely, higher CO_2 emissions are associated with lower efficiency, reflecting persistent reliance on carbon-intensive production. These findings underscore the need to align economic modernization with price-based incentives to meet EU climate goals.

Keywords: CS-ARDL, energy efficiency, energy transition, EU industry
JEL: C23, L60, Q40, Q48

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Introduction

European Union (EU) policy, while navigating the complexities of environmental regulations and competitiveness, is oriented towards energy transition, driven by the understanding that well-designed policies can foster technological advancements and long-term economic benefits rather than solely posing competitive disadvantages. Nonetheless, the issue of the impact of environmental regulations on competitiveness remains contentious (Dechezleprêtre and Sato 2017). There are two opposing views on this topic: the pollution hypothesis, which predicts that firms operating in countries with more stringent environmental regulations will lose competitiveness, and the Porter hypothesis, which argues that more stringent regulations may serve as a catalyst for innovation, enhancing competitiveness by promoting efficiency gains and facilitating the development of novel technologies (Ambec et al. 2010). Transitioning to a more energy-efficient economy can also stimulate economic growth and create high-quality jobs in sectors related to energy efficiency, which is and will continue to be a competitive advantage for both countries and companies (Proskuryakova and Kovalev 2015).

The EU's ambitious climate agenda marked by the European Green Deal (EGD) and the Fit for 55 package has positioned energy efficiency as a cornerstone of its industrial strategy. Industry, responsible for 25% of the EU's final energy consumption and 20% of its direct CO_2 emissions, faces an unprecedented dual mandate: to decarbonize rapidly while maintaining global competitiveness in an era of geopolitical energy instability (Odyssee 2025). While aggregate energy intensity in EU industry improved annually by 1.59% between 2004 and 2023, progress remains uneven across member countries. Against this backdrop, understanding the determinants of energy efficiency progress is not merely an academic exercise but a policy and economic imperative. The EU's industrial strategy, updated in May 2021 following the COVID-19 crisis, is oriented towards an energy transformation based on the idea that environmental ambition can drive innovation and long-term competitiveness (European Commission 2021b). EU energy efficiency measures focus on policy areas with the greatest potential for energy savings and where a harmonized approach across member states is needed. This includes industry and, under the revised directive on energy efficiency, EU countries will be required to achieve an average annual energy savings rate of 1.49% from 2024 to 2030, up from the 2021–2023 requirement of 0.8%, driving energy savings in critical sectors like construction, industry, and transport (European Parliament and the Council of the European Union 2023).

The central aim of this article is to identify and evaluate the determinants driving energy efficiency progress in the EU industrial sector between 2004 and 2023. By combining theoretical insights, policy analysis, and empirical econometric modelling, the study seeks to disentangle the multifaceted factors that have influenced industrial energy efficiency outcomes. The findings aim to inform targeted strategies for accelerating the EU's energy transition while balancing industrial competitiveness.

The study opens with a critical analysis and synthesis of the relevant literature and policy documents, providing a foundation for understanding the conditions shaping the energy transition in the EU. Attention is given to the political and regulatory context influencing the evolution of energy efficiency, followed by an examination of historical and recent trends in industrial energy efficiency across EU member states, with a particular focus on energy intensity developments over the period 2004–2023.

The analytical core of the paper presents the econometric framework used to identify the determinants of industrial energy efficiency in the EU. This section outlines the specification of the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) model, the construction of the variables, and the rationale for controlling for cross-sectional dependence, heterogeneous short-run dynamics, and unobserved common shocks affecting EU economies.

The empirical results are then presented and discussed, highlighting both short-run and long-run relationships between industrial energy efficiency and its key determinants. The paper concludes by synthesizing the main findings and drawing policy-relevant conclusions.

The EU Energy Transition in the Light of New Geopolitical Circumstances – Motivation or Demotivation?

The global energy transition represents a systemic transformation of energy production and consumption, driven by the replacement of high-carbon fossil fuels with renewable and low-carbon sources (Goldthau, Westphal, and Keim 2018; IRENA 2019; Hafner and Tagliapietra 2020). Beyond mitigating climate change (Hallegatte et al. 2016), the transition seeks to improve air quality and energy security (Bressand 2012; Eyl-Mazzega and Mathieu 2019; Król, Makieła, and Mamica 2025). It introduces new economic models and sustainability frameworks, with far-reaching implications for industry, society, and economic resilience. It seemed that the energy transition trend would be a constant social, political, environmental, and economical course for all countries around the world. However, recent decisions made by U.S. President Donald Trump have increased uncertainty in this area and have become a topic of much controversy, especially when contrasted with the global trend of transitioning to renewable energy sources. Donald Trump, both during his first presidency (2017–2021) and following the commencement of his new presidential term on January 20, 2025, has consistently expressed strong support for conventional energy sources primarily coal, oil, and gas at a time when most developed countries are investing in renewable sources, energy efficiency, and decarbonization.

For EU member states, the transition of the energy system has become a strategic goal in the fight against climate change, leading to improved energy security, competitiveness, and economic attractiveness of Europe in the transition to a greenhouse gas (GHG) neutral economy by 2050. A pivotal milestone in the EU's energy transition, aiming towards the goal of becoming the world's first zero-carbon continent by 2050, was the introduction of the energy and climate package in 2008, commonly known as "3x20% by 2020". The package outlined three main objectives to be reached by 2020 (European Commission 2008; Klecha-Tylec, Pach-Gurgul, and Ulbrych 2024):

1) To increase the share of energy derived from renewable energy sources (RES) to 20% of the EU's total energy consumption;
2) To reduce primary energy consumption by 20% relative to projected consumption levels for 2020, as forecasted in 2005;

3) To achieve a 20% reduction in CO_2 emissions compared to 1990 levels.

The goals of the energy and climate package were subsequently reinforced and incorporated into the Europe 2020 Strategy (European Commission 2010), underlining their critical importance for the EU's long-term energy and climate objectives. In October 2014, at the European Council, EU leaders set new climate and energy targets for 2030, including more ambitious reduction thresholds, including tightening the reduction of 40% of greenhouse gas emissions compared to 1990, sourcing at least 27% of energy from renewable sources and improving energy efficiency by the same amount (European Council 2014; Klecha-Tylec, Pach-Gurgul, and Ulbrych 2024).

Ahead of the Paris UN Climate Change Conference COP21/CMP11 (Nov. 30–Dec. 11, 2015), the EU submitted a planned nationally determined contribution (INDC) to the secretariat of the UN Framework Convention on Climate Change (UNFCCC) confirming commitment to reduce its own GHG emissions by at least 40% by 2030 compared to 1990 in line with the European Council's October 2014 conclusions (United Nations 2015). On October 4, 2016, the Council adopted the decision for the EU to ratify the Paris Agreement. Earlier, in September 2015, the Environment Council had approved conclusions outlining the EU's position for the COP21 climate conference in Paris, thereby marking a significant step in supporting international efforts toward the global energy transition. During this meeting, the ministers agreed that the EU would strive for an ambitious, legally binding, and dynamic agreement aimed at limiting global temperature increase to below 2°C.

In June 2017, the European Council reaffirmed the commitment of the EU and its member states to the swift and full implementation of the Paris Agreement, stressing that the agreement is an essential "element in the modernization of industry and the economy in Europe". In November 2018, the European Commission (EC) presented a long-term strategic vision for a modern, competitive, and climate-neutral economy by the 2050 horizon. The strategy illustrates how Europe can lead the way in achieving climate neutrality by introducing innovative technological solutions and aligning policy actions in areas such as industrial policy, finance, and research. The EC has planned to increase energy efficiency by at least 32.5% by 2030, by, among other things, improving low emissions in the transport sector (European Commission 2018).

The EGD (European Commission 2019), presented by the EC on December 11, 2019, set out a new growth strategy for Europe. Its goal was and is to transform the EU into a fair and prosperous society with a modern, resource-efficient, and competitive economy that achieves zero net greenhouse gas emissions in 2050, and in which economic growth will depend less on the use of conventional raw material resources. In December 2020, the European Council approved a new binding EU target to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990. In order to bring selected areas into line with the new target reduction, the EC published a package of legislative proposals (the "Fit for 55%" package) on July 14, 2021.

Energy Efficiency as a Key Pillar of EU Energy Transition

Reducing energy consumption and minimizing waste have become increasingly important priorities for the EU and its Member States. EU legislation seeks to position energy savings as a fundamental driver of a secure, sustainable, and competitive economy. In recent years, the EU has made significant progress in reducing energy consumption and has notably improved its overall energy efficiency, particularly within the framework of the Lisbon Agenda and the subsequent Europe 2020 Strategy (Pach-Gurgul, Śmiech, and Ulbrych 2020). The EU regards energy efficiency as a key pillar of its energy and climate strategy. By reducing overall energy consumption, energy efficiency plays a central role in achieving its climate ambitions, while simultaneously enhancing both current and future energy security and affordability.

To meet the 2030 target of reducing GHG emissions by at least 55% compared to 1990 levels, the EC has revised the Energy Efficiency Directive from 2012, alongside other energy and climate regulations (European Commission 2012). The EU follows the principle of "energy efficiency first," meaning that energy savings are prioritized wherever they are most cost-effective. While fully considering the security of supply and market integration, the Energy Efficiency First principle seeks to ensure that only the energy that is truly needed is produced, investments in stranded assets are avoided, and energy demand is reduced and managed in a cost-effective manner.

This principle emphasizes not only the need to reduce fossil fuel consumption but also the importance of decreasing overall energy production to improve the efficiency of the energy system and minimize its environmental impact. While the "Energy Efficiency First" principle was already embedded in the Regulation on the Governance of the Energy Union and Climate Action (EU/2018/1999) and the Energy Efficiency Directive (EU/2018/2002), the revised Directive (EU/2023/1791), published in the Official Journal on September 20 2023, establishes a more robust and comprehensive legal framework for the implementation of this principle. It significantly elevates the EU's ambition with regard to energy efficiency. It enshrines the principle of "energy efficiency first" as a fundamental tenet of EU energy policy, granting it legal standing for the first time.

In practical terms, this mandates that energy efficiency be considered by member states in all pertinent policy decisions and major investments, both within the energy sector and across non-energy sectors. The 2023 revision follows the EC's proposal for a recast energy efficiency directive, initially put forward in July 2021 as part of the EGD package. This proposal was subsequently strengthened through the REPowerEU plan, presented by the EC in May 2022, with the goal of reducing the EU's dependency on fossil fuel imports from Russia (European Commission 2022). The revised directive from 2023 strengthens the energy efficiency target, making it legally binding for member states to collectively achieve an additional 11.7% reduction in energy consumption by 2030, compared to the projections in the EU reference scenario of 2020. As a result, total EU energy consumption by 2030 should not exceed 992.5 million tonnes of oil equivalent (Mtoe) for primary energy and 763 Mtoe for final energy.

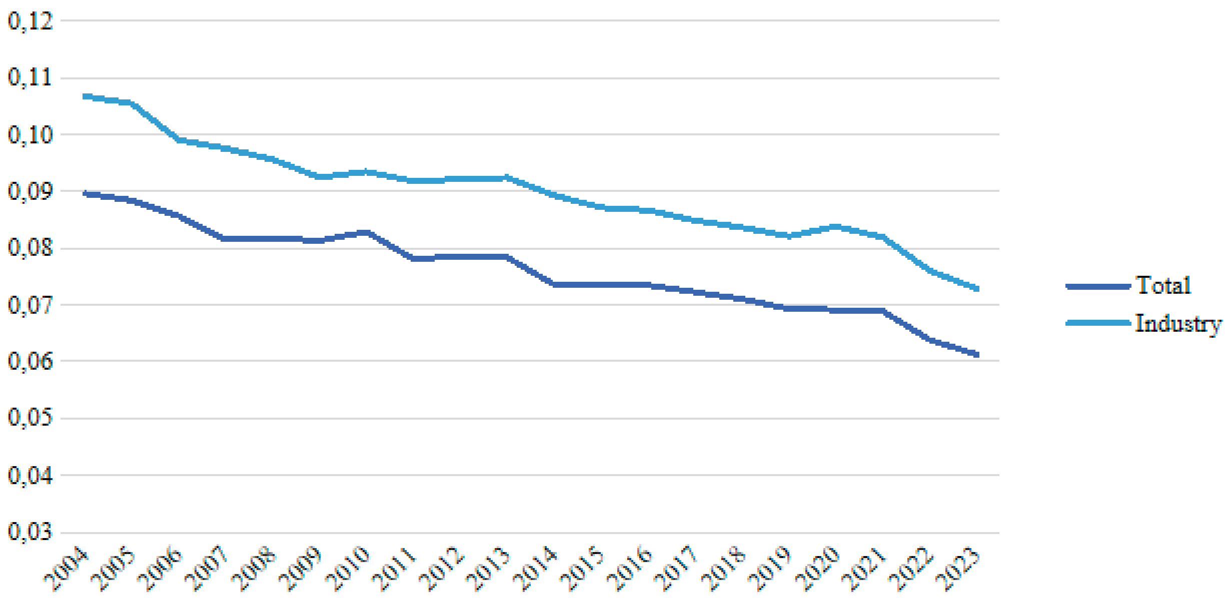
Under the updated framework, EU countries have committed to meeting this target by establishing indicative national contributions. These contributions will be determined using a set of objective criteria that consider national circumstances, such as energy intensity, GDP per capita, energy savings potential, and previous energy efficiency efforts. The directive also introduces an enhanced "gap-filling mechanism," which will be activated if countries fall short of their national contributions. In setting these indicative national contributions, member states could use either the projections of the 2020 reference scenario or its updated version (communicated to them in December 2023). In March 2024, the EC communicated corrected indicative national contributions (also covering the update of the reference scenario) to be used in each country's updated integrated national energy and climate plans (NECPs) in June 2024.

In 2023, primary energy consumption in the EU, which refers to energy contained in natural resources in their unprocessed form, totalled 1,210 Mtoe. This was the lowest level since 1990, marking a 3.9% decrease compared to 2022. Final energy consumption, which refers to energy directly supplied to end-users, reached 894 Mtoe, a decrease of 3%. Unfortunately, this value still exceeds the 2030 target of 763 Mtoe by 17.2% (Eurostat 2025a).

Energy efficiency trends

Energy efficiency is broadly defined in the simplest way as the ratio of output (services, goods, or energy) to the input of energy (e.g., Phylipsen, Blok, and Worrell 1997; Skoczkowski and Bielecki 2016; Sinevičiene, Sotnyk, and Kubatko 2017; Deka et al. 2023; Sallam and Sadraoui 2025; Song, Liu, and Hussain 2025). Although alternative approaches to measuring energy efficiency exist such as estimating efficiency frontiers using data envelopment analysis (e.g., Liu et al. 2020; Zhang et al. 2022) or applying principal component analysis (e.g., Ahmad and Uddin 2025) we rely on a standard measure to ensure the comparability of results and to facilitate the derivation of clear and interpretable policy recommendations. The energy intensity indicator is usually used to assess progress in energy efficiency, which reflects the level of energy consumption per unit of economic output. This is an extremely important topic for the EU, which faces significant challenges arising from dependence on energy imports, limited energy resources, and the need to mitigate the human impact on climate change. Striving to improve energy efficiency is one of the best ways to address these challenges. Reducing primary and final energy consumption contributes to decreasing energy imports, thereby enhancing the security of energy supply to the EU. Cutting energy consumption also translates into a cost-effective reduction in greenhouse gas emissions, thus mitigating the negative impact on climate change.

The data in Figure 1 show EU energy intensity at both macroeconomic and industry levels, where lower values indicate better energy efficiency. From 2004 to 2023, macro-level energy intensity declined consistently from 0.09 to 0.06 (a 1.58% annual reduction), while industry-level intensity fell from 0.11 to 0.07 (1.59%). This reflects a reduction in energy consumption per unit of output, suggesting improvements in energy efficiency or a shift to less energy-intensive production methods.



Note: koe denotes kilograms of oil equivalent.

Figure 1. Final energy intensity at EU average (2004–2023) (koe/EUR2015)
Source: own elaboration based on Odyssee 2025.

Improvements in energy intensity at macro and industrial levels are encouraging, suggesting that overall energy use is becoming more efficient. However, the pace of change differs across member states and highlights a missed opportunity for further improvements in energy efficiency that could lead to better economic and environmental outcomes.

Table 1. Descriptive Statistics of Energy Intensity of Industry by Country (2004–2023, koe)

Country	mean	Std	min	max
European Union	0.090	0.009	0.073	0.107
Austria	0.094	0.006	0.079	0.104
Belgium	0.137	0.009	0.119	0.156
Bulgaria	0.136	0.033	0.105	0.212
Croatia	0.079	0.008	0.064	0.094
Cyprus	0.093	0.017	0.074	0.145
Czechia	0.089	0.023	0.066	0.153
Denmark	0.057	0.008	0.039	0.067
Estonia	0.089	0.031	0.047	0.144
Finland	0.262	0.014	0.241	0.305
France	0.089	0.006	0.079	0.100
Germany	0.079	0.006	0.066	0.088
Greece	0.086	0.011	0.067	0.107
Hungary	0.071	0.009	0.057	0.082
Ireland	0.030	0.011	0.011	0.045
Italy	0.079	0.008	0.063	0.096

Country	mean	Std	min	max
Latvia	0.113	0.015	0.083	0.133
Lithuania	0.066	0.011	0.044	0.085
Luxembourg	0.143	0.027	0.099	0.182
Malta	0.035	0.004	0.029	0.043
Netherlands	0.124	0.016	0.091	0.153
Poland	0.077	0.019	0.052	0.123
Portugal	0.096	0.016	0.061	0.123
Romania	0.077	0.020	0.053	0.129
Slovakia	0.112	0.025	0.074	0.172
Slovenia	0.099	0.019	0.063	0.140
Spain	0.085	0.007	0.073	0.102
Sweden	0.148	0.013	0.123	0.169

Source: own elaboration based on Odyssee 2025.

Based on the descriptive statistics in Table 1, it is possible to assess the progress in the energy intensity of member states' industrial sectors over the past 20 years. The average energy intensity rate for the entire EU serves as a reference point for assessing the position of individual countries; in the period analyzed, it amounted to 0.090. The standard deviation for the EU is 0.009, and the values ranged from 0.073 to 0.107. When analyzing changes in individual countries, there are significant differences in the average energy intensity. The highest averages were recorded in Finland (0.262), Sweden (0.148), and Luxembourg (0.143), significantly exceeding the EU average. In contrast, the lowest mean values were observed in Ireland (0.030), Malta (0.035), and Denmark (0.057).

The variation across countries, measured by standard deviation, also differs significantly: countries with a higher standard deviation were characterised by greater variability over the period analysed, e.g., Bulgaria (0.033), Estonia (0.031), and Luxembourg (0.027). Countries with a lower standard deviation, such as Austria (0.006), France (0.006), and Germany (0.006), had a more stable energy intensity over the period analysed.

Looking at the minimum and maximum values, one can see the range of changes in energy intensity across countries; for example, in Finland, the intensity varied from 0.241 to 0.305, indicating a relatively high and narrow range compared to other countries. In Bulgaria, the range was much wider from 0.105 to 0.212 confirming the greater variability indicated by the higher standard deviation.

In summary, the analysis of descriptive statistics reveals significant differences in average energy intensity between EU member states. Some countries consistently maintained higher or lower values across the period analysed, while others showed greater variability.

Variable selection and model framework

To investigate the determinants and dynamic interactions shaping the energy intensity of industry in the EU (or, more precisely, its inverse, interpreted as energy efficiency), this study employs a panel data framework comprising 27 EU member states over a 20-year period (2004–2023). The key (dynamic) explanatory variables include average industrial energy prices (at constant prices), GDP per capita (in purchasing power parities), net GHG emissions, and renewable energy consumption in industry (as a share of the total). Additionally, we explore the short-run effects of environmentally related tax revenue (as % of total taxes), total environmental taxes (in EUR millions), and the Environmental Policy Stringency Index. This multidimensional dataset captures both economic and environmental policy drivers that potentially influence energy efficiency outcomes across countries and over time.

The selection of explanatory variables was preceded by a literature review and cross-referenced with the availability and consistency of statistical data across the EU-27 panel. The chosen determinants capture the multifaceted nature of industrial energy efficiency, reflecting market mechanisms, structural economic shifts, and the regulatory landscape. A primary driver of efficiency improvements is the trajectory of industrial energy prices. According to the Hicks Induced Innovation Hypothesis, an increase in the relative price of a factor of production (in this case, energy) serves as a market signal that motivates firms to innovate and adopt advanced technologies that utilize that factor more sparingly (Evan and Holý 2021). The role of economic development is examined through a generalized interpretation of the Environmental Kuznets Curve hypothesis. This theory suggests that as national income increases (represented by GDP per capita), economies undergo a profound structural and qualitative transformation.

Countries typically transition from energy-intensive, heavy-manufacturing stages toward higher value-added, high-tech industrial bases, which are inherently more energy-efficient (Stern 2003). Furthermore, GHG emissions are included as a critical determinant due to their link to energy intensity. This is particularly relevant in the industrial sector, where fossil fuel combustion remains an important energy source (European Environment Agency 2023). The decarbonization of industrial processes often necessitates the radical improvement of energy efficiency, particularly as the transition toward renewable energy consumption often coincides with the adoption of highly efficient technologies (Akram et al. 2020). Finally, to account for the impact of the regulatory environment, the model incorporates environmentally related tax revenues and the Environmental Policy Stringency Index (utilized in a related context by Song, Liu, and Hussain 2025). From the perspective of the Porter Hypothesis, such regulatory pressures can trigger "innovation offsets," prompting industries to enhance their energy efficiency to maintain competitiveness in the face of rising environmental compliance costs.

Table 2. The initial diagnostic variables

Description	Unit	Source
Energy intensity of industry (Eint)	koe/EUR2015	Odyssee (2025)
Net greenhouse gas emissions (GHG)	Tonnes per capita	Eurostat (2025b)

Description	Unit	Source
Average energy prices for industry at constant prices (Price)	EUR2015/toe	Odyssee (2025)
Renewable energy consumption of industry (RES)	Percentage of total	Odyssee (2025)
GDP per inhabitant at purchasing power parities (GDP)	EUR2015	Odyssee (2025)
Environmentally related tax revenue (Rev)	Percentage of GDP	OECD (2025a)
Total environmental taxes (Taxes)	EUR millions	Eurostat (2025c)
Environmental Policy Stringency Index (EPS_index)	0–6 index number	OECD (2025b)

Source: own elaboration.

Given the panel structure and the possibility of non-stationarity in the time series data, the analysis begins with panel unit root tests (such as Levin, Lin, and Chu 2002; Im, Pesaran, and Shin 2003) to assess the stationarity properties of each variable. Following this, panel cointegration tests (e.g., Kao) examine the existence of long-run equilibrium relationships between energy intensity and its determinants. To explore the direction and nature of causality, panel Granger causality tests identify both short- and long-term causal dynamics among variables.

This study employs Chudik and Pesaran's (2015) CS-ARDL model to examine the determinants of energy efficiency across a panel of countries. The CS-ARDL approach is particularly well suited to macro panel data, where cross-sectional dependence, unobserved global shocks, and heterogeneous short-run dynamics are likely to be present. Traditional panel estimators may yield biased or inconsistent results in such settings, whereas the CS-ARDL estimator mitigates these concerns by augmenting the regression with cross-sectional averages of both dependent and explanatory variables. This augmentation captures unobserved common factors such as global technological trends, international energy price shocks, or coordinated policy shifts that simultaneously affect all countries. Moreover, this method has been recently utilized in several related studies, including Deka et al. (2023), Ahmad and Udin (2025), Sallam and Sadraoui (2025), and Song, Liu, and Hussain (2025). However, only Ahmad and Udin (2025) considered energy efficiency as the dependent variable, but they measured it in a different way (applying principal component analysis) and focused on a different set of countries (BRICS). The empirical specification estimated in this study is given by the following formula:

$$\ln EE_{it} = \phi_i \ln EE_{i,t-1} + \beta_i' \boldsymbol{X}_{it} + \gamma_i' \overline{\boldsymbol{Z}}_t + u_{it},$$

where $i = 1, \ldots, N$ indexes countries and $t = 1, \ldots, T$ denotes time; $\ln EE_{\mathrm{it}}$ is the natural logarithm of the energy efficiency indicator in country i at time t, while $\ln EE_{i,t-1}$ is its one-period lag, capturing dynamic persistence in energy efficiency, ϕ_i is a country-specific autoregressive coefficient; $\boldsymbol{X}_{\mathrm{it}}$ is a vector of observed explanatory variables affecting energy efficiency (such as income, energy prices, emissions, taxes, renewable energy share, or policy indicators), with an associated country-specific coefficient vector $\boldsymbol{\beta}_i$. $\bar{\mathbf{Z}}_t$ denotes the vector of cross-sectional averages of the variables included in the model, which serves as a proxy for unobserved common factors and global shocks affecting all countries; $\boldsymbol{\gamma}_i$ is the corresponding vector of heterogeneous factor loadings. Finally, u_{it} is an idiosyncratic error term assumed to be weakly cross-sectionally correlated once the common factors are accounted for.

Empirical Results

The empirical analysis is carried out on transformed variables: the energy intensity of industry is inverted to represent energy efficiency (EEff, illustrated by Figure 2 below). Furthermore, whenever an elasticity interpretation of the estimated coefficient is justified, the logarithms of the variables are computed (including EEff, GHG Price, GDP, and Taxes). Given data availability and preliminary test results, the long-term relationship between energy efficiency (the dependent variable) and energy prices, GDP, and GHGemissions is examined. In contrast, the remaining variables of interest (share of renewable energy sources, share of environmental taxation in GDP, environmental policy stringency index, and total environmental taxes) are considered only in the short-term dynamics.

Before proceeding to a formal analysis of the relationships among these variables, the correlations among them in their raw form are studied. Detailed results are given in Table 3 below and can be summarized as follows: strong positive (and significant) correlations exist between the following pairs of variables: GDP and GHG emissions (0.651), energy efficiency and energy prices (0.378), as well as between the environmental policy stringency index and environmental tax revenues (0.333). The strongest negatively correlated variable is renewable energy share with energy efficiency (–0.246), GHG emissions (–0.293), or again with environmental tax revenues (–0.250). Other variables seem to be somewhat less strongly correlated; however, some of these coefficients are still statistically significant.

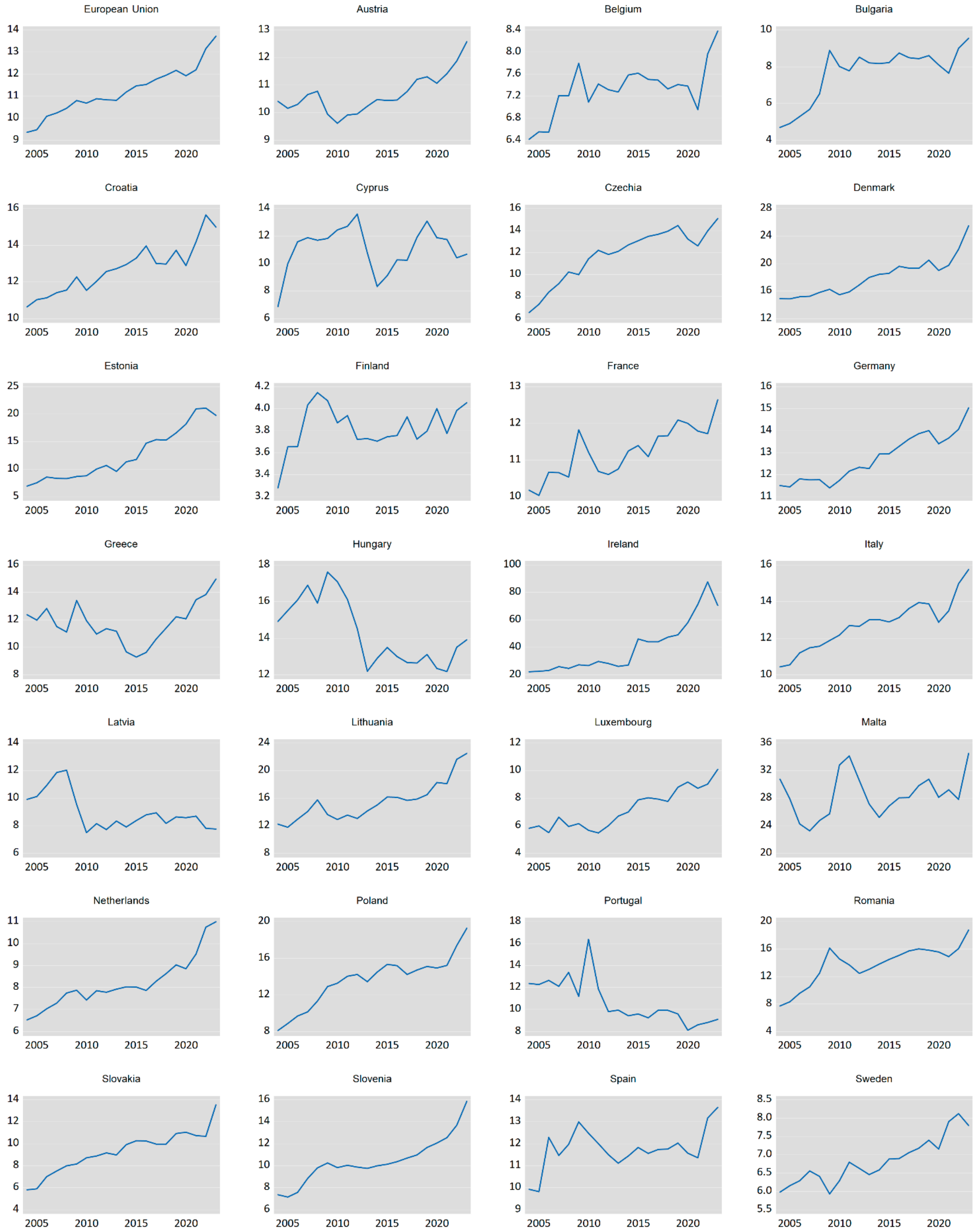


Figure 2. Energy efficiency in the European Union and its member countries, 2004–2023 (EUR2015/koe)
Source: own computations based on Odyssee 2025.

Table 3. Analysis of the correlation between the selected variables

Correlation P-value	Eeff	Prices	GDP	GHG	RES	Rev	Taxes	EPS_index
Energy eff.	1.000							
	–							
Prices	0.378	1.000						
	0.000	–						
GDP	0.224	0.136	1.000					
	0.000	0.002	–					
GHG	0.057	−0.042	0.651	1.000				
	0.199	0.346	0.000	–				
RES	−0.246	−0.148	−0.049	−0.293	1.000			
	0.000	0.001	0.254	0.000	–			
Rev	−0.193	0.125	−0.237	−0.005	−0.014	1.000		
	0.000	0.013	0.000	0.920	0.787	–		
Taxes	−0.067	0.126	0.074	−0.026	−0.250	−0.038	1.000	
	0.275	0.039	0.223	0.673	0.000	0.586	–	
EPS_index	−0.097	0.151	0.224	−0.095	0.140	0.167	0.333	1.000
	0.083	0.007	0.000	0.087	0.012	0.003	0.000	–

Source: own computations based on data described in Table 2.

Empirical investigation of the relationships and causality among these variables is initiated with a battery of panel stationarity tests that were conducted on the variables utilized in the dynamic part of the regression. In general, all variables exhibit non-stationarity in levels at the standard 5% significance levels and attain stationarity in first differences; they are, therefore, integrated of order 1, I(1). Detailed results of these procedures are summarized in Tables 4 and 5 below. Subsequently, panel cointegration tests examine whether some long-run relationships exist among the key variables. Specifically, the Kao (1999) residual-based cointegration test, which relies on an ADF-type regression, is applied. This test unambiguously indicates the presence of cointegration among the five variables considered for the long-run analysis, with a t-statistic of –5.5. and a corresponding p-value below 0.000. We then conduct Fisher ("combined Johansen") cointegration tests to detect the number of cointegrating relationships. Given the limited number of observations, the analysis is conducted using two sub-groups of long-run variables: energy efficiency, energy prices, and GDP, with the fourth variable being either (the log of) GHG emissions or the share of renewable energy. Both tests indicate the existence of two cointegration relationships in these groups[1].

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[1] Detailed results or data and E-views commands for replication are available upon request.

Table 4. Results of panel unit root tests of the levels of the variables relevant for the long-run analysis

Variable	Energy efficiency (ln_eeff)			Energy prices (ln_price)			GDP per capita (ln_GDP)			Net GHG emissions (ln_co2)			Renewable energy (RES)		
Method (test)	**Statistic**	**Prob.**	**Obs.**	**Statistic**	**Prob.**	**Obs.**	**Statistic**	**Prob.**	**Obs.**	**Statistic**	**Prob.**	**Obs.**	**Statistic**	**Prob.**	**Obs.**
Levin, Lin & Chu t*	−0.459	0.323	497	−2.253	0.012	493	0.438	0.669	485	−1.237	0.108	473	−0.318	0.375	495
Im, Pesaran and Shin W-stat	1.479	0.930	497	−2.057	0.020	493	3.562	0.999	485	0.197	0.578	473	2.663	0.996	495
ADF – Fisher Chi-square	63.11	0.185	497	71.52	0.055	493	29.17	0.998	485	66.81	0.113	473	53.76	0.484	495
PP – Fisher Chi-square	77.35	0.020	513	59.18	0.292	513	54.18	0.467	513	48.62	0.681	486	56.96	0.366	513

Notes: For all tests, the null hypothesis is that the panel series contain a unit root. Levin, Lin & Chu t* assumes a common unit root process, whereas the remaining IPS, ADF, and PP assume individual unit root processes. In all cases, the number of cross-sections (countries) is 27, and the number of lags is selected automatically based on the Schwartz Information Criterion (SIC). Tests assume individual constants and no trends. P-values for Fisher tests are computed using an asymptotic Chi-square distribution. All other tests assume asymptotic normality.

Source: own computations based on the data described in Table 2. Software utilized: Eviews 10.

Table 5. Results of panel unit root tests of the first differences of the variables relevant for the long-run analysis

Variable	Energy efficiency (ln_eeff)			Energy prices (ln_price)			GDP per capita (ln_GDP)			Net GHG emissions (ln_co2)			Renewable energy (RES)		
Method (test)	**Statistic**	**Prob.**	**Obs.**	**Statistic**	**Prob.**	**Obs.**	**Statistic**	**Prob.**	**Obs.**	**Statistic**	**Prob.**	**Obs.**	**Statistic**	**Prob.**	**Obs.**
Levin, Lin & Chu t*	−14.21	0.000	477	−13.41	0.000	474	−15.45	0.000	467	−17.50	0.000	453	−16.82	0.000	479
Im, Pesaran and Shin W-stat	−13.61	0.000	477	−12.07	0.000	474	−13.46	0.000	467	−15.95	0.000	453	−15.55	0.000	479
ADF – Fisher Chi-square	266.5	0.000	477	239.8	0.000	474	262.9	0.000	467	307.6	0.000	453	306.0	0.000	479
PP – Fisher Chi-square	326.7	0.000	486	276.5	0.000	486	401.2	0.000	586	428.9	0.000	459	331.8	0.000	486

Notes: See Table 4 above.

Source: own computations based on the data described in Table 2. Software utilized: Eviews 10.

Next, we proceed to the Granger causality analysis via the pairwise Dumitrescu–Hurlin test. The results conducted in the panel setup among the five long-run variables are summarized in Table 6. The main insights are as follows: energy prices and GHG emissions Granger-cause energy efficiency (but not vice-versa), whereas the relationships between energy efficiency and both GDP and the share of renewable energy sources are bi-directional. Additionally, two-way Granger causality is detected between energy prices and GHG emissions, energy prices, and the share of renewable energy, as well as between GDP and renewable energy share. On the other hand, the null hypothesis of no homogeneous causal relationship in any direction cannot be rejected between GDP and greenhouse gas emissions, and the share of renewable energy.

Table 6. Results of the Dumitrescu-Hurlin panel Granger causality test

Null Hypothesis	W-Stat.	Zbar-Stat.	Prob.
LN_PRICE does not homogeneously cause LN_EEFF	7.13308	8.72407	0.0000
LN_EEFF does not homogeneously cause LN_PRICE	2.99817	1.16066	0.2458
LN_GDP does not homogeneously cause LN_EEFF	5.05157	4.91664	9.E-07
LN_EEFF does not homogeneously cause LN_GDP	3.43555	1.96069	0.0499
LN_GHG does not homogeneously cause LN_EEFF	3.55868	2.04827	0.0405
LN_EEFF does not homogeneously cause LN_CO2	2.50071	0.17802	0.8587
RES does not homogeneously cause LN_EEFF	4.59940	4.08956	4.E-05
LN_EEFF does not homogeneously cause RES	4.53845	3.97807	7.E-05
LN_GDP does not homogeneously cause LN_PRICE	2.68241	0.58308	0.5598
LN_PRICE does not homogeneously cause LN_GDP	3.21237	1.55247	0.1206
LN_GHG does not homogeneously cause LN_PRICE	6.08826	6.51998	7.E-11
LN_PRICE does not homogeneously cause LN_CO2	4.38219	3.50405	0.0005
RES does not homogeneously cause LN_PRICE	4.00979	3.01107	0.0026
LN_PRICE does not homogeneously cause RES	4.20569	3.36941	0.0008
LN_CO2 does not homogeneously cause LN_GDP	3.27983	1.55534	0.1199
LN_GDP does not homogeneously cause LN_CO2	3.15853	1.34091	0.1799
RES does not homogeneously cause LN_GDP	4.70923	4.29045	2.E-05
LN_GDP does not homogeneously cause RES	3.47744	2.03732	0.0416
RES does not homogeneously cause LN_CO2	2.45726	0.10123	0.9194
LN_GHG does not homogeneously cause RES	2.59516	0.34500	0.7301

Notes: Number of lags included: 2.

Source: own computations based on data described in Table 2. Software utilized: Eviews 10.

As indicated by Table 6, energy efficiency is Granger-caused by all four other variables retained for the PMG regression analysis. Additionally, as mentioned above, the existence of cointegration relationships among these variables was confirmed. Thus, it is fully justified to utilize the CS-ARDL approach with energy efficiency as the dependent variable, as presented in the methodology section. The key results are presented in Table 7 below.

Table 7. Results of Cross-Sectionally augmented Auto-Regressive Distributed Lag estimations of the determinants of energy efficiency

	Baseline	M2	M3	M4	M5
GDP (long run)	1.065***	1.411***	1.238***	0.798**	0.965*
	(0.009)	(0.006)	(0.001)	(0.016)	(0.062)
En. price (long run)	0.147*	0.160	0.117	0.196**	0.828
	(0.076)	(0.182)	(0.302)	(0.034)	(0.282)
GHG emissions (long run)	−0.257*	−0.727**		−0.224*	0.019
	(0.067)	(0.026)		(0.084)	(0.941)
RES (long run)		−0.764	−0.568	−0.247	
		(0.330)	(0.318)	(0.307)	
Taxes (long run)			−0.269	−0.307**	
			(0.130)	(0.041)	
EPS_index (long run)					−0.137
					(0.134)
Adjustment term	−0.946***	−0.848***	−0.998***	−1.117***	−0.934***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
GDP (short run)	1.067***	1.115***	0.967***	0.891***	0.548**
	(0.000)	(0.000)	(0.001)	(0.006)	(0.030)
Energy prices (short run)	0.112	0.073	0.160*	0.227**	0.124
	(0.124)	(0.281)	(0.082)	(0.036)	(0.391)
GHG emissions (short run)	−0.207	−0.425***		−0.185	0.055
	(0.105)	(0.001)		(0.221)	(0.809)
RES (short run)		−0.213	−0.193	−0.113	
		(0.328)	(0.311)	(0.294)	
Taxes (short run)			−0.138	−0.228*	
			(0.194)	(0.064)	
EPS_index (short run)					−0.056
					(0.114)
CD-stat	0.707	−0.551	1.053	1.574	0.803
CD p-value	0.480	0.581	0.292	0.115	0.422
Observations	486	486	474	474	304
R-squared	0.249	0.205	0.256	0.156	0.162

p-values in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: own elaboration based on data described in Table 2. Software utilized: STATA 15. Package xtdcce2 (Ditzen 2018; 2021).

The results presented in Table 7 indicate that, across all specifications, GDP emerges as a robust and positive long-run determinant of energy efficiency. The estimated elasticities are statistically significant in all models, although their magnitude varies with the inclusion of additional controls. This suggests that higher income levels are associated with sustained improvements in energy efficiency, which is consistent with scale effects, technological upgrading, and structural change accompanying economic development.

The effect of energy prices in the long run is positive but less stable across specifications. While the coefficient is statistically significant in the baseline and in Model M4, it loses significance once additional policy or structural variables are introduced. This indicates that price-based incentives may contribute to long-run efficiency gains, but their impact is sensitive to the broader policy and institutional environment.

GHG emissions exhibit a negative and statistically significant long-run association with energy efficiency in most specifications where they are included. This finding is consistent with the interpretation that higher emission intensity reflects less efficient energy use. However, the effect disappears once the EPS_index is introduced (M5), suggesting that broader environmental policy stringency may absorb part of the variation previously captured by emissions.

The coefficients on the renewable energy share are consistently negative but statistically insignificant across all models. This suggests that, at the aggregate level, increasing the share of renewables does not translate automatically into higher measured energy efficiency, possibly reflecting transitional adjustment costs or the fact that renewables primarily affect the energy mix rather than efficiency per se.

Environmental taxes exhibit a negative long-run effect on energy efficiency, which becomes statistically significant in the most comprehensive specification (M4). This suggests that fiscal instruments may exert a disciplining effect on energy use in the long run, although the magnitude and significance depend on the model specification.

Finally, the EPS_index enters with a negative but statistically insignificant coefficient, indicating that aggregate policy stringency does not have a direct long-run effect on the chosen efficiency measure once other covariates are controlled for.

In the short run, GDP retains a positive and highly significant effect across all specifications, although the estimated coefficients are generally smaller than their long-run counterparts. This demonstrates that cyclical economic expansions are associated with contemporaneous improvements in energy efficiency. Short-run effects of energy prices and GHG emissions are weaker and less consistent. While energy prices become significant in some specifications, and GHG emissions are significant only in Model M2, these effects are not robust across models, suggesting limited immediate adjustment of energy efficiency to price or emission shocks. Short-run coefficients on renewables, environmental taxes, and the EPS_ index are uniformly insignificant, reinforcing the view that policy and structural changes operate primarily through long-run channels rather than immediate responses.

The adjustment term is negative and highly significant in all models, with magnitudes close to unity. This indicates rapid convergence to the long-run equilibrium, suggesting that deviations from the steady-state level of energy efficiency are corrected within one period. The CD statistics and associated p-values suggest that cross-sectional dependence is adequately controlled for in all specifications, supporting the appropriateness of the CS-ARDL framework.

Taken together, the findings suggest that moderately high energy prices and higher GDP per capita contribute positively to energy efficiency in the long run. While this supports a dual strategy of maintaining effective energy price signals and fostering economic growth, caution is warranted. Although higher energy prices do not appear to undermine growth (as no Granger causality from prices to GDP was found, see Table 6 above), these findings are based on in-sample estimates. Extrapolating to out-of-sample scenarios such as sharp administrative energy price hikes would require careful policy consideration.

Robustness checks

To assess the robustness of the baseline results, we re-estimate the core specification using a range of alternative panel estimators that differ in their treatment of dynamics, slope heterogeneity, and cross-sectional dependence. In all cases, the same set of baseline regressors (GDP, energy prices, and GHG emissions) is retained to ensure comparability across models. The results are presented in Table 8.

Table 8. Robustness checks — determinants of energy efficiency estimated with alternative methods

	(1)	(2)	(3)	(4)	(5)
	CCE-pooled OLS in levels	Dynamic CCE-pooled OLS	Dynamic CCE-MG	Dynamic CCE-MG, CSA	CS-ARDL-ECM
GDP	0.976***	0.462***	0.466***	1.192***	1.222***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Energy prices	0.073*	0.129***	0.081***	0.099	0.079
	(0.056)	(0.003)	(0.003)	(0.180)	(0.280)
GHG emissions	−0.059**	−0.038	−0.089	−0.293***	−0.390***
	(0.046)	(0.234)	(0.185)	(0.003)	(0.000)
Lagged energy efficiency			−0.565***	−0.935***	−0.759***
			(0.000)	(0.000)	(0.000)
Adjustment term (ECM)					−1.759*** (0.000)
GHG emissions (long run)					−0.228***
					(0.001)
GDP (long run)					0.694***
					(0.000)

	(1)	(2)	(3)	(4)	(5)
	CCE-pooled OLS in levels	Dynamic CCE-pooled OLS	Dynamic CCE-MG	Dynamic CCE-MG, CSA	CS-ARDL-ECM
Energy prices (long run)					0.046
					(0.286)
Constant	−1.149	−2.355	−0.506*	1.300***	
	(0.367)	(0.159)	(0.082)	(0.007)	
CD-stat			4.312	−0.216	0.084
CD p-value			0.000	0.829	0.933
Observations	513	486	486	486	486
R-squared			0.324	0.213	0.278

p-values in parentheses; * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: own elaboration based on data described in Table 2. Software utilized: STATA 15, package xtdcce2 (Ditzen 2018; 2021).

We first employ a CCE-pooled OLS estimator in levels (Column 1), which provides a static benchmark while controlling for unobserved common factors through cross-sectional averages. The estimated coefficient on GDP is positive and highly significant, while GHG emissions exhibit a negative and statistically significant association with energy efficiency. Energy prices enter with a positive but only marginally significant coefficient. These findings are broadly consistent with the baseline CS-ARDL results, although the static nature of the model limits causal interpretation.

Next, we consider dynamic CCE-pooled OLS specifications estimated in first differences (Column 2). Allowing for dynamics substantially reduces the magnitude of the GDP coefficient, although it remains strongly significant. In contrast, the effect of GHG $_2$ emissions loses statistical significance, suggesting that emission-related effects may operate primarily through longer-run adjustment rather than short-run dynamics. Energy prices remain positive and significant in this specification.

Columns (3) and (4) report results from dynamic CCE mean group (CCE-MG) estimators, which relax the assumption of slope homogeneity across countries. Once heterogeneity is permitted, GDP continues to exert a positive and statistically significant effect, while the coefficients on energy prices and GHG emissions become less stable across specifications. In particular, GHG emissions regain a strong and negative effect when cross-sectional averages are explicitly included in the dynamic CCE-MG model (Column 4), underscoring the importance of adequately controlling for global shocks and common trends.

Finally, Column (5) presents estimates from a CS-ARDL-ECM specification, which conceptually would be the preferred framework, as it explicitly distinguishes between short-run dynamics and long-run equilibrium relationships. The estimated long-run coefficients are qualitatively consistent with the baseline results: GDP positively affects energy efficiency, while GHG emissions exert a negative long-run effect, even when energy prices remain statistically insignificant.

However, the estimated adjustment term is –1.759, indicating an adjustment speed well above unity in absolute value. Such a large coefficient implies overshooting, raising concerns about the stability of the error-correction mechanism. For this reason, and in line with standard practice in the CS-ARDL literature, this estimation strategy is not pursued further.

Overall, the robustness exercises confirm the sign, significance, and economic relevance of GDP as a key determinant of energy efficiency, as well as the generally negative association between GHG emissions and efficiency. At the same time, they underline that policy-relevant variables such as energy prices and emissions are more reliably identified in long-run frameworks with stable adjustment dynamics. Taken together, these results support the baseline findings while justifying our reliance on the stable CS-ARDL specification presented in the main analysis.

Conclusions and Policy Implications

Improving energy efficiency – central to sustainable development strategies – is a cornerstone of EU policy. The "energy efficiency first" principle has been legally codified, obligating member states to prioritize it in all major policy decisions and investments. Despite clear political commitments, progress remains uneven. While the EU's aggregate industrial energy intensity improved by an average of 1.59% annually between 2004 and 2023, statistical analysis reveals significant disparities among member states.

Key findings from the applied econometric CS-ARDL estimates point to economic development as the dominant driver of energy efficiency, while price signals and environmental policies play a more nuanced and specification-dependent role. Structural and policy variables appear to affect energy efficiency primarily through long-run adjustment mechanisms rather than short-run fluctuations. Granger causality tests revealed that energy prices and GHG emissions are causes (in the Granger sense) of energy efficiency, while the relationships between energy efficiency, GDP, and the share of renewable energy are bidirectional.

Our findings are broadly consistent with the existing literature, including Sinevičienė, Sotnyk, and Kubatko (2017), Liu et al. (2020), and Ahmad and Uddin (2025). Similar to all three studies, we identify economic development (GDP) as a robust and positive determinant of energy efficiency, confirming that higher income levels and modernization are closely linked to more efficient energy use. In line with Liu et al. (2020) and Sinevičienė, Sotnyk, and Kubatko (2017), we also find a negative association between emissions and energy efficiency, which reflects the role of pollution intensity or undesirable output in lowering measured efficiency. Our results further resonate with their emphasis on structural and technological upgrading as key transmission channels. In contrast, and closer to Ahmad and Uddin (2025), we employ a CS-ARDL framework that explicitly accounts for cross-sectional dependence; however, while they report a consistently negative effect of energy prices on efficiency, our estimates suggest a positive but less robust price effect, indicating that the role of price incentives strongly depends on the applied measure of energy efficiency and may also be context- and specification-contingent. Overall, the three studies and our results converge on the central importance of growth and decarbonization for improving energy efficiency, while pointing to heterogeneity in how market and policy instruments operate across countries and institutional settings.

This study contributes to the literature in several important ways. First, it provides new cross-country evidence on the determinants of energy efficiency using a CS-ARDL framework that explicitly accounts for cross-sectional dependence, heterogeneous dynamics, and global shocks features that were often overlooked in earlier panel studies. Second, by jointly distinguishing long-run equilibrium relationships from short-run adjustment dynamics, the analysis offers a more nuanced understanding of how economic growth, prices, emissions, and policy-related factors affect energy efficiency over different horizons. Finally, the results yield policy-relevant insights by showing that efficiency gains are primarily driven by long-run structural and decarbonization processes or price evolutions rather than immediate policy, thereby informing the design of growth-consistent and sustainability-oriented energy efficiency strategies.

In summary, moderately high energy prices and higher GDP per capita positively influence energy efficiency in the long run. This indicates that policies should focus on maintaining effective price signals and supporting economic growth, while exercising caution against abrupt administrative price changes. Higher energy prices and carbon costs have dual effects: they encourage investments in efficiency but also risk carbon leakage without proper safeguards. Additionally, geopolitical dynamics and external factors such as the United States' withdrawal from the Paris Agreement create uncertainty and underscore the need for resilient, self-sufficient energy systems and strategic industrial alliances. Separating industrial production from energy consumption requires sectoral transformational interventions. This is also highlighted by "The Clean Industrial Deal," a new document from February 2025, which emphasizes the EU's urgent need to reduce energy intensity in response to high energy costs and global competition. The deal aims to lower energy bills while promoting a transition to clean energy, supporting energy-intensive sectors such as steel and chemicals in decarbonizing and reducing costs. It also seeks to increase demand for EU-made clean products through sustainable procurement criteria and plans to mobilize over €100 billion for clean manufacturing and innovation. Furthermore, it focuses on integrating a circular economy to reduce waste and promote efficient resource use (European Commission 2025). An important initiative appears to be the creation of an integrated platform to monitor progress, share best practices, and enforce compliance. Linking EU financial support to measurable efficiency gains and decarbonization milestones can contribute to fulfilling the EU's dual mandates: climate leadership and industrial competitiveness.

References

Ahmad, M., Uddin, I. (2025), *Enhancing energy efficiency in OECD economies: The role of eco-friendly technology, financial development, and clean energy investment*, "Sustainable Futures", 10, 101258, https://doi.org/10.1016/j.sftr.2025.101258

Akram, R., Chen, F., Khalid, F., Ye, Z., Majeed, M.T. (2020), *Heterogeneous effects of energy efficiency and renewable energy on carbon emissions: Evidence from developing countries*, "Journal of Cleaner Production", 247, 119122, https://doi.org/10.1016/j.jclepro.2019.119122

Ambec, S., Cohen, M.A., Elgie, S., Lanoie, P. (2010), *The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness?*, "SSRN Electronic Journal", 7 (2010s-29), https://doi.org/10.2139/ssrn.1682001

Bressand, A. (2012), *The changed geopolitics of energy and climate and the challenge for Europe. A geopolitical and European perspective on the triple agenda of competition, energy security and sustainability*, "CIEP Paper", 04, https://ciep.energy/media/pdf/uploads/The_changed_geopolitics_of_energy_and_climate_bressand.pdf (accessed: 10.10.2025).

Chudik, A., Pesaran, M.H. (2015), *Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors*, "Journal of Econometrics", 188 (2), pp. 393–420, https://doi.org/10.1016/j.jeconom.2015.03.007

Dechezleprêtre, A., Sato, M. (2017), *The Impacts of Environmental Regulations on Competitiveness*, "Review of Environmental Economics and Policy", 11 (2), pp. 183–206, https://doi.org/10.1093/reep/rex013

Deka, A., Ozdeser, H., Seraj, M., Kadir, M.O. (2023), *Does energy efficiency, renewable energy and effective capital promote economic growth in the emerging 7 economies? New evidence from CS-ARDL model*, "Future Business Journal", 9, 52, https://doi.org/10.1186/s43093-023-00235-y

Ditzen, J. (2018), *Estimating Dynamic Common-Correlated Effects in Stata*, "The Stata Journal: Promoting Communications on Statistics and Stata", 18 (3), pp. 585–617, https://doi.org/10.1177/1536867X1801800306

Ditzen, J. (2021), *Estimating long-run effects and the exponent of cross-sectional dependence: An update to xtdcce2*, "The Stata Journal: Promoting Communications on Statistics and Stata", 21 (3), pp. 687–707, https://doi.org/10.1177/1536867X211045560

European Commission (2008), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – 20 20 by 2020 – Europe's climate change opportunity, COM(2008) 30 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52008DC0030 (accessed: 10.10.2025).

European Commission (2010), Communication from the Commission. Europe 2020, A strategy for smart, sustainable and inclusive growth, COM(2010) 2020 final, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:2020:FIN:en:PDF (accessed: 10.10.2025).

European Commission (2011), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Energy Roadmap $3050, COM(2011) 885 final, https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0885:FIN:EN:PDF (accessed: 10.10.2025).

European Commission (2012), Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance, OJ L 315, https://eur-lex.europa.eu/eli/dir/2012/27/oj/eng (accessed: 10.10.2025).

European Commission (2018), Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank. A Clean Planet for All – A European strategic long-term vision for a prosperous, modern, competitive and climate-neutral economy, COM/2018/773 final, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773 (accessed: 10.10.2025).

European Commission (2019), Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal, COM/2019/640 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640 (accessed: 10.10.2025).

European Commission (2021a), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. "Ready for 55": achieving the EU's 2030 climate target on the road to climate neutrality, COM(2021)550, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0550 (accessed: 10.10.2025).

European Commission (2021b), Commission Staff Working Document. Strategic dependencies and capacities Accompanying the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Updating the 2020 New Industrial Strategy: Building a stronger Single Market for Europe's recovery, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52021SC0352 (accessed: 10.10.2025).

European Commission (2022), Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. REPowerEU Plan, COM/2022/230 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52022DC0230 (accessed: 10.10.2025).

European Commission (2025), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. The Clean Industrial Deal: A joint roadmap for competitiveness and decarbonisation, COM(2025) 85 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52025DC0085 (accessed: 10.10.2025).

European Council (2014), Conclusions on 2030 Climate and Energy Policy Framework, https://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145356.pdf (accessed: 10.10.2025).

European Environment Agency (2023), *Trends and projections in Europe 2023*, https://www.eea.europa.eu/en/analysis/publications/trends-and-projections-in-europe-2023 (accessed: 10.10.2025).

European Parliament and the Council of the European Union (2023), Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast), https://eur-lex.europa.eu/eli/dir/2023/1791/oj (accessed: 10.10.2025).

Eurostat (2025a), *EU primary energy consumption decreased by 4% in 2023*, https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20241220-1 (accessed: 20.02.2025).

Eurostat (2025b), *Domestic net greenhouse gas emissions*, https://ec.europa.eu/eurostat/databrowser/view/sdg_13_10/default/table?lang=en (accessed: 25.03.2025).

Eurostat (2025c), *Environmental taxes by economic activity (NACE Rev. 2)*, https://ec.europa.eu/eurostat/databrowser/view/env_ac_taxind2/default/table?lang=en (accessed: 12.10.2025).

Evan, T., Holý, V. (2021), *Economic conditions for innovation: Private vs. public sector*, "Socio-Economic Planning Sciences", 76, 100966, https://doi.org/10.1016/j.seps.2020.100966

Eyl-Mazzega, M.-A., Mathieu, C. (2019), *Strategic dimensions of the energy transition. Challenges and responses for France*, Germany and the European Union, Institut Français des Relations Internationales, Etudes de l'IFRI, Paris.

Goldthau, A., Keim, M., Westphal, K. (2018), *The Geopolitics of Energy Transformation. Governing the Shift – Transformation Dividends, Systemic Risks and New Uncertainties*, "Stiftung Wissenschaft und Politik (SWP), SWP Comment" No. 42, October, https://www.swp-berlin.org/en/publication/the-geopolitics-of-energy-transformation (accessed: 10.10.2025).

Hafner, M., Tagliapietra, S. (2020), *The Global Energy Transition: A Review of the Existing Literature*, [in:] M. Hafner, S. Tagliapietra (eds.), *The Geopolitics of the Global Energy Transition*, "Lecture Notes in Energy", Vol. 73, Springer, Cham, pp. 1–24, https://doi.org/10.1007/978-3-030-39066-2_1

Hallegatte, S., Bangalore, M., Bonzanigo, L., Fay, M., Kane, T., Narloch, U., Rozenberg, J., Treguer, D., Vogt-Schilb, A. (2016), *Shock Waves: Managing the Impacts of Climate Change on Poverty*, World Bank, Climate Change and Development, Washington, https://openknowledge.worldbank.org/server/api/core/bitstreams/aa3a35e0-2a20-5d9c-8872-191c6b72a9b9/content (accessed: 10.10.2025).

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

IRENA (2019), *A New World. The Geopolitics of the Energy Transformation*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jan/Global_commission_geopolitics_new_world_2019.pdf (accessed: 15.03.2025).

Kao, C. (1999), *Spurious regression and residual-based tests for cointegration in panel data*, "Journal of Econometrics", 90 (1), pp. 1–44, https://doi.org/10.1016/S0304-4076(98)00023-2

Klecha-Tylec, K., Pach-Gurgul, A., Ulbrych, M. (2024), *The European Union energy transition in the context of the Fit for 55 and REPowerEU strategies*, "Horizons of Politics", 15 (53), pp. 225–246, https://doi.org/10.35765/hp.2758

Król, M., Makieła, K., Mamica, Ł. (2025), *Towards a cleaner environment: Determinants of willingness to pay for clean air and renewable energy in Poland*, "Entrepreneurial Business and Economics Review", 13 (3), pp. 201–214, https://doi.org/10.15678/EBER.2025.130311

Lescaroux, F. (2008), *Decomposition of US manufacturing energy intensity and elasticities of components with respect to energy prices*, "Energy Economics", 30 (3), pp. 1068–1080, https://doi.org/10.1016/j.eneco.2007.11.002

Levin, A., Lin, C.-F., Chu, C.-S.J. (2002), *Unit root tests in panel data: asymptotic and finite-sample properties*, "Journal of Econometrics", 108 (1), pp. 1–24, https://doi.org/10.1016/s0304-4076(01)00098-7

Liu, H., Zhang, Z., Zhang, T., Wang, L. (2020), *Revisiting China's provincial energy efficiency and its influencing factors*, "Energy", 208, 118361, https://doi.org/10.1016/j.energy.2020.118361

Odyssee (2025), *Odyssee database*, https://odyssee.enerdata.net/ (accessed: 5.04.2025).

OECD (2025a), *Environmental tax*, https://www.oecd.org/en/data/indicators/environmental-tax.html (accessed: 5.04.2025).

OECD (2025b), *OECD Environmental Policy Stringency Index*, https://data-explorer.oecd.org/vis?lc=en&df[ds]=dsDisseminateFinalDMZ&df[id]=DSD_EPS%40DF_EPS&df[ag]=OECD.ECO.MAD&dq=.A..&pd=%2C&to[TIME_PERIOD]=false (accessed: 5.04.2025).

Pach-Gurgul, A., Śmiech, S., Ulbrych, M. (2020), *The effect of energy prices on energy intensity improvement – the case of the chemical industry in the V4 countries*, "Post-Communist Economies", 33 (5), pp. 566–580, https://doi.org/10.1080/14631377.2020.1793605

Phylipsen, G.J.M., Blok, K., Worrell, E. (1997), *International comparisons of energy efficiency – Methodologies for the manufacturing industry*, "Energy Policy", 25 (7–9), pp. 715–725, https://doi.org/10.1016/S0301-4215(97)00063-3

Proskuryakova, L., Kovalev, A. (2015), *Measuring energy efficiency: Is energy intensity a good evidence base?*, "Applied Energy", 138, pp. 450–459, https://doi.org/10.1016/j.apenergy.2014.10.060

Sallam, M.A.M., Sadraoui, T. (2025), *Energy Efficiency and Industrial Competitiveness: Case Study of the GCC Region Using CS-ARDL and PMG-ARDL Approach*, "International Journal of Energy Economics and Policy", 15 (4), pp. 454–464, https://doi.org/10.32479/ijeep.19425

Sinevičienė, L., Sotnyk, I., Kubatko, O. (2017), *Determinants of energy efficiency and energy consumption of Eastern Europe post-communist economies*, "Energy & Environment", 28 (8), pp. 870–884, https://doi.org/10.1177/0958305X17734386

Skoczkowski, T., Bielecki, S. (2016), *Efektywność energetyczna – polityczno-formalne uwarunkowania rozwoju w Polsce i Unii Europejskiej*, "Polityka Energetyczna/Energy Policy Journal", 19 (1), pp. 173–184.

Song, F., Liu, Z., Hussain, H. (2025), *Assessing the role of energy efficiency, environmental policy stringency, and green energy for achieving carbon neutrality goals in BRICS economies*, "Energy Strategy Reviews", 57, 101546, https://doi.org/10.1016/j.esr.2024.101546

Stern, D.I. (2003), *The Environmental Kuznets Curve*, [in:] *Internet Encyclopaedia of Ecological Economics*, https://isecoeco.org/pdf/stern.pdf (accessed: 15.10.2025).

United Nations (2015), Paris Agreement, http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf (accessed: 21.06.2024).

Zhang, L., Mu, R., Zhan, Y., Yu, J., Liu, L., Yu, Y., Zhang, J. (2022), *Digital economy, energy efficiency, and carbon emissions: Evidence from provincial panel data in China*, "Science of The Total Environment", 852, 158403, https://doi.org/10.1016/j.scitotenv.2022.158403

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Zarządzanie transformacją energetyczną: stymulowanie poprawy efektywności energetycznej w przemyśle UE

Artykuł koncentruje się na identyfikacji kluczowych czynników determinujących poprawę efektywności energetycznej w sektorze przemysłowym Unii Europejskiej w latach 2004–2023. Analiza została osadzona w strategicznych ramach Europejskiego Zielonego Ładu oraz pakietu „Fit for 55” i odnosi się do wyzwania, jakim jest przyspieszenie transformacji energetycznej przemysłu przy jednoczesnym utrzymaniu jego globalnej konkurencyjności. W badaniu zastosowano model CS-ARDL (*Cross-Sectionally Augmented Autoregressive Distributed Lag*), który pozwala uwzględnić zależności przekrojowe oraz zróżnicowaną dynamikę krótkookresową pomiędzy państwami członkowskimi. Wyniki empiryczne wskazują, że wzrost gospodarczy oraz rosnące ceny energii stanowią istotne determinanty poprawy efektywności energetycznej przemysłu zarówno w krótkim, jak i długim okresie. Z kolei wyższy poziom emisji CO_2 wiąże się z niższą efektywnością energetyczną, co odzwierciedla utrzymującą się zależność od produkcji energochłonnej i wysokoemisyjnej. Uzyskane rezultaty podkreślają potrzebę spójnego łączenia modernizacji struktury gospodarczej z bodźcami cenowymi jako warunku realizacji unijnych celów klimatycznych.

Słowa kluczowe: CS-ARDL, efektywność energetyczna, transformacja energetyczna, przemysł UE