Balancing economic growth and emission reductions: an empirical study of the European Union

Anita Zombory
PhD student at
the Doctoral School of Economics,
University of Szeged,
professor of economics,
Szeged, Hungary
Email: zombory.anita@gmail.com

A key problem today is reducing greenhouse gas (GHG) emissions and environmental damage without hampering economic growth. This study aims to analyse the main determinants of GHG in the European Union (EU) countries for the period 2004–2022 in view of the Paris Agreement and the Green Deal objectives. This analysis aims to examine the validity of the environmental Kuznets curve (EKC) in EU member states. We aim to explore if any increase in foreign direct investment (FDI) and the share of the service sector shows significantly effective carbon dioxide (CO_2) emissions. The results show if economic growth (real gross domestic product [GDP] per capita), final energy consumption per capita, and the share of fossil fuels have a significant positive effect on GHG emissions. Reducing fossil fuels and increasing energy efficiency can lower emissions. The significant impact of capital leakage on CO_2 emissions cannot be clearly determined from the panel analysis. Growth in the services sector's share of GDP contributes to emission reductions. Fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS), fixed effect, random effect panel models, cointegration models, *k*-means cluster analysis and comparative analysis were used for the analysis. The models suggest a possible turning point in the EKC; however, due to the complexity of the phenomenon, the hypothesis cannot be clearly confirmed for all 27 member states.

Keywords:
environmental Kuznets curve hypothesis,
European Union,
fully modified ordinary least squares,
dynamic ordinary least squares,
outward foreign direct investment,
CO_2 emissions

Regional Statistics, Vol. 16. No. 3. 2026
Online first: Zombory 1–41; DOI: 10.15196/RS160307

Introduction

Climate change and environmental sustainability have received increasing attention in recent decades at the global and regional levels. The reduction in greenhouse gas (GHG) emissions has emerged as a high-priority objective in international political and economic discourse, especially for the European Union (EU), which has made ambitious climate policy commitments under the Paris Agreement and the European Green Deal. To effectively mitigate climate change, it is essential to identify the key drivers of emissions and understand their action mechanisms.

This study aims to identify variables that significantly influence per capita CO_2 emissions. Specifically, we examined if the environmental Kuznets curve (EKC) hypothesis holds for the 27 of the European Union (EU) member states. The analysis explores if outward foreign direct investment (OFDI) as a percentage of GDP, and the size of the services sector relative to GDP, are associated with per capita CO_2 emissions.

Furthermore, this study critically evaluates the EKC hypothesis – particularly the claim that foreign direct investment (FDI) can play a meaningful role in reducing a country's carbon emissions. We also assessed how the expansion of the services sector influences emission levels.

This research may contribute toward evaluating the effectiveness of the EU's climate policy measures and support the further development of the Sustainable Development Strategy by identifying key factors that drive emission reductions.

Green Deal policy objectives

The Green Deal is a communication presented by the European Commission (EC) (December 11, 2019), which is a package of policy measures [1] committed to environmental action. Its primary objective is preserving the EU's natural capital and protecting public health. A key priority of the European Green Deal is the creation of a resource-efficient and competitive economy that achieves net-zero GHG emissions by 2050 (Hafner–Tagliapietra 2020). It aims to achieve economic growth without using excess resources such as energy. To reduce environmental degradation, the United Nations adopted the Paris Agreement, a multilateral [2] accord that entered into force on November 4, 2016 [3]. The EU member states are united in their commitment to reduce GHG emissions and keep the global temperature rise below 2°C, with specific targets. The EC adopted the European Climate Action Plan in 2021, establishing that the EU and its member states have a legal obligation to reduce emissions [4]. A press release from the EU on October 17, 2023 [5] announced that the EC had approved the EU's submission for an updated NDC (nationally determined contribution) to reduce net GHG emissions by at least 55% by 2030 compared with 1990 levels. The EU's long-term strategy to meet its environmental targets includes increasing the use of renewable energy sources, improving energy efficiency, and promoting greener agriculture and transport, such as electric vehicles [6]. To improve energy security, the EC presented a REPowerEU plan on May 18, 2022, in response to by the Russian–Ukrainian war. The plan aims to quickly reduce the EU's dependence on Russian imports of natural gas, coal, and oil. As a result, promoting EU energy autonomy and the transition to clean energy has emerged as a priority. The main objectives of the plan are energy savings, including reducing energy consumption [7] diversification of energy supply and faster deployment of renewable energy sources [8]. The EU has committed to reduce GHG emissions by 80–95% by 2050 compared with 1990 levels [9]. As stated in the EU energy roadmap 2050 (ER2050), the transition from fossil fuels to renewable energy sources is not only important, but the key objectives are to reduce final energy use and implement decarbonization processes (Nieto et al. 2020). The issues of environmental degradation and climate change cannot be confined to a single country or region but must be addressed at the global level. Of course, possible solutions are not only being considered for the EU member states, but also for countries worldwide. The focus is on the relationship between environmental degradation and economic growth, for which the environmental Kuznets hypothesis serves as a theoretical and empirical framework (Leal–Marques 2022). The EKC is one of the most widely used methods for analysing environmental performance. It is an inverted U-shaped curve, derived from Kuznets' work in 1955, which originally investigated the relationship between income and income inequality. Since then, the EKC has been widely used to study the relationship between environmental protection and economic development. The EKC shows that environmental degradation increases rapidly during the early stages of economic growth, while at a certain level of income, the tipping point, degradation begins to decline as clean technologies and innovations spread (Kuznets 2019).

Conceptualizing the Kuznets environmental curve

The concept of the EKC was introduced in the early 1990s by Grossman–Krueger (1991). The EKC theory was developed to explain the inverted U-shaped relationship between economic development and environmental degradation (Gyamfi et. al 2020, Ekins 1997). A significant body of research focuses on the EKC phenomenon, which suggests an inverse relationship between economic growth and environmental degradation (Kuznets 2019, Stern 1998, 2004). Studies have extended the relationship between income and carbon emissions to other macroeconomic factors, such as energy consumption. Shahbaz et al. (2015) investigated the impact of urban growth and energy consumption In Malaysia, specifically pollution between 1970 and 2011. They showed that energy consumption increases pollution, while urban growth is inversely related to pollution (Shahbaz et al. 2015).

Using the Google Scholar search engine, we collected publications that explicitly measured the relationship between environmental degradation and economic growth and modelled the validity of the EKC. The basic question that arises in the literature is how GDP growth affects CO_2 emissions while considering additional indicators. In all these cases, the aim is to examine if an inverted U-shaped curve can be observed. That is, when development attains a certain level in the economy, does the direction of the curve reverse, at which point CO_2 emissions begin to decline (Sinha et al. 2019). This study investigates the relationship between GDP growth, energy use, energy intensity, the share of renewable energy, clean and fossil energy, and CO_2 emissions. Table 1 shows the indicators used for the analysis and consolidates studies that have examined the fulfilment of the EKC hypothesis.

Table 1

Indicators used for analysis

Variables	Unit of measurement	Literature	Description
Net GHG emissions per capita[a] 2004–2022	TOE per capita (tons per capita, CO_2 equivalent)	All literature cited is included.	Greenhouse gas emissions per capita, measured in tons of CO_2 mass equivalent.
Final energy consumption per capita[b] 2004–2022	TOE per capita	Leal–Marques (2022), Le–Ozturk (2020), Sulaiman–Abdul-Rahim (2017), Koc–Bulus (2020)	Final energy uses per capita, which includes end-users such as services, industry.
Renewables, clean energy share[c] 2004–2022	%	Gill et al. (2018), Bilgili et al. (2016), Jebli et al. (2016), Sarwat et al. (2022)	Share of renewables in total energy consumption; clean energy includes nuclear energy.
Share of fossil energy[c] 2004–2022	%		Share of fossil energy in total energy consumption.
Real GDP per capita[d] 2011–2022	Euro (2010) per capita	All cited literature included.	GDP measures the total value of final goods and services produced by the economy over a given period.
Energy intensity[e] 2004–2022	MJ/thousand USD (2015)	Bekun et al. (2021), Grossman–Krueger (1991), Du et al. (2019), Ahmad–Wu (2022)	The amount of energy used to produce unit GDP, which indicates the economic efficiency of energy use.
Energy productivity[f] 2004–2022	Euro/kg oil equivalent		GDP produced by using one unit of gross energy (energy equivalent to 1 kg of oil).

Sources: a) [10], b) [11], c) [12], d) [13], e) [14], f) [15].

Final energy consumption has become the most frequently added variable for the EKC estimates. Energy consumption, as a major driver of environmental degradation and climate change, has been analysed together with several environmental indicators. The inclusion of energy consumption in the assessment of the EKC has been done in parallel with the model development (Leal–Marques 2022). The results reported by Le–Ozturk (2020) show that globalization and energy consumption increase CO_2 emissions. Their study evaluated the relationship between CO_2 emissions and energy consumption in the Malaysian economy between 1975 and 2015. Their findings show that energy consumption and CO_2 emissions have no effect on economic growth, while energy consumption and economic growth have a positive effect on CO_2 emissions (Sulaiman–Abdul-Rahim 2017). Koc–Bulus (2020) investigated the dynamic short- and long-term correlations between GDP per capita, energy consumption per capita and carbon dioxide (CO_2) emissions per capita in South Korea between 1971 and 2017. The results of the ARDL model show that increases in GDP per capita and energy consumption increases CO_2 emissions per capita. Final energy uses per capita measure the final use of energy in a country, excluding non-energy uses of energy carriers [11].

Gill et al. (2018) investigated the existence of the EKC in Malaysia for the period 1970–2011. The study also examines the potential of renewable energy sources to mitigate GHG emissions. The long-run significant positive coefficient of GDP indicates that GHG emissions increase with economic growth. The results suggest that Malaysia needs a high GDP level to reach the tipping point of the EKC. Therefore, it can be argued that economic growth alone cannot reverse environmental degradation in Malaysia. Bilgili et al. (2016) used CO_2 emissions as the dependent variable and GDP, GDP squared, and renewable energy consumption as independent variables. The results support the EKC hypothesis for the panel and show that GDP per capita has a positive impact and GDP^2 per capita has a negative effect on CO_2 emissions, whereas renewable energy consumption has a negative effect on CO_2 emissions. Jebli et al. (2016) investigate the causal relationships between CO_2 emissions, gross domestic product (GDP) per capita, renewable and non-renewable energy consumption, and international trade for 25 OECD (Organisation for Economic Co-operation and Development) countries over the period 1980–2010. The results also show that increasing non-renewable energy consumption increases CO_2 emissions. Higher trade levels or increased use of renewable energy reduce CO_2 emissions. These results suggest that increased trade and greater use of renewable energy are effective strategies to combat global warming. Sarwat et al. (2022) aimed to verify the EKC hypothesis for BRICS (Brazil, Russia, India, China, South Africa, Egypt, Ethiopia, Iran, Saudi Arabia, United Arab Emirates, Indonesia) countries, considering the factors of natural resources, renewable energy, and globalization. The heterogeneous panel causality test also confirms a two-way Granger causality relationship between all variables and CO_2 except globalization, which means the results of the causality analysis on panel data are consistent with the results obtained using the method of moments quantile regression (MMQR), that is, one method confirms the conclusions of the other. On this basis, it is recommended to promote the use of renewable energy sources in BRICS countries.

Table 2

Statistical methodology used in publications to prove the environmental Kuznets hypothesis

Methodology	Additional variables for EKC hypothesis analysis	Resources	Results	Areas
CO_2 emissions GDP				
ARDL	GDP per capita, energy consumption per capita, renewable energy consumption per capita, trade openness, and carbon dioxide (CO_2) per capita	Koc–Bulus (2020)	EKC N-shaped curve	South Korea (1971–2017)
ARDL, OLS	Renewable energy consumption	Gill et al. (2018)	The tipping point has not been reached	Malaysia (1970–2011)
FMOLS, DOLS	Renewable energy consumption	Bilgili et al. (2016)	EKC (inverted U-shape)	17 OECD countries (1977–2010)
FMOLS, DOLS	Renewable and non-renewable energy consumption	Jebli et al. (2016)	EKC (inverted U-shape)	25 OECD countries (1980–2010)
FMOLS, DOLS	Renewable energy consumption	Sarwat et al. (2022)	EKC (inverted U-shape)	BRICS (1990–2014)
Dynamic panel	Patent	Balin–Akan (2015)	EKC N-shaped curve	27 developed countries (1997–2009)
ARDL	Patent	Oyebanji et al. (2022)	EKC N-shaped curve	Spain
FEQR	Patent	Li et al. (2021)	EKC (inverted U-shape)	China
Patent model	Patent	Raza et al. (2022)	EKC (inverted U-shape)	Pakistan
Dynamic panel	Energy intensity	Bekun et al. (2021)	EKC (inverted U-shapes)	EU (1990–2017)
ARDL	Energy consumption, agriculture, industry, services sector emissions	Songur et al. (2024)	EKC met in all, except industrial sector	38 OECD countries

Source: author's own contribution based on Google Scholar.

Bekun et al. (2021) investigated Granger causality between GDP growth and carbon emissions. A similar causal direction is observed between energy intensity and carbon emissions. Both have a significant impact on the environment.

The relationship between greenhouse gases per capita, economic growth, R&D, and renewable energy was studied in 28 OECD countries between 1994 and 2010. They found that R&D reduces the impact of GHG emissions in these countries. Scale, composition, and technology effects are the three stages that characterize the relationship between environmental degradation and economic development. The scale effect indicates that economic development increases environmental degradation, that is, economic growth has a negative impact on the environment. Negative impact is the result of the intensive use of resources to meet the growing demand and output. This intensive consumption of energy is from fossil fuels, which are cheap, abundant, and easy to transport. The composition effect is characterized by structural changes in the economy, which can have either positive or negative effects on the environment because of economic development (Grossman–Krueger 1991). The technology effect refers to the mitigating effect of economic development on environmental degradation. This is attributable to the fact that higher income levels increase investment in R&D, replacement of old and polluting technologies, and the introduction of stringent environmental regulations (Du et al. 2019, Ahmad–Wu 2022). Table 2 shows the statistical methods used in publications to analyse the environmental Kuznets hypothesis.

Testing the validity of the environmental Kuznets hypothesis using statistical methods

A dynamic panel model was used for the analysis. Panel regression is a statistical analysis method used to examine panel data, also known as longitudinal data. Panel data are multiple observation units, such as countries, and are repeatedly recorded over time. They include both a temporal and a cross-sectional dimension. Panel regression is used to model phenomena in which we want to understand changes over time, such as the economic growth of a country over time. Alternatively, we want to consider individual differences between observation units, for example the impact of different economic structures across countries. Panel regression enables to separate time and individual effects and provides precise estimates than a simple cross-sectional or time-series analysis (Wooldridge 2010).

We applied the fixed effect model (FE) panel data modelling technique, which is often used when the data comprise of both a time and a cross-sectional dimension (panel data) as the aim is to account for the unique unobserved characteristics of cross-sectional units, such as countries. The fixed effect model addresses the specific unobserved characteristics of each cross-sectional unit to avoid confounding the effects of other variables. The basic assumption of FE is that each cross-sectional unit, in this case a country, has a specific characteristic that is constant over time and that affects the dependent variable. These specific effects are called “fixed effects”, and the model aims to consider these effects so that more accurate estimates can be obtained. The fixed-effects model is based on ordinary least squares (OLS) estimation with the condition that there is no autocorrelation or heteroskedasticity in the residuals (Wooldridge et al. 2016).

$$y_{it} = \alpha_i + \beta x_{it} + \varepsilon_{it}$$

where y_{it} is the dependent variable, CO_2 emissions per capita, for the i-th cross-sectional unit for the 27 EU member states and for the t-th period 2004–2022. α_i is a unique unobservable effect for the i-th unit that remains constant over time and is thus treated as a fixed effect. It considers individual factors that are not measured but still have an impact on the dependent variable. β is the effect of the independent variables. x_{it} denote independent variables (fossil, renewable, clean energy share, real GDP per capita, final energy use per capita, energy intensity, energy productivity and recession changes with dummy variables) for the t-th period of the i-th cross-sectional unit.ε_{it} is the error (residual) term.

In the random effect model (RE), we assume that groups have time-invariant unobserved effects that are uncorrelated with each explanatory variable. The model assumes that individual effects are uncorrelated with the explanatory variables and are randomly distributed across cross-sectional units. This model allows for variability between cross-sectional units without explicitly accounting for the effect of individual characteristics. The requirements for the random effects model include the absence of autocorrelation, homogeneity of the error term, and the assumption that the country-specific effect is independent of all explanatory variables during all time periods.

$$y_{it} = \beta_0 + \sum \beta_p x_{it} + v_{it}$$

The dependent variable y_{it} is CO_2 emissions per capita for the i-th cross-sectional unit for 27 EU member states and t-th period 2004–2022. β_0 is the general intercept (constant). x_{it} is the explanatory variable for the i-th cross-sectional unit t-th period. β_p are the coefficients of the explanatory variables. The random effect is associated with the i-th cross-sectional unit, which is unique but varies across units. This random effect represents the variation between cross-sectional units. v_{it} is a pooled error term (Wooldridge 2010).

The inverse chi-square, inverse normal test and logit tests in Appendix Table A1 are typically used to assess for panel unit roots and the stationarity of the variables over time. The inverse chi-square measures the extent to which variable deviates from the assumption that there is a unit root, that is non-stationary. All the variables have very high values (around 125–130), indicating that the test strongly rejects the null hypothesis of a unit root. Thus, the variables, that is, their behavior over time, can be considered stable. The inverse normal test uses the inverse of the normal distribution to assess for unit roots. The values are negative (between about –6.7 and –6.9) for all variables, indicating that the null hypothesis of a unit root can be rejected at a conventional significance level. Thus, the temporal pattern of the variables is constant, as there is no evidence of temporal instability. The logit test uses logit-transformed data to test for the presence of unit roots. Again, the results are negative (between about –6.4 and –6.6) and significant, confirming that we can reject the null hypothesis for the presence of a unit root. Thus, the temporal behavior of variables is stationary, that is, there are no unit roots. All variables are significant, and this is particularly important as the presence of unit roots may bias the results.

The statistical indicators in Appendix Table A2 describe the basic properties of the data, including distributions, standard deviations, and tests of normality. The data range widely, indicating heterogeneity of the data. The median value of real GDP per capita is below the mean at 20,705; which indicates that some very high values pull the mean upwards. Standard deviation shows the dispersion of data around the mean. The standard deviation of real GDP per capita is very high (16,862.9), indicating that economic development varies significantly across countries. Energy intensity has a smaller standard deviation, suggesting a narrower distribution of values. Skewness measures the asymmetry of the distribution. Positive skewness (real GDP per capita, final energy consumption): the distribution is skewed to the right, that is, there are some very high values alongside several lower values. Negative skewness for renewable energy, the distribution is skewed to the left, as most of the data are concentrated around the higher values. Kurtosis (peakedness) measures the degree to which distribution is more or less peaked than a normal distribution. A high value of Kurtosis (9.8) for final energy consumption indicates that the distribution is sensitive to extreme values and has a long tail. Negative kurtosis for fossil energy, clean energy indicates flatter distributions, with data less concentrated around the mean. The Doornik–Hansen test, Shapiro–Wilk and Jarque–Bera tests examine if variables follow a normal distribution. Low p-values (usually below 0.05) indicate that the distribution is significantly different from normal. For all variables, the p-values are very low, such as for real GDP per capita at 6.59334e–64, indicating that the data do not follow a normal distribution. It can be concluded that distribution of the data is not normal; therefore, the use of non-parametric methods may be justified. Some of the variables show extreme values (e.g., real GDP per capita, fossil fuel use), indicating differences between countries. Therefore, the data must be transformed to make them more manageable for further analysis.

The variables were also tested for multicollinearity. Multicollinearity refers to a strong correlation between explanatory variables in a regression model. This can cause problems in the analysis as it reduces the ability to accurately measure the impact of each explanatory variable and can make the estimated coefficients unstable. Variance inflation factor (VIF) values were used to check the degree of multicollinearity. The VIF measures the extent to which a given variable is correlated with other explanatory variables (Wooldridge 2019).

$$\mathrm{VIF}_j=\frac{1}{1-R_j^2}$$

VIF ≤ 1: no multicollinearity. 1 < VIF ≤ 5: acceptable level of multicollinearity, analysis is generally reliable. 5 < VIF <10: high multicollinearity, which may be a problem. VIF> 10: severe multicollinearity that needs to be addressed because the accuracy of the coefficients and the stability of the model are at risk (Wooldridge et al. 2016).

All variables have a VIF below 5 (see in Appendix Table A3), which indicates that there is no significant multicollinearity in the model. After testing for data reliability, panel models were used to find significance in the factors affecting CO_2 emissions. The dependent variable is CO_2 emissions per capita, for which the variables are listed in Table 3. The first differential of the data, the change over time, was considered.

Table 3

Short-term impact models

Variables	RE		FE	
	coefficient	p-value	coefficient	p-value
Constants (β0)	0.363598	0.0168**	0.358037	0.0335**
Recession dummy variables	0.380014	0.0230**	0.364658	0.0409**
Paris agreement dummy variables	–0.402146	0.0091***	–0.395546	0.0179**
d_real_GDP_per_capita	8.54606e–05	0.2780	9.02344e–05	0.2727
d_real_GDP_per_capita^2	4.07138e–09	0.3735	4.39513e–09	0.3469
d_finerenergy_cons_per_capita	2.45929	<0.0001***	2.36027	0.0034***
d_energyproductivity	–0.605100	0.0473**	–0.628350	0.0801*
d_ren_energy_tot_cons	–0.0142573	0.5952	–0.0101448	0.7081
d_services value added gdp	–0.0816620	0.0193**	–0.0737334	0.0621*
d_net_outflow_gdp%	–0.0003259	0.0719*	–0.000327701	0.0833*
Durbin–Watson statistics				2.07
R^2		0.6096		0.43
Wooldridge test		0.128		0.128
Durbin–Watson		2.07		
Breusch–Pagan test		0.07278		
Rho		–0.0730		
Wald joint test				6.03713e–16
Hausman test		0.426		
F-statistic				0.00001
Joint		0		1.01172e–07

Note: * p<0.05; ** p<0.01; *** p<0.001.
Source: author's own contribution using Gretl software.

Table 3 shows the results of the short-term panel models. Based on the results of the random effects (RE) and fixed effects (FE) regressions, the annual change in GHG emissions is determined by the structure of energy use and the economic structure. In both models, fossil energy consumption has a significant and strong positive effect on emissions, implying that any increase in fossil energy use increases emissions directly and immediately. This correlation is particularly strong in the

RE model ($\beta = 2.459$; $p < 0.0001$) but also significant in the FE model ($\beta = 2.360$; $p = 0.0034$), confirming the dominant role of fossil energy in short-term environmental pressures. In contrast, technical energy efficiency, that is, energy output per unit input, is negatively signed and significant in the RE model ($\beta = -0.605$; $p = 0.0473$), while it appears as a marginal case in the FE model ($p = 0.0801$), suggesting that technological progress and efficient energy production can reduce emissions in the short term. A similar positive effect is observed for economic structural change, with an increase in the service sector's share of GDP reducing emissions in both models (RE: $\beta = -0.0817$; $p = 0.0193$), indicating that the shift from industrial production to a knowledge and service-based economy is associated with annual emission reductions. The impact of political events can also be detected. In the post-Paris climate agreement period, emissions decreased significantly, indicating that international climate policy commitments can influence environmental performance in the short term. The effect of GDP and the Kuznets curve is not confirmed in the short-term models: neither GDP nor its squared term is significant in either model. This suggests a nonlinear relationship between economic growth and environmental pressure, which may be predictable in the long term but not evident in the short run. The statistical reliability of the models is supported by several diagnostic tests. The Durbin–Watson statistic is around 2 in both models, confirming that there is no autocorrelation between the residuals. As the Wooldridge test is also non-significant ($p = 0.128$), there is no first-order autocorrelation in the panel structure. The Hausman test ($p = 0.426$) result indicates that the random effects model is not biased and can, therefore, be reliably fitted. The R^2 value of the RE model (0.6096) is higher than that of the FE model (0.43), indicating a better fit to the differenced data. Overall, the short-term models suggest that the fundamental drivers of emission variations are the type of energy use, economic structure, and climate policies. Fossil energy is the dominant driver of emissions, while technical efficiency, penetration of the service sector, and international climate policies are a crucial factor in reducing emissions. The models are robust, well-fitting, and provide a reliable basis for drawing short-term environmental policy conclusions.

The relationship between variables was also examined using cointegration models fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS). These cointegration models are used to examine the long-run equilibrium relationship between economic time series, specifically when the time series are non-stationary but there is a linear combination between them that is stationary. This indicates that although each series may follow a trend or wander randomly on its own, they move together and are linked by a long-run equilibrium relationship. The purpose of this study is to hypothesize or decide if a long-run equilibrium relationship exists between the variables under study (Phillips–Hansen 1990, Kao–Chiang 2000).

The FMOLS (model is a special estimation method that is applied to panel or time series data when there is a long-run cointegrated relationship between variables. In such cases, the traditional OLS method may not be reliable because the residuals are non-stationary or autocorrelated; therefore, the estimated parameters may be biased and inconsistent. This problem is corrected by the FMOLS method, which is suitable for estimating regression relationships where variables move together in the long run but follow separate paths in the short run (e.g., GDP and GHG emissions). The method automatically corrects for autocorrelation and heteroskedasticity between residuals, facilitating reliable statistical inference. The FMOLS parameters converge to the true values (consistency) as the sample size increases, making it ideal for medium- and long-term analysis (Phillips–Hansen 1990).

$$y_t=\beta_0+\beta_{(1)\ x1t}+\beta_{(2)\ x2t}+ u_t$$

In the equation, y_t is the dependent variable, representing GHG emissions per capita. The coefficients $\beta_{1,}$ $\beta_{2,}$ … correspond to the independent variables, including real GDP per capita, share of renewables in total energy consumption, service sector's share as a percentage of GDP, and final energy consumption.

The DOLS is a regression estimation method that is used when there is a long-term cointegrating relationship between the variables under study; however, we also considered the impact of short-term dynamics in the model. The specificity of DOLS is the fact that it extends the classical regression with lagged and "lead" differences of the explanatory variables, thus managing possible dynamic biases and ensuring the parameters are unbiased.

The starting point of the DOLS model is a cointegrated relationship:

$$y_t=\beta_0+\beta_{(1)\ x1t}+\beta_{(2)\ x2t}+ u_t+\sum_{j=-p}^{q}\left(\gamma_j \Delta x_{1,t-j}\right)+\sum_{j=-p}^{q}\left(\delta_j \Delta x_{2,t-j}\right)$$

$$\log(\mathrm{GHG}_{it})= \beta_0+\beta_1\cdot \mathrm{REN\_ERERERGY\_TCON}_{it}+\beta_2\cdot \mathrm{ENERGYPRODUCT}_{it}+\beta_3\cdot \mathrm{SERVICES\_GDP}_{it}+\beta_4\cdot \mathrm{FIENERGYCONSit}+\beta_5\cdot \mathrm{ZLOGREAL\_GDP}_{it}+\beta_6\cdot \mathrm{ZLOGREAL\_GDP}_{it}{}^2+\sum_{j=-p}^{q}\left(\delta_j \Delta x_{2,t-j}\right)$$

The model not only estimates the long-run cointegrating relationship but also incorporates lagged and lead differences of the explanatory variables, thereby correcting for dynamic biases that occur in ordinary least squares regression. This method is especially useful when the economic or social variables under study (e.g., GDP, energy consumption, environmental pressures) exhibit a long-term equilibrium movement but experience short-term deviations or fluctuations. For instance, if the aim is to examine if a structural but not an immediate relationship exists between economic growth and GHG emissions (e.g., EKC hypothesis), DOLS is suitable because it separates long-term equilibrium effects from short-term dynamic fluctuations.

Table 4

Panel analysis of factors affecting CO_2 emissions

Variables	FMOLS		DOLS	
	coefficient	p-value	coefficient	p-value
logreal gdp_per_capita	+1.806	0.0769**	2.7151	0.0906**
zlogreal gdp_per_capita	–11.351	0.1252	–8.5633	0.4504
zlogreal gdp_per_capita^2	7.3909	0.0145**	7.5403	0.0928**
fienergyconsumption_per_capita	+1.105	0.004***	0.8409	0.2104
energyproductivity	–0.511	0.000***	–0.6587	0.0022***
ren_energy_tcon	–0.091	0.000***	–0.0873	0.0000***
services value added of gdp	–0.115	0.000***	–0.1025	0,0043***
lognet_outflow_gdp%	0.0076	0.795	0.0129	0,6307
Pedroni non-deterministic trend				
Panel ADF statistic	–1.66	0.0484**		
Weighted ADF	–2.88	0.0020***		
Group PP-statistic	–3.15	0.0008***		
Pedroni non-deterministic trend				
Panel ADF statistic	–2.35	0.0093***		
Weighted ADF	–3.14	0.0008***		
Group PP-statistic	–2.27	0.0116**		
Pedroni non-deterministic intercept or trend				
Panel ADF statistic	–1.90	0.0286**		
Weighted ADF	–3.21	0.0007***		
Group PP-statistic	–4.56	0.0000***		
Kao residual cointegration test				
ADF	–3.8466	0.0001***		
Durbin–Watson statistic	2.06			

Note: ** p<0.01; *** p<0.001.
Source: author's own contribution using eView software.

Table 4 shows the results of the long-run panel cointegration models. A detailed evaluation of the FMOLS and DOLS models clearly shows that the evolution of CO_2 emissions is permanently influenced by economic growth, the structure of energy use, and the characteristics of the economic structure. These models focus on deeper, equilibrium relationships rather than year-on-year fluctuations, making them particularly well suited for exploring sustainability trends and environmental-economic linkages. The impact of economic growth on emissions is positive in both models, but the relationship is non-linear. The logarithmic of GDP per capita variable is positive and marginally significant (FMOLS: $\beta = 1.806$; $p = 0.0769$; DOLS: $\beta = 2.7151$; $p = 0.0906$), suggesting that economic growth increases CO_2 emissions in the long term. The EKC hypothesis posits that economic growth initially leads to environmental degradation; however, the assumption that environmental indicators start improving after achieving a certain income level is partially justified. The squared term of the standardized GDP (ZLOGREAL_GDP^2) is positive and significant in FMOLS ($\beta = 7.3909$; $p = 0.0145$) and appears as a marginal case in DOLS ($\beta = 7.5403$; $p = 0.0928$). This pattern raises the possibility of an inverted U-shaped relationship where economic growth increases initially and subsequently decreases emissions. However, the linear GDP term is not statistically significant at conversational levels, so the evidence for a stable and robust EKC remains inconclusive.

The structure of energy use is a key determining factor. Fossil energy consumption has a positive effect on emissions and is significant in FMOLS ($\beta = 1.105$, $p = 0.004$), while it does not reach statistical significance in DOLS. This suggests that fossil energy drives emissions in the long term, but the strength of the effect is dependent on the model specification. In contrast, technical energy efficiency, that is, energy output per unit input, has a significant negative effect in both models (FMOLS: $\beta = -0.511$, DOLS: $\beta = -0.6587$), indicating that efficient energy use reduces emissions in the long run. Renewable energy use is also strongly negative and significant in both models (FMOLS: $\beta = -0.091$, DOLS: $\beta = -0.0873$), confirming that renewables contribute substantially in reducing emissions in the long run – even if this effect is not always observable in the short run. The impact of economic restructuring is clearly visible. An increase in the services sector's share in GDP has a significant negative effect on emissions in both models (FMOLS: $\beta = -0.115$, DOLS: $\beta = -0.1025$), indicating that the transformation of the industrial structure of the economy through the expansion of services has a positive environmental impact in the long term. The net capital outflow (lognet_outflow_gdp%) is not significant in any of the models and is, therefore, not considered a determinant of long-term emissions. Cointegration tests confirm the statistical robustness of the models. The significant results of the Pedroni and Kao tests confirm the presence of a long-run equilibrium relationship between the variables under consideration. The value of the Durbin–Watson statistic (2.06) indicates no autocorrelation between the residuals, supporting model stability and reliability. Overall, the FMOLS and DOLS models suggest that the long-term evolution of CO_2 emissions is primarily determined by economic growth, the structure of energy use, and economic structure. Fossil energy and GDP growth increase emissions, while renewable energy, technical efficiency, and the expansion of the service sector reduce emissions. The EKC hypothesis is partially supported but not conclusively established. The models are statistically robust and provide a valuable basis for informing long-term environmental policy decisions.

Statistical test of the EKC hypothesis

Much of the empirical work on the EKC hypothesis assumes a nonlinear relationship between income levels and environmental damage (Panayotou 1993). The calculation of the turning point is based on an econometric regression in which per capita CO_2 emissions are modelled as a function of real GDP per capita and its squared term. This specification allows for empirical testing of the EKC hypothesis for the countries under study over the relevant period.
dif_greenhouse_emissions= $\beta_0 + \beta_1 *$dif_1 real GDP per capita + $\beta_2 *$dif_1 real GDP per capita^2.

This step helps us determine the level of real GDP per capita at which CO_2 emissions per capita turn (i.e., the tipping point). Differentiation involves taking the first derivative of the equation with respect to GDP per capita and setting it to zero to estimate the value where emissions show the largest change.

$$\beta_1 + \beta_2 * \text{dif\_1 real GDP per capita} = 0$$

This regression model is used to determine how the level of GDP per capita (and its squared value) affects countries' CO_2 emissions per capita, and the calculation of the turning point helps to identify the GDP level at which CO_2 emissions change direction.

$$\text{Turning point for } CO_2 \text{ emissions per capita} = \frac{\beta 1}{2\beta 2}$$

The squared GDP variable (d_1 real GDP per capita^2) is a key variable in the empirical modelling, as the inverted U-shaped relationship in the data is precisely demonstrated by the opposite sign coefficients of the linear (d_1 real GDP per capita) and squared (d_1 real GDP per capita^2) terms of GDP. This approach is widely used in the analysis of the EKC curve (Grossman–Krueger 1991, Stern 2004).

Table 5

Regression values of real GDP per capita

Variables	Coefficients	p-value
d_rel_gdp (β1)	0.000149205	0.0035***
d_real_gdp2 (β2)	–1.86391e–08	0.0113**

Note: ** p<0.01; *** p<0.001.

$$\text{Turning point of } CO_2 \text{ emissions per capita} = -\frac{\beta 1}{2\beta 2} = -\frac{0.000149205}{2*-0.0000000186391} =$$
$$3{,}996.97 \text{ euro/capita}$$

If the variables β_1 and β_2 are fitted only to the model, β_2 becomes significant and negative, indicating the turning point.

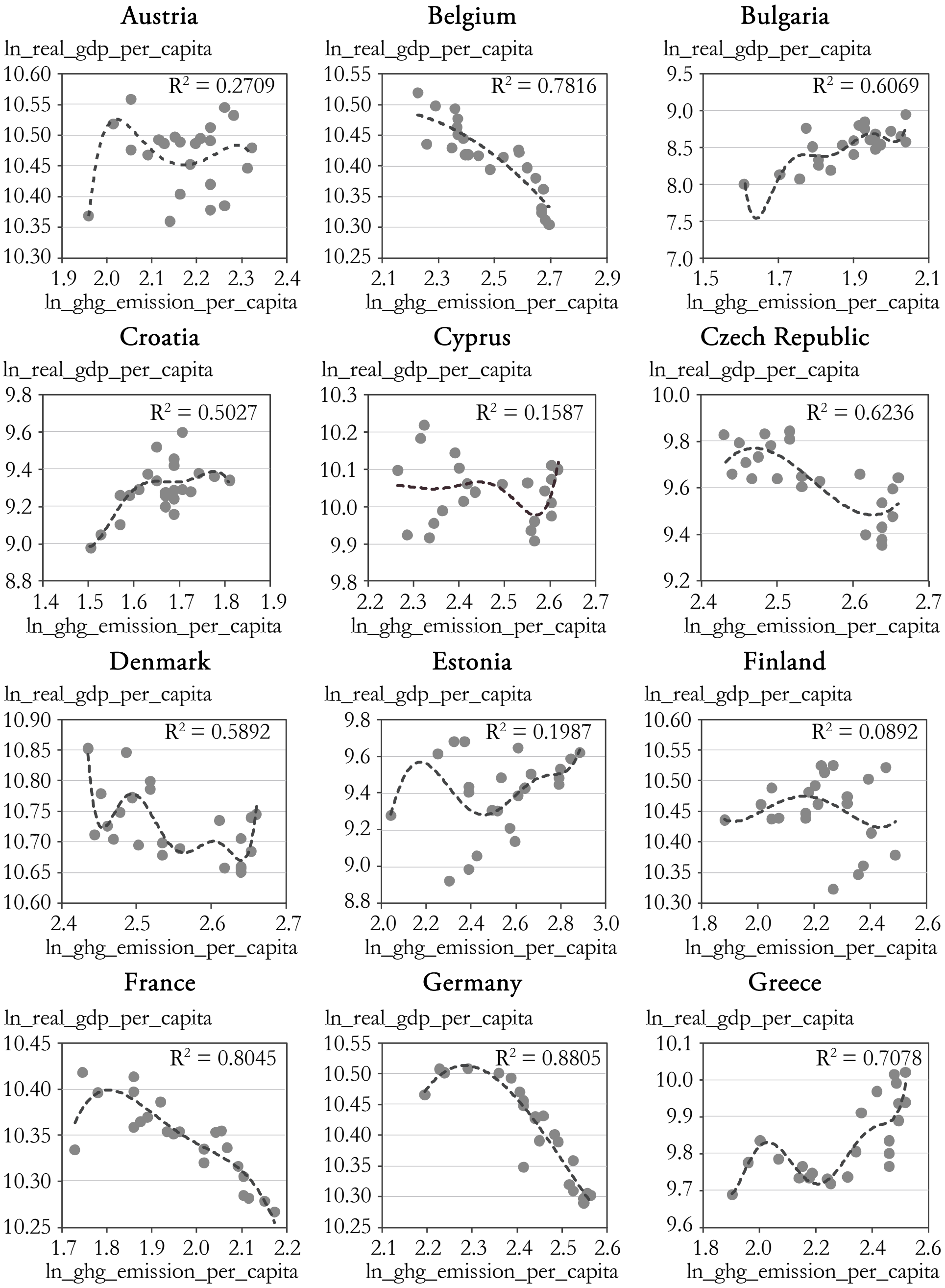
When fitting all other independent variables into the model, as shown in Tables 3–4, β_1 does not show significance, suggesting that the countries have not yet reached the turning point. The squared variable of real GDP per capita is positive and shows a small effect, providing weak evidence for a nonlinear (inverted U-shaped) relationship of the EKC curve.

Next the independent variables using linear regression analysis on the dependent variable are examined. In Appendix Figure A1 shows that an increase in GDP per capita corresponds to an increase in CO_2 emissions per capita. There is a positive slope for final energy use per capita, energy intensity, and the share of fossil energy, all of which contribute to higher GHG emissions. Improvements in energy productivity and increases in the share of clean and renewable energy sources show a negative slope, indicating their role in reducing GHG emissions.

Figure 1 shows scatter plots of the relationship between GHG emissions per capita (ln_ghg_emission_per_capita) and real GDP per capita (ln_real_gdp_per_capita), based on data for EU member states. Each point represents a single period (year). The plots, representing a dotted trend line, show a polynomial fit. The inverted U-shape is consistent with the EKC hypothesis, where output first increases and then decreases as income rises. Similarly, other shapes, such as a U-shape, differ from or do not confirm with the EKC. The R^2 value indicates the explanatory power of the model, that is, how much of the total variance in the dependent variable the explanatory variables can explain. A low R^2 value indicates that the model has a limited ability to capture the relationships under investigation. This suggests that changes in GHG emissions are not strongly correlated with GDP per capita. There is considerable heterogeneity across EU member states. The graphs show the correlation between GDP per capita and CO_2 emissions per capita per for member states over the time series 2000–2022. The analysis cannot establish a causal relationship between the two variables, as other factors also influence CO_2 emissions. The objective is to determine if there is a correlation between the variables and whether the slope of the function is negative or positive, that is, whether CO_2 emissions decrease or increase with improving real GDP per capita. For Sweden, Germany, Belgium, the Czech Republic, France, Malta, Ireland, and the Netherlands, we observe a curve with a negative slope, which does not correspond to the inverted U-shape predicted by the classical EKC hypothesis, but rather it indicates that CO_2 emissions per capita decrease as GDP per capita increases. The points represent one observation unit, which is a year in this case. For example, in the case of Sweden, as real GDP per capita increases, GHG emissions per capita decrease, which explains approximately 54% of the variation in GHG emissions. Real GDP per capita has increased to a greater or lesser extent in all the EU member states, but the slope of the curve is not always the same. If the slope is negative and the explanatory power is high, then an increase in real GDP per capita may decrease GHG emissions, or conversely an increase. For Bulgaria, Estonia, Greece, Croatia, Italy, Lithuania, Latvia and Luxembourg, economic growth is associated with an increase in CO_2 emissions. In Cyprus, Austria, Hungary, Poland and Finland, there is a weak relationship between the two variables.

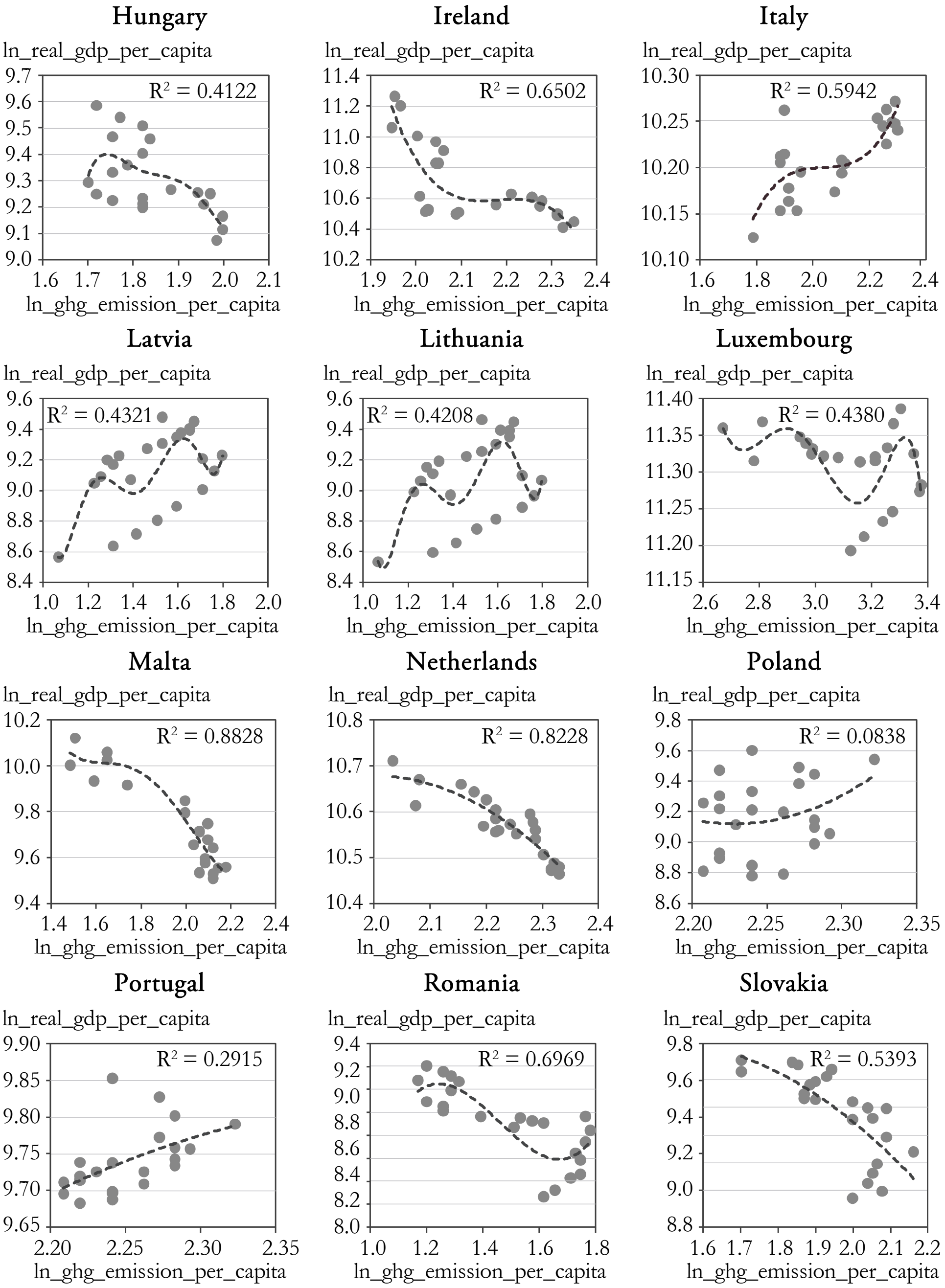
Figure 1

Scatter plots of EU member states as a function of GDP per capita and GHG emissions per capita



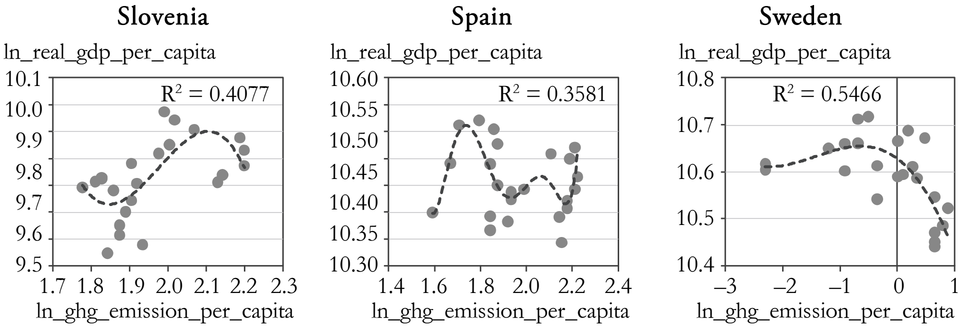
(Figures continue on the next page.)

(Continued.)



(Figures continue on the next page.)

(Continued.)



Source: author's own contribution using Gretl software.

Validity and critiques of the environmental Kuznets curve

There are several criticisms regarding the validity of the EKC. The main criticism raised by Arrow et al. (1995) is that the EKC model implicitly assumes that economic growth is sustainable. However, if higher economic activity is not sustainable in the long term, then the pursuit of rapid growth during the early stages of development, when environmental degradation is still increasing, may be counter-productive. If economic growth is not based on a stable foundation – for example, if it is characterized by over-exploitation of natural resources or persistent pollution – then it may decline over time.

If there is an EKC-type link, it is partly or largely attributable to trade, which reallocates polluting industries worldwide. The decline in environmental damage in developed countries and the increase in middle-income countries is owing to changes in the structure of production rather than being a natural consequence of rising income levels (Stern 1998).

Environmental regulations in developed countries may further encourage the relocation of polluting industries to developing countries. These effects may result in an apparent reduction in pollution intensity as incomes rise; however, in reality, environmental pressures are merely geographically displaced (Lucas et al. 1992). Owing to the spatial variation in environmental regulations, a country's level of pollution may be directly related to the openness of international trade (Grossman–Krueger 1991).

Professional publications provide a broad interpretation of the EKC hypothesis. Examining EU member states as a group of countries, we found no clear evidence that member states have reached a tipping point. Moreover, as GDP growth alone does not explain the decline in environmental degradation, additional explanatory variables are needed. Based on this conclusion, we closely examined the critical analysis by Stern (1998) and Lucas et al. (1992), who argue that it cannot be clearly stated that GDP per capita growth alone affects CO_2 emissions; other factors also play a role. As shown in Tables 3 and 4, we included the share of the services sector in GDP [16] in the model and the share of OFDI in the GDP, both measured as percentages. The OFDI indicator was sourced from the World Bank database and represents FDI made by domestic firms abroad. It shows how much FDI domestic companies invest abroad, that is, the extent to which they invest in companies in other countries. The purpose is to measure a country's economic expansion and international investment activity and is measured as a percentage of GDP [17].

The analysis of the impact of OFDI on CO_2 emissions is based on four different panel models, as presented in Tables 3 and 4. Results from two short-run (random effects and fixed effects) and two long-run cointegration models (FMOLS and DOLS) are compared. The variable representing OFDI is LOGNET_OUTFLOW_GDP%, which denotes the ratio of net capital outflows to GDP. Based on the short-run models, the impact of OFDI is negative and marginally significant. In the RE model, the coefficient is –0.0003259 (p = 0.0719), while in the FE model it is –0.0003277 (p = 0.0833). This suggests that when capital outflows to the rest of the world increase in a country, domestic CO_2 emissions decrease slightly, although the effect is only marginally statistically significant. An explanation for this is the "pollution haven" hypothesis, which suggests that companies relocate their polluting activities to countries with less stringent environmental regulations. This may reduce domestic emissions while production continues abroad. However, it is important to stress that the effect is weak and not always significant; therefore, the results should be interpreted with caution.

By contrast, the long-run models FMOLS and DOLS do not show a significant relationship between OFDI and CO_2 emissions. In the FMOLS model, the coefficient is +0.0076 (p = 0.795), while it is +0.0129 (p = 0.6307) in the DOLS model, indicating positive signs and a lack of statistical significance. This indicates that in the long term, capital outflows abroad are not associated with a decline in domestic output but may contribute to a slight increase. This may be because the reinvestment of foreign investment income in the home country increases economic activity and energy demand, or foreign production may not be completely substituting domestic production. Overall, the results indicate that OFDI does not exert a strong or consistent influence on CO_2 emissions. In the short run, there is a minor negative effect; however, over time, this relationship fades or even reverses. This suggests that inward capital flows are not a reliable environmental policy tool for reducing emissions. The pollution haven hypothesis is only partially supported: even if it operates, its effect is weak and short-lived. Therefore, OFDI is not a key driver of environmental sustainability, and emission reductions should be achieved through improvements in domestic energy efficiency, use of renewables, and economic restructuring.

The effect of OFDI on a country's CO_2 emissions may initially appear contradictory, since logically one would expect that if firms in a country prefer to invest abroad, this would reduce domestic economic activity and hence emissions, as assumed by Lucas et al. (1992). Yet, several economic and industrial mechanisms may explain why OFDI can lead to increased CO_2 emissions in a given country. The literature on the effects of FDI on the emitting country is limited, as it is based on the host country. Borghesi et al. (2016) examined the relationship between OFDI and carbon emissions from the home-country perspective of the emitting country for Italy. The results confirm that some sectors, especially those exposed to carbon leakage, are likely to relocate their production to countries with less stringent environmental regulations (Borghesi et al. 2016). The results of the FMOLS estimation method show that China's FDI is a significant contributor to environmental pollution, as the relationship between energy consumption and environmental degradation is positive and significant (Yang et al. (2021). The leakage of OFDI can damage the environment through the transfer of polluting and low-quality technologies. This phenomenon is a "double-edged sword", as OFDI leakage across various sectors such as manufacturing, natural resources, and infrastructure development can not only contribute to economic growth but can also exacerbate environmental degradation and increase the environmental burden on the domestic economy. The impact of OFDI on the home country is complex, as it can be both positive and negative in terms of economic growth and environmental sustainability (Osabuohien-Irabor–Drapkin 2024). The economic growth generated by OFDI can also increase energy consumption and carbon emissions in the home country. This may be due to an increase in production activities. Moreover, OFDI may encourage companies to expand or improve their production capacity, including industrial production and manufacturing. Increased production is often associated with higher energy consumption, especially if the energy sources are not renewable. Very often, OFDI not only provides access to foreign markets but also facilitates the global expansion of supply chains. Increased production and the expansion of international trade require more energy for transport and logistics, which results in higher CO_2 emissions. In OFDI, companies in the emitting country can create new technological developments, infrastructure, and industries that can be energy intensive (Shahbaz et al. 2015). The published results are divisive, with evidence supporting both views.

Table 6 clearly shows that the evolution of emissions in both the short- and long-term is determined by the structure of energy use, economic structure, and technical efficiency. Final energy consumption per capita (TOE/capita) has a significant and positive effect over both time horizons, that is, a more energy-intensive lifestyle directly increases emissions. Conversely, the share of renewable energy is significant and negative in the long term, confirming that the penetration of sustainable energy sources structurally reduces emissions. Energy productivity and the weight of the services sector as a share of GDP are significant emission-reducing factors in both the short and long term, indicating that technological efficiency and economic restructuring play a key role in reducing environmental pressures. The impact of OFDI (outward capital flows) is weakly significant in the short term, but not significant in the long term, and thus cannot be considered a stable environmental factor. The effect of economic growth is significant and positive in the long term, that is, GDP growth increases emissions in the long term. Although there are signs of an inverted U-shaped pattern in the EKC curve (GDP^2 is positive and significant, while GDP is not), the hypothesis cannot be clearly confirmed as significance is lost in a multivariate model. The model's robustness is supported by the absence of autocorrelation (DW, Wooldridge) and multicollinearity (VIF < 5), and the cointegration relationships are confirmed by Pedroni and Kao tests. All this indicates that the estimates are statistically robust, thus justifying the use of long-run models (FMOLS, DOLS).

Table 6

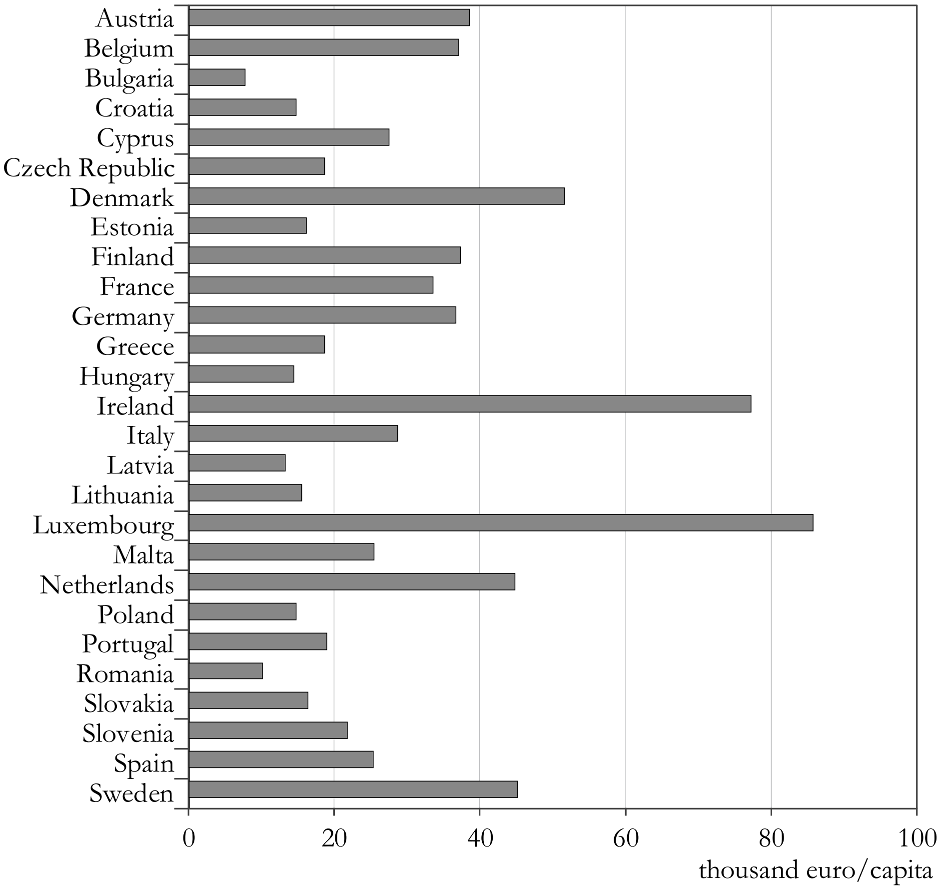
Comparison of short- and long-term impact of factors affecting CO_2 emissions

Variable	Short-run (RE/FE)	Long-run (FMOLS/DOLS)	Conclusion
Final energy consumption per capita (TOE/capita)	Significant	Significant	Emission-increasing
Share of renewable energy in total energy consumption (%)	Not significant	Significant	Emission-reducing
Energy productivity (EUR/kg oil equivalent)	Significant	Significant	Emission-reducing
Share of services in GDP (%)	Significant	Significant	Emission-reducing
OFDI as % of GDP	Weakly significant	Not significant	No robust effect
LOG real GDP per capita (FMOLS/DOLS) dif_ real GDP per capita	Not significant	Significant	Economic growth increases emissions in the long term
EKC hypothesis FMOLS/DOLS ZLOG real GDP per capita ZLOG real GDP per capita^2 FE/RE dif_ real GDP per capita dif_ real GDP per capita^2	Significance is observed when two variables are included, but it disappears when additional variables are added to the model.	GDP^2 is significant (positive) in both models, while GDP itself is not.	Inverted U-shape appears in the long term, but not fully supported by the model
Cointegration	–	Confirmed by Pedroni–Kao tests	FMOLS and DOLS application is justified
Autocorrelation test (DW, Wooldridge)	Not significant	Not significant	No autocorrelation problem in either model
Multicollinearity (all variables)	VIF < 5	VIF < 5	No multicollinearity present

As it is not possible to clearly determine if OFDI has any effect on GHG emissions based on the panel models, a comparative analysis was performed. In Figures 2–5, we compared real GDP per capita, OFDI, CO_2 emissions per capita, and ecological footprint data for 2022. The purpose of the comparison is to examine whether countries with a high OFDI as a percentage of GDP have higher GDP per capita growth, CO_2 emissions per capita and ecological footprint. Luxembourg, Ireland, and the Netherlands meet all three criteria except for the ecological footprint. For Luxembourg, all four indicators are extremely high.

Figure 2

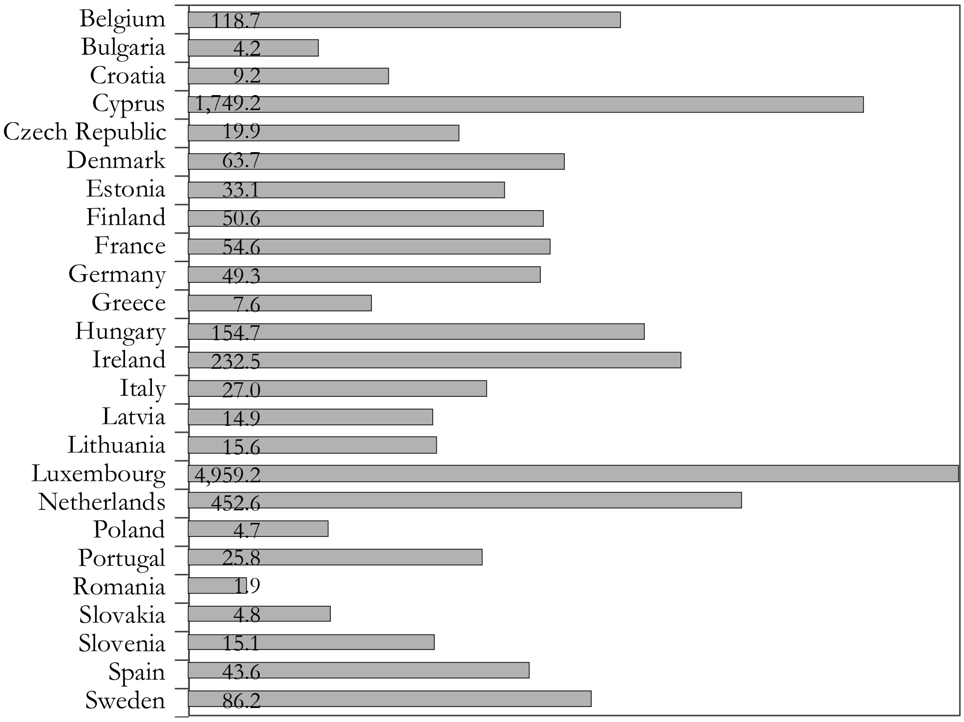
Real GDP per capita in the EU member states, 2022



Source: author's own contribution based on [16].

Figure 3

Working capital outflows in the EU member states, 2022 (GDP, %)



Note: No data are available for Austria and Malta.
Source: author's own contribution based on [20].

Figure 4

CO₂ emissions per capita in the EU member states, 2022

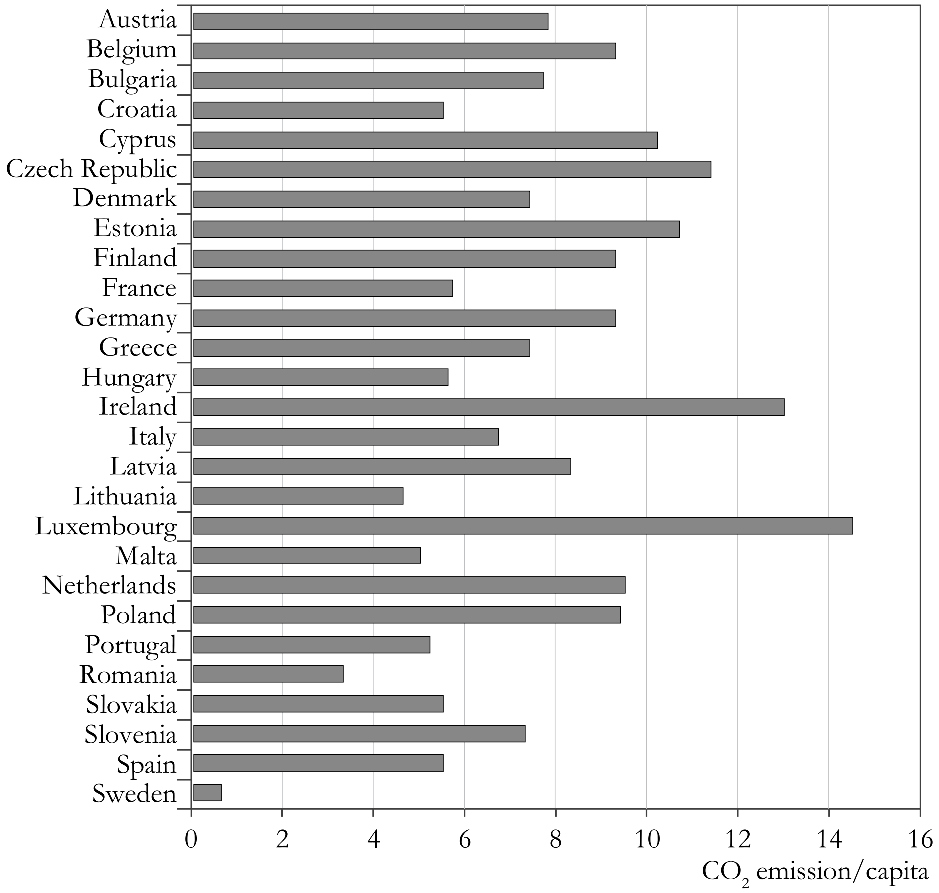
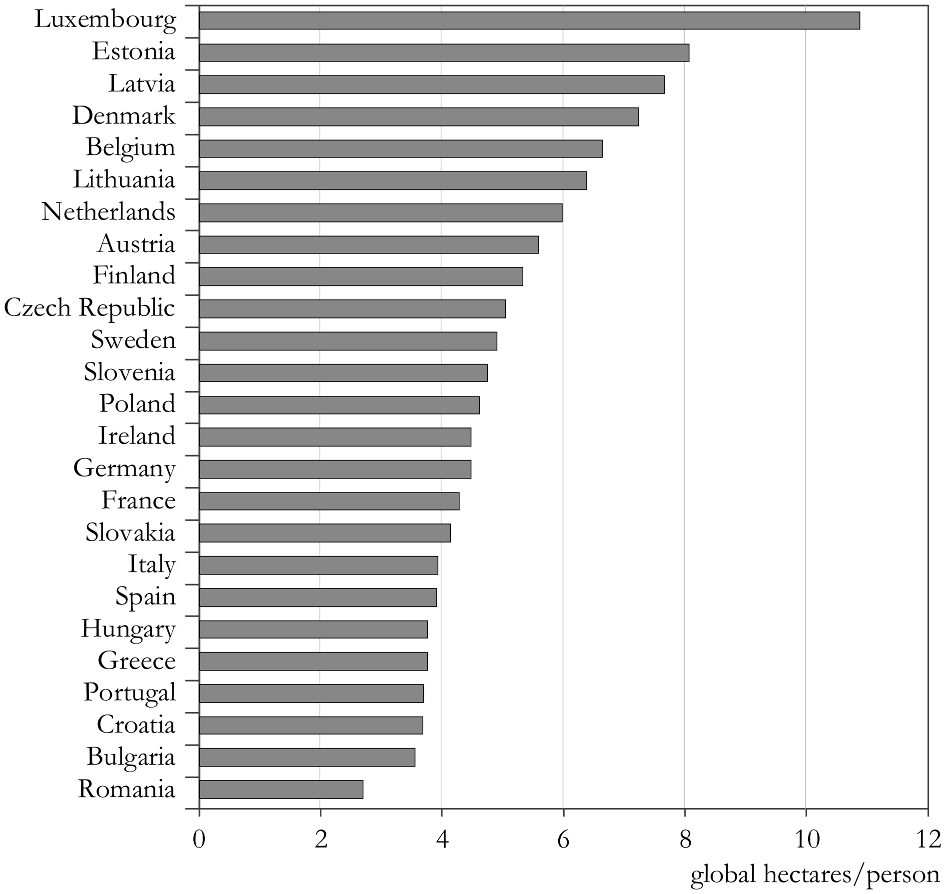


Figure 5

Ecological footprint per capita in the EU member states, 2022



Source: [18].

To better understand the context, countries were clustered using the *k*-means clustering method. The aim of clustering is to create homogeneous groups of similar observations while keeping the groups as distinct as possible from each other. We used the *k*-means clustering technique for the EU 27 member states, aiming to organize EU countries into clusters with similar characteristics (Pelle et al. 2021, Schmitt–Starke 2011). For the economic indicators, we used a quadratic Euclidean distance, which is calculated between individuals **i** and **k** using the following formula, where **j** is an index denoting individuals or variables:

$$d_{ik}^2 = \sum_j \left(x_{ij} - x_{kj}\right)^2$$

The distribution between clusters need not be proportional, but greater inequality can provide important information. This analysis aims to achieve a clustering that minimizes differences within each cluster. In *k*-means cluster analysis, the centroid is the average of the points assigned to the cluster. The more homogeneous a cluster, the smaller the distance of the points from the centroid. Single-element clusters indicate outliers that are significantly different from the others. Variables are standardized for comparability. In this case, six clusters were constructed without excluding outliers because the aim is to include all countries. The number of countries was distributed unevenly between the clusters. Table 6 shows the characteristics of the clusters, positive and negative averages, and variance of the clusters. For this analysis we used data from 2022. Standardized variables were used in the analysis to avoid bias due to differences in units of measurement.

Table 7

Statistical clustering of EU member states, 2022

	Cluster					
	1	2	3	4	5	6
Countries	Ireland	Bulgaria Greece Spain France Croatia Italy Lithuania Hungary Portugal Romania Slovenia Slovakia	Czech Republic Germany Estonia Latvia Poland Finland	Belgium Denmark Netherlands	Luxembourg	Sweden
Source	0.00	0.3358	0.2004	0.1163	0.00	0.00
Zscore: real GDP per capita	2.506	–0.5589	–0.3494	0.7877	2.9541	0.8188
Zscore working capital outflow	–0.0929	–0.2899	–0.29149	–0.1132	4.5118	–0.23552
Zscore: GHG emissions per capita	1.7920	–0.5944	0.7042	0.3712	2.2915	–2.3372
Zscore: ecological footprint per one person	–0.3826	–0.6223	0.3772	0.7922	3.1310	–0.1483

Source: author's own contribution using SPSS statistical software package.

For the clustering, the variables including ecological footprint, working net capital outflow, real GDP per capita, and GHG emissions were also considered. Ecological footprint is an indicator that measures how much natural resources a given human community or individual uses relative to the Earth's biocapacity. It includes energy consumption, food production, built environment, and waste management. The carbon footprint is often expressed in global hectares (gha), which indicates the amount of land and water needed to sustain a given lifestyle [19]. Compared to the ecological footprint, carbon footprint reveals how sustainable emissions are relative to the available natural resources (Zhen–Freire 2023). Several studies have examined the significant relationship between carbon footprint and CO_2 emissions (Amer et al. 2024). We found it useful to include the carbon footprint as an indicator in the cluster analysis because the ecological footprint specifically measures how much natural resources a country uses and to what extent it pollutes the environment. To understand the relationship between economic development and environmental pressure, it is essential to include the carbon footprint in the cluster analysis. This helps to compare the environmental impacts of countries. For example, the co-presence of a high GDP per capita and a high carbon footprint may indicate that economic growth has a high environmental cost.

Three of the six groups of countries are considered outliers: Ireland, Luxembourg and Sweden. As we are testing the variables for all 27 member states, we retained them in the database. For the sake of clarity, we have summarized our evaluation of the results in Table 8.

Table 8

Results of the cluster analysis for EU member states

	Cluster					
	1	2	3	4	5	6
Countries	Ireland	Bulgaria Greece Spain France Croatia Italy Lithuania Hungary Portugal Romania Slovenia Slovakia	Czech Republic Germany Estonia Latvia Poland Finland	Belgium Denmark Netherlands	Luxembourg	Sweden
Real GDP per one person	high	low	low	high	extremely high	high
Working capital outflows	medium	low	low	medium	very high	low
GHG emissions per capita	high	low	high	high	extremely high	low
Ecological footprint per capita	low	low	high	high	extremely high	medium

These results once again highlight the heterogeneity across member states, which indicates that they operate at different levels of development. Belgium, the Netherlands, and Denmark have higher-than-average real GDP growth per capita, which leads to a higher-than-average increase in their ecological footprint. Luxembourg is a notable outlier in all respects, with very high GDP growth per capita, which results in a very high increase in its ecological footprint. The growth of OFDI is also extremely high, as confirmed by previous measurement results. This high value does not necessarily reflect real capital outflows in the real economy. Luxembourg is a global financial center with several investment funds, holding companies, and banks formally incorporated there. These entities often function only as financial transfer points, that is, they move capital to other countries without conducting real economic activities in Luxembourg (UNCTAD 2016). Previous findings also support the view that this high economic growth does not lead to efficiency gains and GHG emission reductions. For the other country groups, we found no correlation between OFDI and CO_2 emissions. Thus, we can support the panel analysis finding that the significance between CO_2 emissions and OFDI is due to the extremely high values of Luxembourg.

Based on Stern's research, we analysed the evolution of the services sector's share in GDP across EU member states and the trend of CO_2 emissions per unit of GDP. We aimed to investigate whether the decline in CO_2 emissions is primarily associated with the expansion of the services sector or rather with improvements in energy productivity.

Based on Figure A2 in Appendix, the increase in the service sector's share in GDP contributes to the reduction in CO_2 intensity in Malta, the Netherlands, Luxembourg, Cyprus, Croatia, Spain, Greece, Denmark, and Belgium. In Bulgaria, where the share of the service sector has changed very little over the past 12 years, producing one unit of GDP results in approximately 100 tons of CO_2 emissions. Countries such as Czechia, Estonia, Greece, Latvia, Cyprus, and Poland emit around 50 tons of CO_2 per unit of GDP. In these countries, the service sector accounts for approximately 50% of GDP, except for Cyprus, where it reaches 80%. In Sweden, Finland, Portugal, Austria, the Netherlands, Malta, Luxembourg, Italy, France, Spain, Germany, Denmark, and Belgium, the share of the service sector exceeds 60% of GDP, and CO_2 emissions per unit of GDP are approximately 20 tons. The figures also reveal that in most countries, the reduction in emissions is greater than the increase in the share of the service sector, indicating that technological modernization, declining energy intensity, and increasing energy productivity play an important role. This implies that the decrease in emissions is not solely driven by the expansion of the service sector.

Table 9 summarizes the results collected from publications and compares them with our own results.

Table 9

Pros, cons, conceptualization of results

Author	Claim	Own results
Sulaiman–Abdul-Rahim (2017), Koc–Bulus (2020)	Energy consumption and economic growth have positive effects on CO_2 emissions (developing countries)	Increases in energy consumption per capita and GDP per capita increase CO_2 emissions per capita, which depend on other factors.
Gill et al. (2018), Sabri et al. (2024), Kitole et al. (2024)	Economic growth alone can't reverse environmental degradation (developing countries)	Evidence of a significant effect of energy intensity growth and energy productivity on CO_2 emissions.
Bilgili et al. (2016), Wang et al. (2023a), Jebli et al. (2016), Akbar et al. (2024)	GDP per capita has a positive effect on CO_2 emissions, and GDP per capita squared has a negative effect on CO_2 emissions, and renewable energy consumption has a negative effect on CO_2 emissions. Increasing non-renewable energy consumption increases CO_2 emissions.	The first part of the statement can be substantiated. The share of renewable energy sources does not show significance in the short-term model, as its proportion is still too low across the member states to be detectable. In the long term, however, it shows considerable significance.
Grossman–Krueger (1991), Hinrich Foundation (2024)	A resource-intensive economy increases CO_2 emissions.	There is clear evidence. Energy intensity shows significant increases in CO_2 emissions.
Arrow et al. (1995), Herrington (2020)	The EKC model implicitly assumes that economic growth is sustainable.	Energy intensity growth has an environmentally destructive effect. GDP per capita growth alone does not solve environmental problems, and it does not show significance in combination with other influencing factors. Sustained economic growth cannot be unequivocally maintained, as CO_2 emissions remain closely linked to energy consumption and economic growth.
Stern (1998), Barrett et al. (2023)	The reduction of environmental damage in middle-income countries depends on the transformation of the production structure and not on the increase in income levels.	Evidence in the model. The high share of the services sector as a % of GDP shows strong significance across all three models. In contrast, real GDP per capita growth shows low significance.
Lucas et al. (1992), Borghesi et al. (2016), Wang et al. (2023b)	Developed countries shift polluting industries to developing countries with the intensity of capital outflows, thereby reducing their own environmental degradation.	There is no clear evidence of a negative or positive impact of OFDI on environmental degradation.

Conclusion

In this analysis, we examined the GHG emission performance of EU member states, with a particular focus on the strategic objectives of the Green Deal, which include reducing emissions and sustaining economic growth. In our analysis, we used panel regression models to investigate the phenomenon of the EKC, with the panel models proving to be the most appropriate.

Our results indicate that per capita real GDP, final energy consumption, and increases in energy intensity have a positive impact on GHG emissions. In contrast, improvements in energy productivity and a higher share of renewable energy sources contribute to emission reductions. The impact of the Paris Agreement on lowering emissions is statistically marginal, whereas periods of economic recession had a mitigating effect on emission levels.

In testing the Kuznets hypothesis, when GDP per capita and its exponent were included in the model, the EKC phenomenon was demonstrated, and the data were used to determine the tipping point. However, when additional independent variables were included, the parameter β_2 did not show a significant effect, indicating that the clear validity of the EKC hypothesis cannot be confirmed in all cases. There is considerable variation between member states: Sweden, Germany, Belgium, the Czech Republic, France, Malta, Ireland, and the Netherlands experienced a decrease in GHG emissions with increasing GDP.

An important criticism of the EKC hypothesis is that some EU member states can reduce GHG emissions on their own territory by relocating energy-intensive industries abroad. However, our results do not allow a clear statement that FDI has a positive or negative impact on CO_2 emissions.

Growth in the services sector as a share of GDP has shown a significant negative effect in reducing emissions. In countries where the services sector's share exceeds 50% of GDP, CO_2 emissions per unit of GDP are lower, indicating that the shift in economic structure towards services may have a positive impact on reducing emissions.

Overall, the results show that GHG emissions are influenced by a combination of factors and, therefore, require a comprehensive and integrated approach to policy design. The heterogeneity of member states is a key element of the EU's overall performance and countries should be committed to improving energy efficiency and supporting sustainable growth. Future research may wish to further investigate the role of individual sectors and the actual impact of industry relocation on meeting EU emissions targets.

Acknowledgements

This study was written within the framework of the Doctoral School of Economics at the University of Szeged.

Appendix

Table A1

Analysis of stationarity of variables

Variables	Inverse chi-square	Inverse normal test	Logit test
Real GDP per capita	128.701***	–6.87829***	–6.59133***
Total final energy consumption per capita	126.011***	–6.7473***	–6.43811***
Energy intensity	126.576***	–6.77384***	–6.4699***
Renewable energy ratio	129.074***	–6.9048***	–6.61567***
Fossil energy share	125.19***	–6.70334***	–6.38985***
GHG emissions per capita	125.313***	–6.71072***	–6.39739***
Clean energy ratio	125.268***	–6.70715***	–6.39427***

Note: *** p<0.001.
Source: author's own contribution using Gretl software.

Table A2

Descriptive statistics of variables

Description	Real GDP per capita	Total final energy consumption per capita	Energy intensity	Share of renewable energy
Average	24,974.0	2.45656	3.85725	17.8138
Median	20,705.0	2.15000	3.50000	16.1825
Minimum	2,990.00	0.930000	1.10000	0.102000
Maximum	88,120.0	9.63000	9.10000	66.0020
Source	16,862.9	1.32385	1.34803	11.9567
Deviation	1.50798	2.79560	1.00424	0.950875
Peak	2.87330	9.80375	1.37116	0.930868
Doornik–Hansen test	6.59334e–64	7.13595e–278	2.06139e–12	2.58741e–05
Shapiro–Wilk	2.3982e–21	8.74619e–29	7.65828e–11	4.07483e–13
Jarque–Bera test	2.47241e–85	0	9.94276e–17	3.44545e–20
	Fossil energy share	Clean energy share	GHG emissions per capita	
Average	52.7847	47.1946	9.03966	
Median	50.4300	49.5700	8.30000	
Minimum	1.09000	0.00000	–0.700000	
Maximum	100.000	98.5100	29.5000	
Source	26.9210	26.8901	4.57306	
Deviation	0.0826152	–0.0834966	1.21238	
Peak	–0.980297	–0.977258	3.03387	
Doornik–Hansen test	1.03133e–07	1.1481e–07	2.17426e–25	
Shapiro–Wilk	8.21384e–10	1.02368e–09	3.71114e–16	
Jarque–Bera test	2.58741e–05	2.74005e–05	3.29915e–95	

Source: author's own contribution using Gretl software.

Table A3

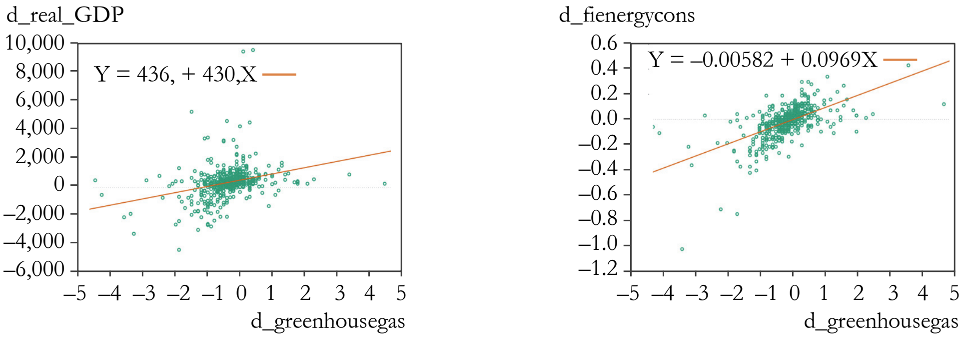
Results of multicollinearity testing of variables

Variable	VIF
d_real_GDP	4.898
d_real_gdp2	2.786
d_fienergycons	3.275
d_energyintensity	1.088
d_energyproduct	3.115
d_renergy	1.144
d_Fossilfuel	1.395
FDI_GDP	1.183

Source: author's own contribution using Gretl software.

Figure A1

Regression analysis of factors affecting CO_2 emissions per capita, with least squares fit

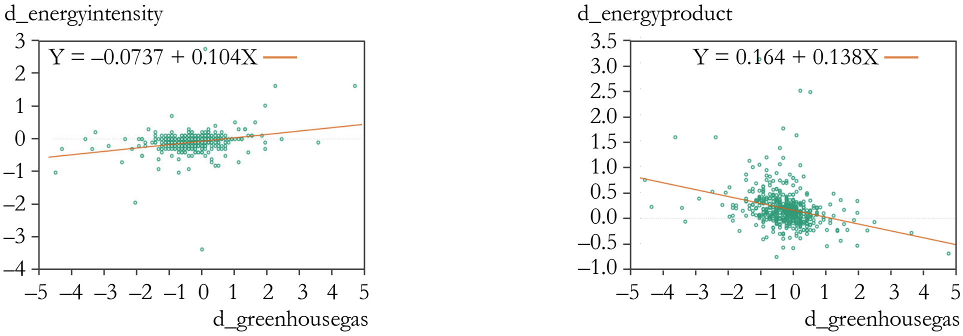


a) d_real_GDP versus d_greenhousegas

b) d_fienergycons versus d_greenhousegas

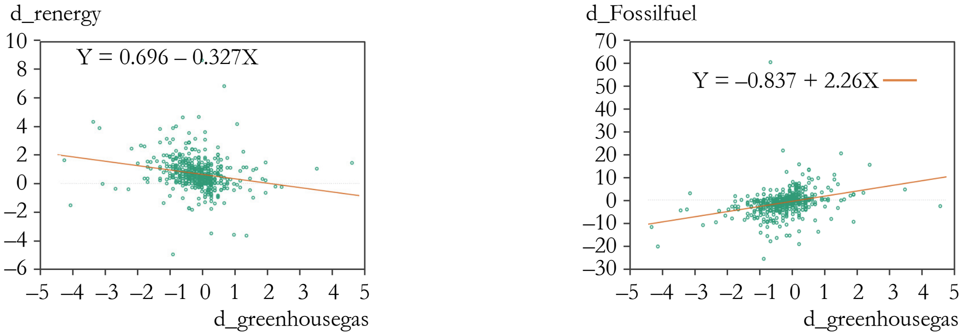
c) d_energyintensity versus d_greenhousegas

d) d_energyproduct versus d_greenhousegas



(Figures continue on the next page.)

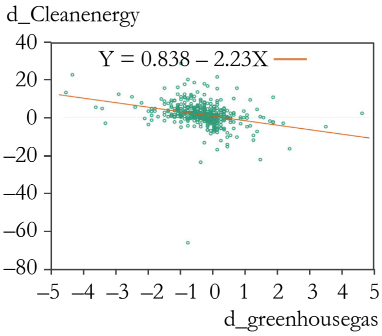
(Continued.)



e) d_renergy versus d_greenhousegas

f) d_fossilfuel versus d_greenhousegas

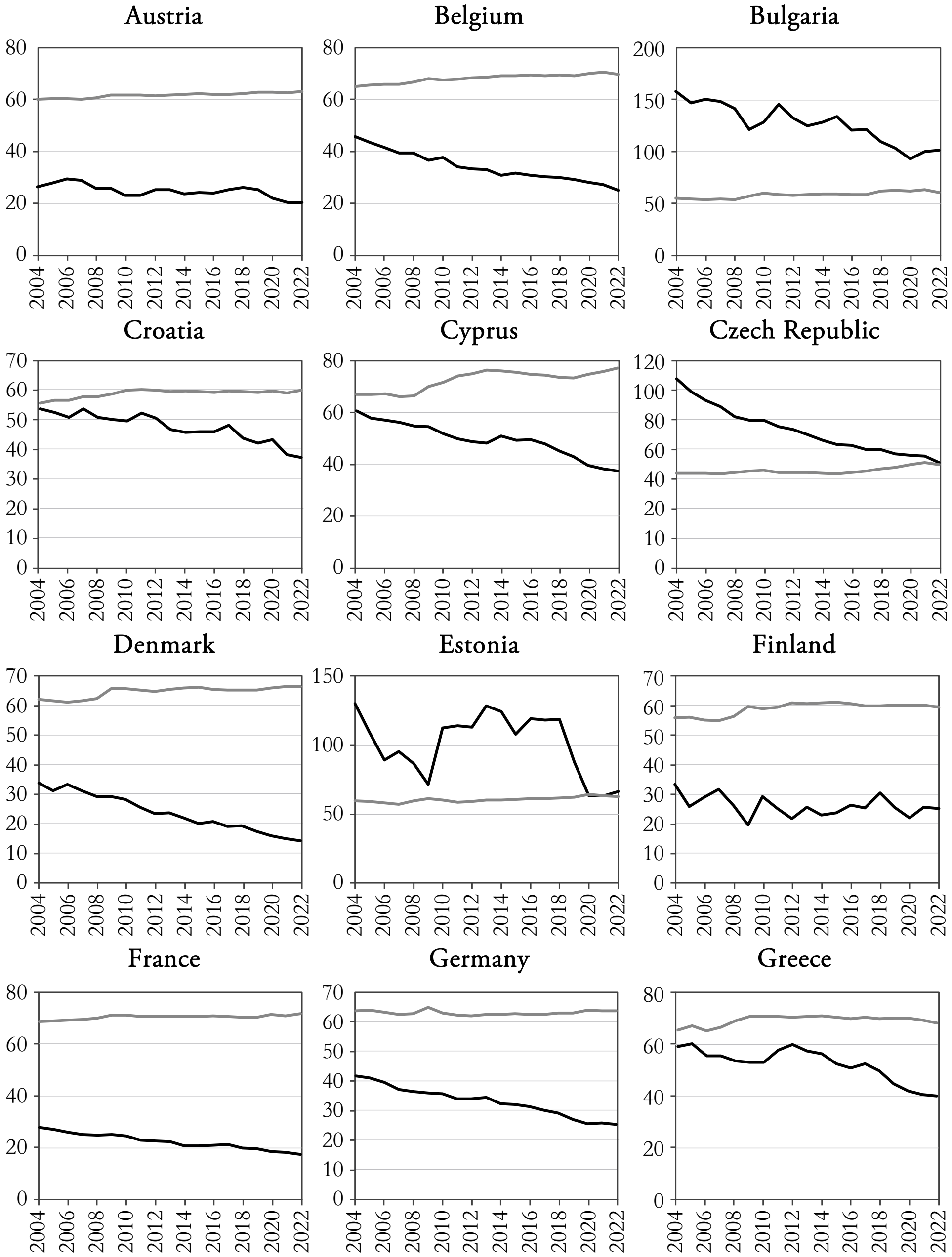
g) d_cleanenergy versus d_greenhousegas



Source: author's own contribution using Gretl software.

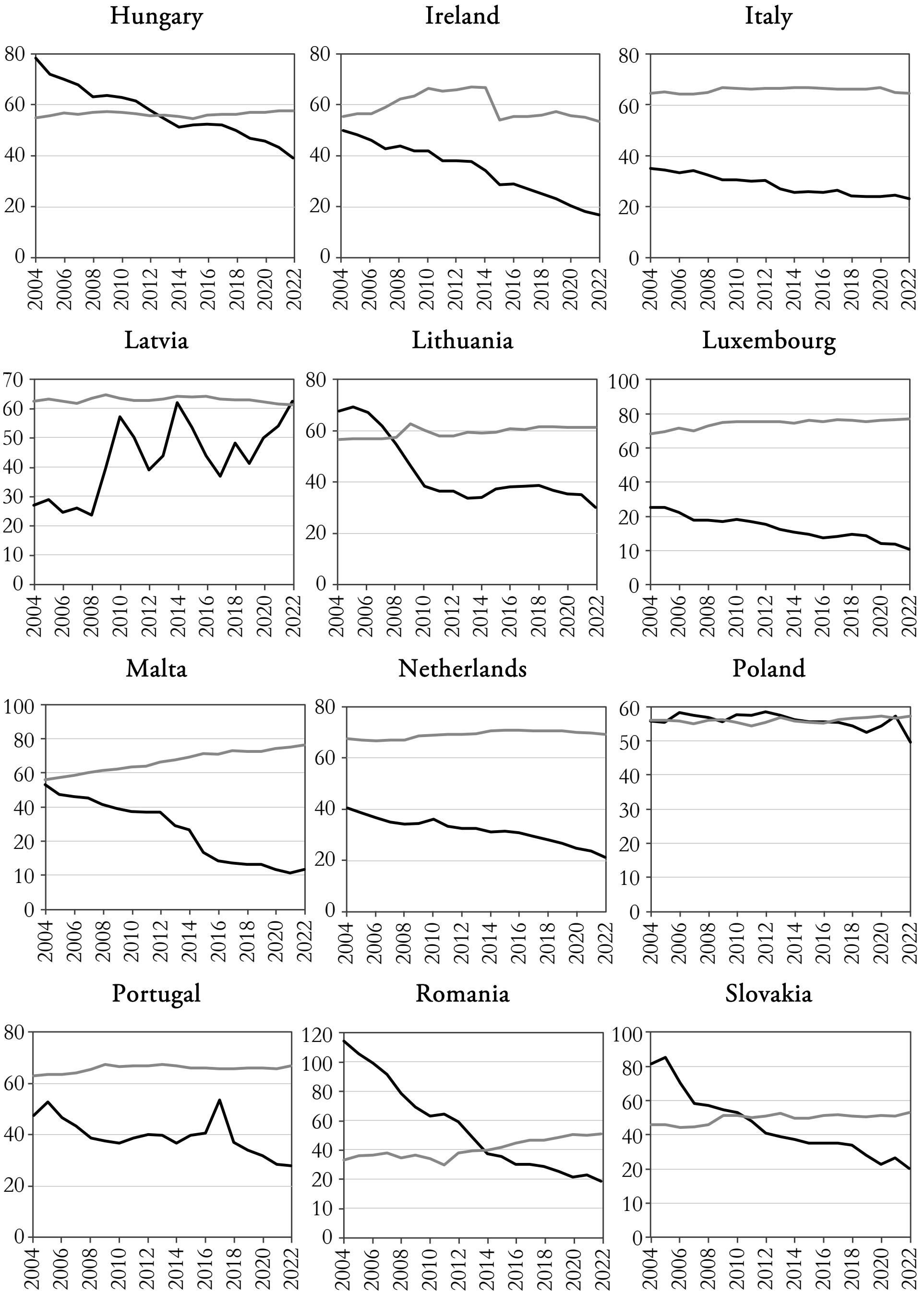
Figure A2

Structural economic change and decarbonization in the European Union



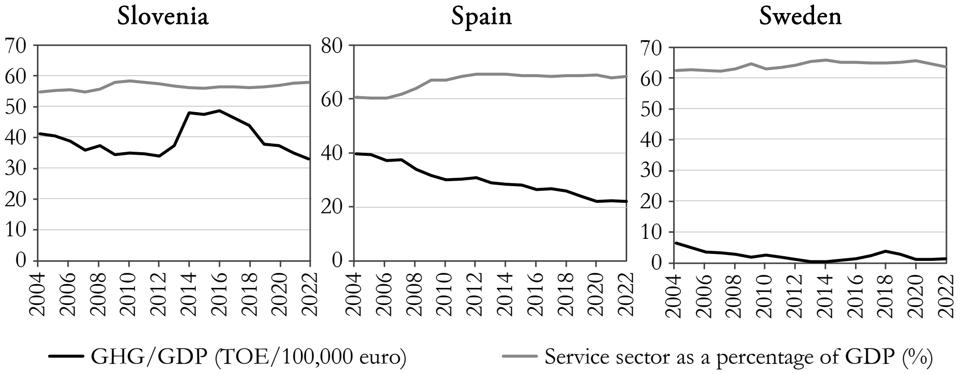
(Figures continue on the next page.)

(Continued.)



(Figures continue on the next page.)

(Continued.)



Source: author's own contribution based on Eurostat data.

REFERENCES

AHMAD, M.–WU, Y. (2022): Natural resources, technological progress, and ecological efficiency: does financial deepening matter for G-20 economies? *Resources Policy* 77: 102770. https://doi.org/10.1016/j.resourpol.2022.102770

AKBAR, A.–GUL, A.–SOHAIL, M.–HEDVICAKOVA, M.–HAIDER, S. A.–AHMAD, S.–IQBAL, S. (2024): Impact of renewable and non-renewable energy resources on CO_2 emission: empirical evidence from SAARC *International Journal of Energy Economics and Policy* 14 (1): 141–149. https://doi.org/10.32479/ijeep.15049

AMER, E. A. A. A.–MEYAD, E. M. A.–MEYAD, A. M.–MOHSIN, A. K. M. (2024): The impact of natural resources on environmental degradation: a review of ecological footprint and CO_2 emissions as indicators *Frontiers in Environmental Science* 12: 1368125. https://doi.org/10.3389/fenvs.2024.1368125

ARROW, K.–BOLIN, B.–COSTANZA, R.–DASGUPTA, P.–FOLKE, C.–HOLLING, C. S.–PIMENTEL, D.–JANSSON, B. O.–LEVIN, S.–MÄLER, K. G.–PERRINGS, D. (1995): Economic growth, carrying capacity, and the environment *Ecological Economics* 15 (2): 91–95. https://doi.org/10.1016/0921-8009(95)00059-3

BALIN, B. E.–AKAN, D. M. (2015): EKC hypothesis and the effect of innovation: a panel data analysis *Journal of Business Economics and Finance* 4 (1): 81. 10.17261/Pressacademia.201519952

BARRETT, C. B.–ORTIZ-BOBEA, A.–PHAM, T. (2023): Structural transformation, agriculture, climate, and the environment *Review of Environmental Economics and Policy* 17 (2): 1234–1278. https://doi.org/10.1086/725319

BEKUN, F. V.–ALOLA, A. A.–GYAMFI, B. A.–YAW, S. S. (2021): The relevance of EKC hypothesis in energy intensity real-output trade-off for sustainable environment in EU-27 *Environmental Science and Pollution Research* 28 (37): 51137–51148. https://doi.org/10.1007/s11356-021-14251-4

BILGILI, F.–KOÇAK, E.–BULUT, Ü. (2016): The dynamic impact of renewable energy consumption on CO_2 emissions: a revisited environmental Kuznets curve approach *Renewable and Sustainable Energy Reviews* 54: 838–845. https://doi.org/10.1016/j.rser.2015.10.080

DU, K.–LI, P.–YAN, Z. (2019): Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data *Technological Forecasting and Social Change* 146: 297–303 https://doi.org/10.1016/j.techfore.2019.06.010

EKINS, P. (1997): The Kuznets curve for the environment and economic growth: examining the evidence *Environment and Planning A* 29 (5): 805–830. https://doi.org/10.1068/a290805

GYAMFI, B. A.–BEIN, M. A.–OZTURK, I.–BEKUN, F. V. (2020): The moderating role of employment in an environmental Kuznets curve framework revisited in G7 countries *Indonesian Journal of Sustainability Accounting and Management* 4 (2): 241–248. https://doi.org/10.28992/ijsam.v4i2.283

GILL, A. R.–VISWANATHAN, K. K.–HASSAN, S. (2018): A test of environmental Kuznets curve (EKC) for carbon emission and potential of renewable energy to reduce green house gases (GHG) in Malaysia *Environment, Development and Sustainability* 20: 1103–1114. https://doi.org/10.1007/s10668-017-9929-5

GROSSMAN, G. M.–KRUEGER, A. B. (1991): Environmental impacts of a North American free trade agreement *National Bureau of Economic Research Working Paper No. 3914*. https://doi.org/10.3386/w3914

HERRINGTON, G. (2020): Update to limits to growth: comparing the World3 model with empirical data *Journal of Industrial Ecology* 25 (3): 614–626. https://doi.org/10.1111/jiec.13084

JEBLI, M. B.–YOUSSEF, S. B.–OZTURK, I. (2016): Testing environmental Kuznets curve hypothesis: the role of renewable and non-renewable energy consumption and trade in OECD countries *Ecological Indicators* 60: 824–831. https://doi.org/10.1016/j.ecolind.2015.08.031

KAO, C.–CHIANG, M.-H. (2000): On the estimation and inference of a cointegrated regression in panel data *Advances in Econometrics*15: 179–222.

KITOLE, A. F.–SESABO, J. K.–ADESIYAN, O. F.–IGE, A. O.–OJO, T. O.–EMENIKE, CH. U.–KHUMALO, N. Z.–KASSEM, H. S.–ELHINDI, K. M. (2024): Greening the growth: a comprehensive analysis of globalization, economic performance, and environmental degradation in Tanzania *Sustainability* 16 (24): 10983. https://doi.org/10.3390/su162410983

KOC, S.–BULUS, G. C. (2020): Testing validity of the EKC hypothesis in South Korea: role of renewable energy and trade openness *Environmental Science and Pollution Research* 27 (23): 29043–29054. https://doi.org/10.1007/s11356-020-09172-7

LE, H. P.–OZTURK, I. (2020): The impacts of globalization, financial development, government expenditures, and institutional quality on CO_2 emissions in the presence of environmental Kuznets curve *Environmental Science and Pollution Research* 27 (18): 22680–22697. https://doi.org/10.1007/s11356-020-08812-2

LEAL, P. H.–MARQUES, A. C. (2022): The evolution of the environmental Kuznets curve hypothesis assessment: a literature review under a critical analysis perspective *Heliyon* 8(11): e11521. https://doi.org/10.1016/j.heliyon.2022.e11521

LI, W.–ELHEDDAD, M.–DOYTCH, N. (2021): The impact of innovation on environmental quality: evidence for the non-linear relationship of patents and CO_2 emissions in China *Journal of Environmental Management* 292: 112781. https://doi.org/10.1016/j.jenvman.2021.112781

LUCAS, R. E.–WHEELER, D.–HETTIGE, H. (1992): *Economic development, environmental regulation, and the international migration of toxic industrial pollution, 1960–88* (Vol. 1062) World Bank Publications.

OSABUOHIEN-IRABOR, O.–DRAPKIN, I. M. (2024): The spillover effects of outward FDI on environmental sustainability in developing countries: exploring the channels of home country institutions and human capital *Environment, Development and Sustainability* 26 (8): 20597–20627. https://doi.org/10.1007/s10668-023-03494-5

OYEBANJI, M. O.–CASTANHO, R. A.–GENC, S. Y.–KIRIKKALELI, D. (2022): Patents on environmental technologies and environmental sustainability in Spain *Sustainability* 14 (11): 6670. https://doi.org/10.3390/su14116670

PANAYOTOU, T. (1993): Empirical tests and policy analysis of environmental degradation at different stages of economic development *World Employment Programme Research Working Paper* International Labour Organization.

PHILLIPS, P. C. B.–HANSEN, B. E. (1990): Statistical inference in instrumental variables regression with I(1) processes *The Review of Economic Studies* 57 (1): 99–125. https://doi.org/10.2307/2297545

RAZA, M. Y.–CHEN, Y.–TANG, S. (2022): Assessing the green R&D investment and patent generation in Pakistan towards CO_2 emissions reduction with a novel decomposition framework *Sustainability* 14 (11): 6435. https://doi.org/10.3390/su14116435

SABRI–AIMON, H.–AMAR, S. (2024): Economic growth and environmental degradation in Indonesia: the roles of investment, inflation, income inequality, fossil consumption, and poverty *International Journal of Sustainable Development and Planning* 19 (5): 532–543. https://doi.org/10.18280/ijsdp.190532

SARWAT, S.–GODIL, D. I.–ALI, L.–AHMAD, B.–DINCA, G.–KHAN, S. A. R. (2022): The role of natural resources, renewable energy, and globalization in testing EKC theory in BRICS countries: method of moments quantile *Environmental Science and Pollution Research* 29: 23677–23689. https://doi.org/10.1007/s11356-021-17557-5

SHAHBAZ, M.–LEAN, H. H.–SHABBIR, M. S. (2015): Environmental Kuznets curve hypothesis in Pakistan: cointegration and causality analysis *Renewable and Sustainable Energy Reviews* 47: 200–206. https://doi.org/10.1016/j.rser.2012.02.015SONGUR, M.–UĞURLU, E.–MURATOĞLU, Y.–ŞANLI, D. (2024): *Testing the Kuznets curve hypothesis at the sector level: evidence from PNARDL for OECD countries* (preprint). https://doi.org/10.21203/rs.3.rs-4016803/v1

STERN, D. I. (1998): Progress on the environmental Kuznets curve *Environment and Development Economics* 3 (2): 173–196.

STERN, D. I. (2004): The rise and fall of the environmental Kuznets curve *World Development* 32 (8): 1419–1439. https://doi.org/10.1016/j.worlddev.2004.03.004

SULAIMAN, C.–ABDUL-RAHIM, A. S. (2017): The relationship between CO_2 emissions, energy consumption and economic growth in Malaysia: a three-way linkage approach *Environmental Science and Pollution Research* 24: 25204–25220. https://doi.org/10.1007/s11356-017-0092-1

YANG, T.–DONG, Q.–DU, Q.–DU, M.–DONG, R.–CHEN, M. (2021): Carbon dioxide emissions and Chinese OFDI: from the perspective of carbon neutrality targets and environmental management of home country *Journal of Environmental Management* 295: 113120. https://doi.org/10.1016/j.jenvman.2021.113120

WANG, Q.–ZHANG, F.– LI, R. (2023a): Revisiting the environmental Kuznets curve hypothesis in 208 countries: the roles of trade openness, human capital, renewable energy and natural resource rent *Environmental Research* 216 (3): 114637. https://doi.org/10.1016/j.envres.2022.114637

WANG, Q.–YANG, T.–LI, R.–WANG, X. (2023b): Reexamining the impact of foreign direct investment on carbon emissions: does per capita GDP matter? *Humanit Soc Sci Commun* 10: 406. https://doi.org/10.1057/s41599-023-01895-5

WOOLDRIDGE, J. M. (2010): *Econometric analysis of cross section and panel data* MIT press.

WOOLDRIDGE, J. M. (2019): Correlated random effects models with unbalanced panels *Journal of Econometrics* 211 (1): 137–150. https://doi.org/10.1016/j.jeconom.2018.12.010

WOOLDRIDGE, J. M.–WADUD, M.–LYE, J. (2016): *Introductory econometrics: Asia Pacific edition with online study tools 12 months* Cengage AU.

ZHEN, N.–FREIRE, C. (2023): The inter-links between the economic complexity and carbon footprint *UNCTAD Background Paper* United Nations Conference on Trade and Development, Geneva.

INTERNET SOURCES

BORGHESI, S.–FRANCO, C.–MARIN, G. (2016): Outward foreign direct investment patterns of Italian firms in the EU ETS *SEEDS Working Paper* (1). https://www.sustainability-seeds.org/papers/RePec/srt/wpaper/0116.pdf (downloaded: September 2025)

HAFNER, M.–TAGLIAPIETRA, S. (2020): The geopolitics of the global energy transition *Springer Open.* https://library.oapen.org/bitstream/handle/20.500.12657/39553/2020_Book_TheGeopoliticsOfTheGlobalEnerg.pdf?sequence=1 (downloaded: September 2025)

HINRICH FOUNDATION (2024): *Carbon dioxide emissions: a resource wealth paradox.* https://www.hinrichfoundation.com/research/infographic/sustainable-trade/carbon-dioxide-emissions (downloaded: May 2026)

KUZNETS, S. (2019): Economic growth and income inequality. In: *The gap between rich and poor* pp. 25–37., Routledge. https://cooperative-individualism.org/kuznets-simon_economic-growth-and-income-inequality-1955-may.pdf (downloaded: September 2025)

UNITED NATIONS TRADE AND DEVELOPMENT [UNCTAD] (2016): *World investment report 2016 – Investor nationality: policy challenges.* https://unctad.org/en/PublicationsLibrary/wir2016_en.pdf (downloaded: September 2025)

WEBSITES/DATABASES

[1] https://www.consilium.europa.eu/hu/policies/green-deal/ (downloaded: October 2024)
[2] https://unfccc.int/process-and-meetings/the-paris-agreement (downloaded: March 2025)
[3] https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en (downloaded: March 2025)
[4] https://www.consilium.europa.eu/hu/press/press-releases/2023/10/16/paris-agreement-council-submits-updated-ndc-on-behalf-of-eu-and-member-states/ (downloaded: March 2025)
[5] https://ec.europa.eu/commission/presscorner/detail/en/mex_23_5067 (downloaded: July 2024)
[6] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en (downloaded: July 2024)
[7] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R1854&from=SK (downloaded: March 2024)
[8] https://www.consilium.europa.eu/hu/policies/eu-recovery-plan/repowereu/ (downloaded: March 2024)
[9] https://energy.ec.europa.eu/system/files/2014-10/roadmap2050_ia_20120430_en_0.pdf (downloaded: May 2026)
[10] https://ec.europa.eu/eurostat/databrowser/view/sdg_13_10/default/table?lang=en (downloaded: September 2024)
[11] https://ec.europa.eu/eurostat/databrowser/view/sdg_07_11/default/table (downloaded: September 2024)
[12] https://www.iea.org/countries (downloaded: September 2024)
[13] https://ec.europa.eu/eurostat/databrowser/view/sdg_08_10/default/table (downloaded: September 2024)
[14] https://www.iea.org/energy-system (downloaded: September 2024)
[15] https://ec.europa.eu/eurostat/databrowser/view/sdg_07_30/default/table?lang=en (downloaded: January 2025)
[16] https://data.worldbank.org/indicator/NV.SRV.TOTL.ZS (downloaded: March 2025)
[17] https://data.worldbank.org/indicator/BM.KLT.DINV.WD.GD.ZS (downloaded: March 2025)
[18] https://data.footprintnetwork.org/#/compareCountries?cn=all&type=EFCpc&yr=2022 (downloaded: March 2025)
[19] https://data.footprintnetwork.org/#/compareCountries?type=EFCpc&cn=11,255,27,98&yr=2022 (downloaded: March 2025)
[20] https://data.worldbank.org/indicator/BM.KLT.DINV.CD.WD (downloaded: May 2026)