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Environmental degradation, income and economic complexity: Evidence from European countries

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Abstract

Recent energy tensions caused by conflicts in Ukraine and the Middle East have added to the pressure that global warming exerts for an energy transition towards low-carbon energy sources. This study combines two time series approaches with the aim of delving deeper into the relationship between environmental degradation and economic growth and to test the environmental Kuznets curve (EKC) hypothesis, using information from 20 European countries between 2007 and 2021. Overall, the obtained results suggest the existence of a N-shaped nexus between emissions and income per capita. Additionally, we evaluated stability of this nexus and the potential existence of an asymmetric adjustment. In most countries we find asymmetries in the adjustment of emissions to positive and negative changes in income, but not so much in economic complexity. However, notable differences are observed between countries, which could be indicating their differentiated phase in the EKC curve.

Keywords: economic growth; economic complexity; environmental degradation; greenhouse gas emissions; Europe

JEL Classification: : C38; C55; O44; Q20; Q50

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1. Introduction

The recent climate summit in Azerbaijan—Conference of the Parties (COP29) to the United Nations Framework Convention on Climate Change—closed with a new minimal agreement, postponing until 2035 the increase in financing for developing countries to protect themselves against climate disasters. The conference has once again highlighted the urgency of moving from an energy model based on fossil fuels to one based in renewable energies. Faced with these challenges, more nations are aiming for the decarbonization of energy resources in order to mitigate greenhouse gas (GHG) emissions and the effects of climate change. According to the European Environment Agency (EEA, 2023), 22.5% of energy consumed in the European Union (EU) in 2022 was generated from renewable energy sources (RES). In October 2023, the EU signed an update of the Renewable Energy Directive with the objective of ensuring that the consumption of renewables reaches a weight of 45% in 2030. This objective is aimed at reducing growing environmental degradation.

Total primary energy supply comes fundamentally from solid fuels (including hard coal), crude oil and petroleum products, natural gas, nuclear energy, and renewables. Sources of RE can be, in turn, divided in biomass and renewable waste, solar, wind, geothermal, hydropower, tide, wave and ocean, and hydrogen. As opposed to non-renewable energy, which comes from finite sources that could get used up, renewables do not face that constraint and can be used for electricity generation, space and water heating and cooling, as well as transportation. Other sources of energy, such as wind and solar, have variable supply and are usually referred to as variable RES. According to some authors (e.g. Raynaud et al., 2018), these intermittent sources and are expected to play a key role in increasing the share of renewables in the energy mix.

However, in spite of the potential and the growing importance of RES, their penetration in most power grids is still low, and it varies considerably between different countries (Carty and Claveria, 2024). This diversity in the renewables development in European countries was noted by Papież et al. (2018), who found that between 1995 and 2014 all EU countries increased their shares of RES but that the growth was uneven, and that the relative weight of different types of renewables in total RES also differed considerably across countries.

The present study aims to test the hypothesis of the environmental Kuznets curve (EKC), which suggests an inverted *U*-shaped relationship between economic growth and environmental degradation (Grossman and Krueger, 1991). Unlike most previous research, we test the EKC hypothesis using not only economic growth but also development, proxied by Harvard Growth Lab's economic complexity index (ECI).

Further on, previous studies of the EKC have focused on a wide variety of countries and regions. However, the EU economies have usually been neglected. Some exceptions are the works of Auci and Trovato (2011), Frodyma et al. (2022), López-Menéndez et al. (2014), Marinas et al. (2018), and Mohammed et al. (2024). We see the EU as a particularly important case study because of its common environmental policy, which is becoming increasingly restrictive in the past two decades. An example of Europe's commitment to overcome the challenges posed by climate change and increasing environmental degradation is the *European Green Deal* approved in 2020, which aims to transform the EU into a resource-efficient economy with no net emissions of GHGs by 2050 (Hainsch et al., 2022).

The EKC offers an ideal conceptual framework for the analysis of the changing relationship between economic growth and environmental degradation. In their seminal study, Grossman and Kreuger (1991) found a non-linear relationship between both variables. This finding led Panayotou (1993) to label this nexus as the EKC. Following the studies by Selden and Song (1994) and Grossman and Kreuger (1995), more focused on the long-term relationship between both variables, the hypothesis pointed to a *N*-shaped nexus, suggesting that after the environmental improvement caused by increasing technological development, there can be yet a rebound in the degradation of the environment beyond a given growth threshold. Since then, a large number of empirical studies have been carried out testing the EKC hypothesis (Akbostancı et al., 2009; Khalfaoui et al., 2023; Magazzino et al., 2023; Wang et al., 2023, 2024). Although the evidence is mostly in favour, there are studies that reject the hypothesis of an EKC for specific countries or groups of countries (e.g., Jóźwik et al., 2021; Leal and Marques, 2020; Tchapchet Tchouto, 2023).

Progress in the study of EKC has occurred simultaneously from a theoretical and an empirical perspective, producing feedback in both fields. From methodological perspective, the main advances in the study of the ECK could be categorised into four large groups. First, the use of new indicators of environmental degradation. Second, the incorporation of additional explanatory variables that amplify or moderate the effect of economic growth on the environment. Third, the use of new econometric techniques that allow modeling different aspects of the interaction between both variables. And finally, the testing of the hypothesis beyond national boundaries, carrying out studies at the sectoral or regional level.

In accordance with these guidelines, the present study seeks to provide new evidence by (i) testing not only the relationship between environmental degradation and income, but also the link between emissions and economic complexity, (ii) incorporating a wide range of additional explanatory variables that to the best of our knowledge have never before been used to evaluate the relationship between economic growth and environmental degradation, and (iii) combining two alternative methodological approaches with the aim of delving into different aspects of the relationship between environmental degradation and development. First, the EKC is tested within a fixed-effects panel model framework. Second, we apply a non-linear autoregressive distributed lag (NARDL) country-by-country analysis to assess the stability of this relationship and to test for the existence of asymmetries in the adjustment of GHG emissions to positive and negative changes in income and development at a national level.

With the aim of analysing the nexus between economic growth and environmental degradation, we built a panel dataset for 20 European countries between 2007 and 2021, incorporating a broad set of additional variables from different areas that allows that allow us to evaluate, among other things, the role of environmental policies, energy dependence or the deployment of renewable energies such as wind and solar energy.

The remainder of this paper is structured as follows. Section 2 assesses the current state of research surrounding the EKC hypothesis. Section 3 describes the data. The next section briefly describes the methodology and presents the results. Finally, Section 6 summarises the main findings, states the limitations of the study, and future lines of research.

2. Literature review

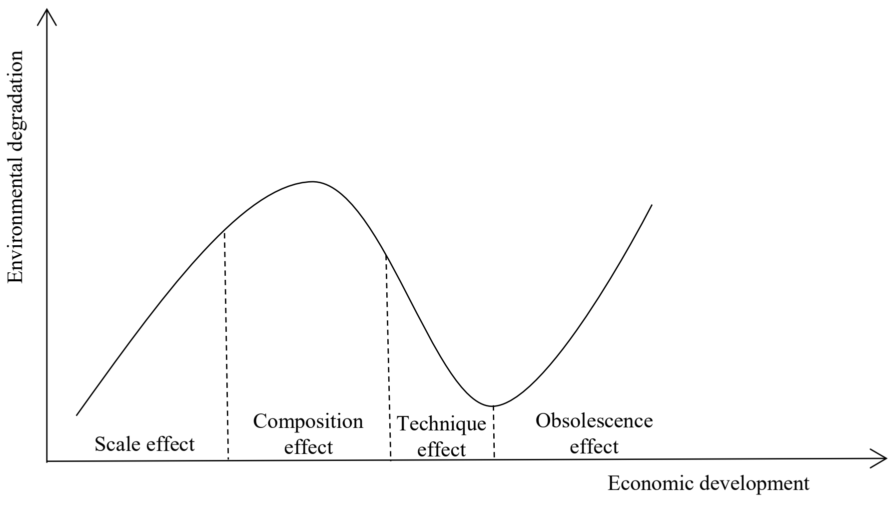
In their seminal work, Meadows et al. (1972) formalised for the first time the relationship between economic growth and environmental pollution. With the intensification of research on this topic, it rapidly became evident that the relationship between pollution and economic growth might be non-linear. In that sense, Grossman and Krueger (1991) were the first to notice an inverted-*U* curve that best described the examined relationship in 42 countries. The basic idea of the EKC is that the relationship between environmental degradation and economic growth can be described through three phases. During the initial phase of growth, the economy demands a high level of natural resource utilization. As this initial phase highly depends on the primary and secondary economic sector, it's standard by-product is an increase of environmental pollution (Stern, 2004, 2017). Grossman and Krueger (1991) referred to this as the *scale effect*.

As the economy continues to develop, its structure starts to change, shifting towards the tertiary sector and the knowledge economy. A rise of the services sector eventually starts to reduce the emission of environmental pollutants in comparison to the previous agrarian and industrial economies, and technological progress enables cleaner production. Therefore, although this phase starts with a positive association between growth and environmental degradation, structural economic changes induce an inflection point after which the association turns negative. This phase was labelled as the *composition effect*. Copeland and Taylor (2004) formally described this phenomenon, and it was later on embraced in most EKC-related studies (Dinda, 2004; Guo and Shahbaz, 2024).

In the third stage of this process, the *technique effect* kicks in. Grossman and Krueger (1991) explained it as a negative impact of further economic progress on environmental degradation, that happens for at least two reasons. The first one relates to modern technologies and cleaner production. The other one relates to the general finding that as the society evolves, the general public awareness of environmental issues increases, so various political, non-governmental, and corporate activities related to ecological sustainability get intensified (Hens et al., 2018; Quintana-García et al., 2022; Zhang et al., 2013). As a consequence of both mentioned forces, the pollution per unit of output should decrease.

The stated three phases of the growth-pollution nexus are sometimes summarized in the dictum *grow first and clean later* (Wang et al., 2024). However, recent research was able to assess longer time series of income and environmental degradation, which have sometimes even revealed a fourth phase of the cycle. If the scale effect overpowers the composition and technique effect, a new turnaround point occurs, leading to an again positive association of growth and environmental degradation. Álvarez-Herránz et al. (2017) call this the (technical) *obsolescence effect*. In this manner, the Kuznets curve may become N-shaped (Álvarez-Herránz et al., 2017; Wang et al., 2024; Ullah et al., 2024; Guo and Shahbaz, 2024). The stated dynamics in the income-pollution relationship can be depicted as in Figure 1.

Figure 1. *N*-shaped EKC curve



Since the early 2000s, the body of EKC research has grown exponentially (Dogan et al., 2020; Hussain and Dogan, 2021), reflecting the growing social awareness about climate change and environmental degradation, and the importance of research aimed at facilitating the transition towards resource-efficient economies. All this shows that the EKC has a global reach, attracting a wide range of researchers and policy analysts. That being noted, the empirical results extracted from all these studies are extremely heterogeneous and context-dependent. They differ with regard to the chosen environmental pollution indicator, the examined set of control variables, the methodological framework of the study at hand, the analysed set of countries, and the examined time period. The stated issues have induced a seemingly unending debate over the validity of EKC and its proper functional form. A detailed meta-analysis of previous related studies is far beyond the scope of this paper, but interested readers may consult meticulous literature surveys by Dinda (2004), Stern (2017) or Guo and Shahbaz (2024).

Being a purely empirical phenomenon, the EKC is prone to various statistical misspecifications and its empirical verifications are often not statistically robust. Stern (2017) pointed to omitted variable bias and methodological issues, such as the non-stationarity of variables and the potentially problematic choice of estimator, as the two most often errors in the empirical assessments of EKC. Carson (2010) introduced very similar arguments in one of the earlier EKC surveys. Guo and Shahbaz (2024) further accentuated the need to innovate EKC estimation in terms of adding relevant socio-economic and environmental control variables, as well as in terms of cutting edge, non-linear estimation techniques. Let us delve deeper into these issues, address their importance and explain the way we plan to take them into account.

First, it is vital to relate this strand of literature to the finding of Verbeke and de Clerq (2006). They rightly noticed that both income and pollution are often non-stationary variables, and that regression-type EKC estimations that are dominant in the literature often lead to spurious results. Through their Monte Carlo simulation analysis with randomly generated income and pollution data, they found that as much as 40% of EKC estimations result with false positives, i.e. a spurious U-inverted relationship. Much of the empirical literature thus might be biased towards falsely confirming the existence of EKC. In that context, it seems crucial to account for non-stationarity in any further econometric examination of EKC. In that vein, Stern (2017) also highlights the need to rely on cointegration analysis of level data in EKC research instead of first-differencing the data.

Another aspect worth acknowledging relates to the potential asymmetric effects in the growth-pollution conundrum. Fosten et al. (2012) provided one of the first contributions in that sense. As the authors noticed, international protocols aimed at reducing greenhouse gas emissions (e.g. the Kyoto Protocol or the recent European Green Deal) induce a stronger reaction of emissions if they are atypically high due to legislative stringency measures and possible penalties. On the other hand, there is no specific impulse to bring short-run deviations back to their steady state levels when environmental degradation is at very low levels. In line with this premise, Fosten et al. (2012) indeed find asymmetric threshold effects in the sense that short-run deviations are corrected more quickly for larger values of greenhouse gas emissions. Later on, several other papers also focused on different non-linear estimation techniques to assess possible asymmetries in the EKC relationship. For example, Wang et al. (2023) further explored this issue, establishing income inequality as the threshold variable in the EKC framework for a panel of 56 countries. In the high inequality regime, economic growth seemed to decrease environmental pollution, while the opposite effect kicks in when inequality raised. This highlights the necessity of keeping income inequality under control if policymakers want to pursue the goal of an environmentally sustainable economic growth.

Given the recently found non-linear behaviour of GHG emissions (Gaies et al., 2022; Haug and Ucal, 2019), it comes as no surprise that a proliferation of non-linear/asymmetric EKC assessments was recorded in the last couple of years. Upon correctly acknowledging the asymmetric nature of the EKC relationship, recent studies have started to convincingly confirm its validity. For example, Uche et al. (2023) validated the EKC for India using a NARDL model, while Qalati et al. (2023) use the NARDL model to find support for the EKC in G7 economies and a sample of seven developing countries. In a similar line, several authors have recently confirmed the existence of EKC using various forms of quantile regressions. Adebayo et al. (2022), Chien (2022), and Yang et al. (2022) applied quantile analysis to emerging market economies. Jahanger et al. (2022) analysed NAFTA countries, while Balsalobre-Lorente et al. (2023) used a similar approach for Central and Eastern European economies.

Both NARDL and quantile regression frameworks have to date been quite underused because most empirical work focused on EKC has evolved around linear econometric models, in particular linear cointegration tests (Qalati et al., 2023). Guo and Shahbaz (2023) thus even emphasised this line of modelling as a prospective direction for future research of EKC. For this reason, we also add to the literature by utilizing the NARDL framework in our study. An additional argument for this choice is that NARDL allows for a flexible treatment of both I(0) and I(1) time series (Greenwood-Nimmo and Shin, 2013; Shin et al., 2014). As this feature is present in our dataset, any other empirical specification that combines differenced and level data would cast doubt on the reliability of obtained results. Similar argumentation in the EKC context was also provided by Stein (2017).

As Guo and Shahbaz (2023) pointed out, further innovations in EKC specifications should surely include a wider set of control variables. First, we should acknowledge the efforts made in energy diversification, specifically with regards to RES and their potential moderating role in the EKC relationship (Yao et al., 2019). Some efforts have already been made in that sense. Jebli and Youssef (2015) did not find empirical support for the EKC in the Tunisian case, but found that RES considerably decreased air pollution. Zhao et al. (2022) found that solar energy and eco-innovations significantly inhibited CO_2 emissions in G7 countries. Al-Mulali et al. (2016) went a step further, finding that renewable energy consumption acted as a necessary condition for the validity of EKC in seven major world regions. Acknowledging these findings, we also augment our EKC specifications with wind and solar as control variables, with the goal of discerning their role of pollution inhibitors and questioning the general robustness of EKC hypothesis.

The literature is also abundant with various other institutional and socio-economic variables used as controls in EKC specifications. Guo and Shahbaz (2023) provided a thorough survey of phenomena that were found to significantly influence the empirical validity of EKC. Some of these include financial development (e.g. Shahbaz et al., 2020) and trade openness (e.g. Magazzino et al., 2023), as they stimulate economic growth and in turn affect the overall level of environmental degradation. Guo and Shahbaz (2023) especially accentuated population density as a potentially relevant control variable that should be assessed in future EKC studies. To date, it has only marginally been examined in e.g. Wang et al. (2023) to validate the EKC.

3. Data

The present study is based on a panel dataset that links environmental degradation—proxied by GHG per capita emissions—to income per capita and development—proxied by Harvard Growth Lab's index of economic complexity—for 20 European countries. The sample period extends from 2007 to 2021. The selection of countries is done according to the availability of information. Consequently, with the aim of having a sufficiently long period of time and covering the different areas of the continent, a dataset with information for 20 countries was created. These economies are distributed across the four main regions of Europe: Central

Europe (Austria, Belgium, France, Germany, Netherlands), Northern Europe (Denmark, Finland, Sweden, and Ireland), Southern Europe (Croatia, Greece, Italy, Portugal, Slovenia, and Spain) and Eastern Europe (Bulgaria, Czechia, Hungary, Slovakia, and Slovenia).

The dataset also incorporates a wide range of energy and socio-political indicators, which were chosen to reflect a wide variety of potential determinants on the relationship between emissions and development. Table 1 presents a detailed explanation of each variable and its units of measurement. The data used was sourced from Eurostat, The World Bank, OECD and the United Nations (UN).

Table 1. List of variables

Variable	Explanation	Units
GHG emissions	Total greenhouse gas emissions excluding land use, land use change and forestry	kt of CO_2 equivalent
Per capita income	Average income per capita	current $USD
Complexity	Economic complexity index - Assesses the current state of a country's productive knowledge	Index
Wind energy	Share of gross renewable energy consumption attributable to wind	%
Solar energy	Share of gross renewable energy consumption attributable to solar (photovoltaic + geothermal)	%
Taxes on pollution	Sum of tax revenue from pollution and resource taxes	Millions of euros
Energy intensity	Final energy consumption over GDP	MJ/$2011 PPP GDP
Energy imports	Percent of total energy imported	%
Urban population	Percent of population living in urban areas	%
Population density	Total population over land area	People per square km. of land area
Industry consumption	Final energy consumption by the industry sector	GWh
Transportation consumption	Final energy consumption by the transportation sector	GWh
Household consumption	Final energy consumption by households	GWh

Notes: GDP for Gross Domestic Product, USD for US dollars, GWh stands for Gigawatts per hour, MJ for Megajoule, PPP for purchasing power parity.

Following recent research by Balsalobre-Lorente et al. (2022) and Tchapchet Tchouto (2023), this study evaluates the effective impact of economic complexity on environmental degradation as a proxy of development. Economic development requires the accumulation of productive knowledge and its use in both more and more complex industries. Harvard Growth Lab's Country Rankings assess the current state of a country's productive knowledge, through the ECI. Countries improve their ECI by increasing the number and complexity of the products they successfully export. The introduction of this index allows us to incorporate the interactions between environmental degradation and development beyond a strictly economic sense.

Taxes on pollution are incorporated as a proxy indicator of a nation’s economic attitude towards pollution. Recent studies have found evidence of the impact of environmental taxes on the development of renewables (Dogan et al., 2022; Fang et al., 2022). In the context of the debate as to whether the deployment of renewables is capable of decoupling increased economic output with increased emissions, energy intensity has been specifically named as a possible mechanism for achieving this (Aydin and Turan, 2020), hence its introduction in the study. Energy imports were added to introduce the very relevant question of energy independency in Europe, which has been shown to be crucial as a result of the war in Ukraine and the consequent effects that the has had on energy policies in the region (Chu et al., 2023; Hille, 2023; Kuzemko et al., 2022; Osička and Černoch, 2022).

Population density and the percentage of urban population are also used in order to capture the effect population distribution on environmental degradation. Grodzicki and Jankiewicz (2022) recently proved that increases in the urbanisation levels harmed the air quality. Finally, we incorporated ‘energy consumption’, divided into three distinct sectors (industry, transportation and household) to investigate any sector-specific relationship to energy consumption.

Figure 2 shows each country’s distribution of GHG emissions per capita during the sample period. In the box-plot it can be seen that Ireland, Czechia and the Netherlands are the three countries with the highest levels of emissions during the period 2007–2021, as opposed to Sweden, which is the country with the lowest average level. However, when the results are grouped by region (Figure 3), the emerging picture highlights the lower-average level of emissions per capita observed in Western Europe, and also the greater dispersion observed in Northern Europe during the period under study.

Figure 2. Distribution of GHG emissions per capita by country – 2007 to 2021

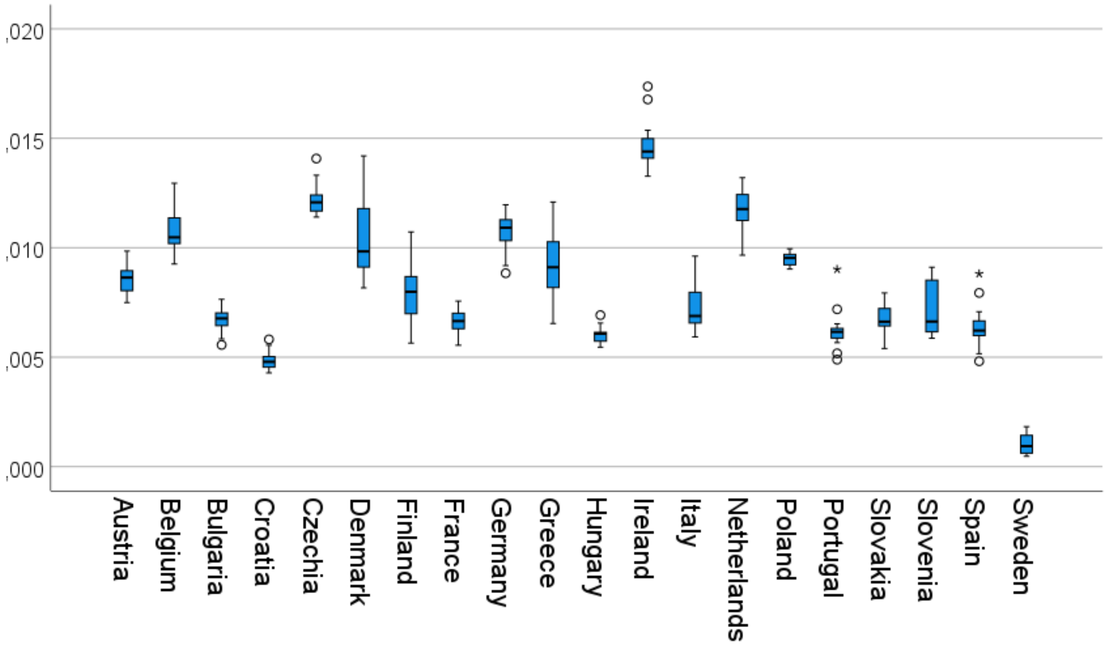
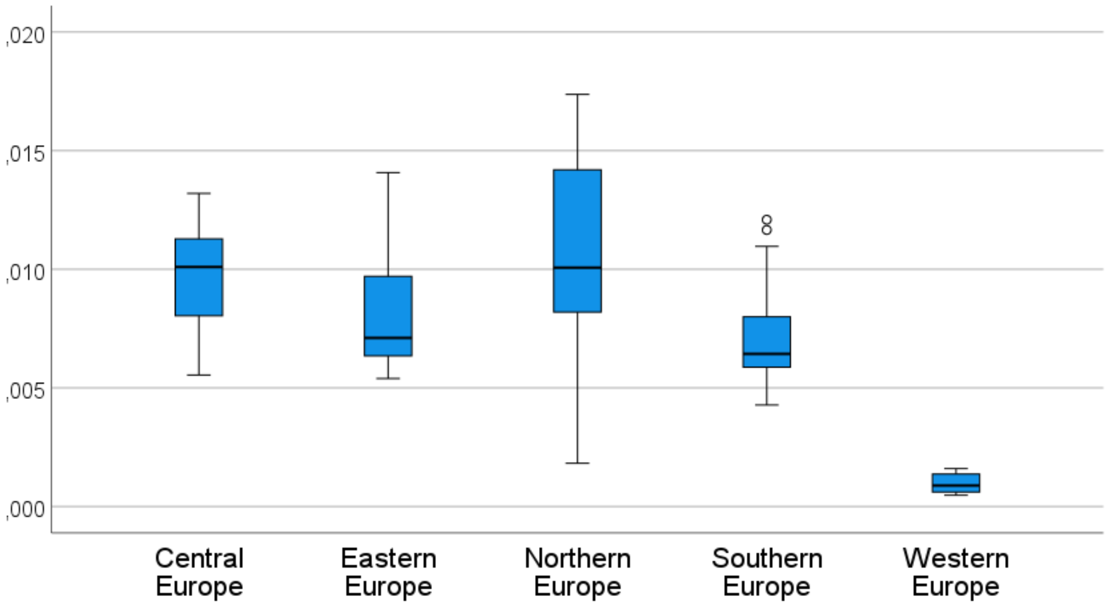


Figure 3. Distribution of GHG emissions per capita by region – 2007 to 2021



4. Empirical analysis

4.1. Methods

With regards to the empirical approach, the relationship between environmental degradation—proxied by GHG emissions per capita—and economic growth—measured as per capita income—is first examined by means of a fixed-effects panel model. The model can be specified as follows:

$$Y_{it} = \beta_0 + \beta_1 X_{it} + \beta_2 X_{it}^2 + +\beta_3 X_{it}^3 + \gamma Z_{it} + \alpha_i + \delta_t + \varepsilon_{it} \quad (1)$$

Where Y_{it} is the dependent variable (emissions per capita) for country *i* in year *t*, for *i*=1,…,*N* and *t*=2007,…,2021. The main explanatory variable is income per capita (X). Vector Z_{it} includes control variables. Unobserved time-invariant country-specific characteristics are collected in α_i, which is a set of *N*-1 dummy variables multiplied by their respective regression coefficients to account for country fixed effects. We also added *T*-1 dummy variables to account for time fixed effects, noted in Equation (1) as δ_t. This allows controlling for time-varying differences in suicide rates common to all countries (e.g., the 2008 financial crisis).

As a robustness check, we replicated the analysis iteratively incorporating a set of control variables (deployment of wind energy, deployment of solar energy, taxes on pollution, energy intensity, energy imports, urbanization, density, and energy consumption in industry, transportation and households respectively). For a detailed explanation of each variable see Table 1. The models were estimated using heteroskedasticity- and autocorrelation-consistent (HAC) standard errors.

As an additional robustness check, we used development as the exogenous variable. We used the index of economic complexity constructed by Harvard Growth Lab's and available at the World Bank's web. The ECI proxies development by assessing the current state of a country's productive knowledge. Countries improve their ECI by increasing the number and complexity of the products they successfully export. The ECI allows us to evaluate the relationship between environmental degradation and development beyond a strictly economic sense. See Carty and Claveria (2024) for a recent assessment of the nexus between development and variable RES.

Apart from testing the EKC by estimating the panel model contained in Equation (1) for the different specifications, a complementary analysis is carried out to evaluate the existence of an asymmetric adjustment of GHG emissions in the face of increases or decreases in income. and development. See Claveria and Sorić (2025) for a recent application between economic uncertainty and redistribution. We use a NARDL framework that allows us to test for the existence of a long-term relationship between economic growth and environmental degradation. We used linear interpolation to extract monthly data from the annual variables, and conducted the analysis at a country level.

Our estimation strategy is largely conditioned by the fact that the assessed dataset is consisted of a mixture of stationary and integrated time series, i.e. I(0) and I(1). This prevented us from framing the study within a standard Johansen cointegration or vector autoregression (VAR) analysis, and led us to use an autoregressive distributed lag (ARDL) model. Here we depart from panel data econometrics and opt for a time series approach, modelling each considered EU country individually. As Fosten et al. (2012) denote, time series estimations of EKC might offer more nuanced information because panel data view of EKC has a potentially implausible assumption that all considered countries share a common development path.

The proposed ARDL methodology has some noteworthy benefits. On the one hand, it allows for a combination of stationary and non-stationary variables (Pesaran et al., 2001). On the other hand, it also preserves valuable degrees of freedom by allowing for different lag orders for each variable at hand. Besides, the ARDL model is robust to bi-directional feedback effects between dependent variable and regressors, conditioned to a correct specification of the lag order so that regressors become weakly exogenous (Mohaddes et al., 2022).

Finally, and most importantly, the proposed framework allows examining whether there are differences in the effects of positive and negative changes in income. This type of specification has recently proved to be very helpful in acknowledging the true nature of EKC (Qalati et al., 2023; Uche et al., 2023). Therefore, in order to capture these potential asymmetries, we used the non-linear ARDL framework of Shin et al. (2014):

$$\Delta Y_t = a_0 + \theta_1^+ X_{t-1}^+ + \theta_1^- X_{t-1}^- + \rho Y_{t-1} + \delta Z_t + \sum_{j=1}^{p-1} a_j \Delta Y_{t-j} + \sum_{j=0}^{q_1^+-1} \pi_{1,j}^+ \Delta X_{t-j}^+ + \sum_{j=0}^{q_1^--1} \pi_{1,j}^- \Delta X_{t-j}^- + e_t, \tag{2}$$

where Y_t is again emissions per capita, X_t is the chosen development indicator (income per capita or complexity), Z_t is a vector of control variables. Further on, $X_t^+ = \sum_{j=1}^{t} max(\Delta X_t, 0)$

and $X_t^- = \sum_{j=1}^{t} min(\Delta X_t, 0)$ are positive and negative partial sums of development. The optimal lag structure of the model (p, q_1^+, and q_1^-) was determined using the general-to-specific approach (Greenwood-Nimmo and Shin, 2013).

We assessed three separate specifications of Equation (2). In the first one, carbon emissions were regressed on income per capita. The second specification used HDI as an alternative regressor. In addition, we replicated the analysis by adding control variables to the first specification, both for income and development. For brevity, in the present paper, we only present the NARDL results with controls.

We tested for cointegration using a standard Wald test ($\boldsymbol{H_0}$: $\rho = \theta_1^+ = \theta_1^- = 0$) and for the existence of significant asymmetries in both the long term ($\boldsymbol{H_0}$: $\theta_1^+ = \theta_1^-$) and short term ($\boldsymbol{H_0}: \sum_{j=0}^{q_1^+-1} \pi_{1,j}^+ = \sum_{j=0}^{q_1^--1} \pi_{1,j}^-$). Should the short-term and/or long-term behaviour be symmetric (non-rejection of $\boldsymbol{H_0}$: $\theta_1^+ = \theta_1^-$ and/or $\boldsymbol{H_0}: \sum_{j=0}^{q_1^+-1} \pi_{1,j}^+ = \sum_{j=0}^{q_1^--1} \pi_{1,j}^-$), we re-estimated the model in its analogous symmetric variant, ARDL instead of NARDL. We also graphed the evolution of dynamic multipliers, which show how environmental degradation responds to positive and negative unit changes in income per capita:

$$m_{h,\omega}^+ = \sum_{j=0}^{h} \frac{\partial Y_{t+j}}{\partial X_t^+} \text{ and } m_{h,\omega}^- = \sum_{j=0}^{h} \frac{\partial Y_{t+j}}{\partial X_t^-}, h = 0, 1, 2, ... \quad (3)$$

4.2. Results

In this section, we evaluate the relationship between environmental degradation and income, controlling for a set of socio-political, economical and energy factors, and accounting for country fixed effects and for time fixed effects. Results of the estimated models are presented in Table 2. When examining the results of the relationship between per capita GHG emissions and per capita income, evidence is obtained in favor of an *N*-shaped relationship. When re-estimating the model including each of the controls independently, the relationship is practically not altered, with the exception of the model in which the 'urbanisation' variable is included—which refers to the percentage of population living in urban areas—, where the intensity is somewhat lower.

Table 2. Panel regression results – Emissions and economic growth

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
income	0.0005***	0.0004***	0.0004***	0.0005***	0.0006***	0.0005***	0.0004**	0.0004***	0.0004***	0.0004***	0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
income^2	-0.0001***	-0.0001**	-0.0001***	-0.0001***	-0.0001***	-0.0001***	-0.0001*	-0.0001***	-0.0001***	-0.0001***	-0.0001***
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0002)
income^3	0.0000**	0.0000	0.0000**	0.0000**	0.0000**	0.0000*	0.0000	0.0000**	0.0000**	0.0000**	0.0000**
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
wind energy		-0.0051									
		(0.0035)									
solar energy			-0.0068*								
			(0.0038)								
taxes				0.0033							
				(0.0043)							
intensity					0.0010*						
					(0.0005)						
imports						-0.0001***					
						(0.8190)					
urbanisation							0.0001				
							(9.9354)				
density								-0.0001***			
								(1.7040)			
industry									0.0005		
									(0.0005)		
transport										0.0004	
										(0.0003)	
household											0.0009*
											(0.0005)

Notes: Robust (HAC) standard errors between brackets. Column (1) reports fixed-effects panel estimates for baseline model. Columns (2) to (11) reports estimates for each of the covariates. See Table 1 for a definition of each variable. *, **, *** Indicate statistical significance at the 10%, 5%, and 1% level respectively.

Table 3. Panel regression results – Emissions and economic complexity

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
complexity	0.0065***	0.0074***	0.0042*	0.0066***	0.0060***	0.0068***	0.0065	0.0071***	0.0064***	0.0052***	0.0067***
	(0.0020)	(0.0021)	(0.0025)	(0.0019)	(0.0024)	(0.0014)	(0.0020)	(0.0016)	(0.0020)	(0.0019)	(0.0021)
complexity²	-0.0027	-0.0029	-0.0017	-0.0028	-0.0038**	-0.0027	-0.0027	-0.0027	-0.0028	-0.0017	-0.0035
	(0.0029)	(0.0030)	(0.0028)	(0.0028)	(0.0029)	(0.0018)	(0.0029)	(0.0029)	(0.0029)	(0.0029)	(0.0031)
complexity³	0.0004	0.0003	0.0003	0.0004	0.0008	0.0004	0.0004	0.0003	0.0004	0.0001	0.0007
	(0.0008)	(0.0009)	(0.0008)	(0.0008)	(0.0005)	(0.0008)	(0.0008)	(0.0008)	(0.0008)	(0.0008)	(0.0009)
wind energy		-0.0081**									
		(0.0049)									
solar energy			-0.0082*								
			(0.0047)								
taxes				0.0011							
				(0.0048)							
intensity					-0.0002						
					(0.0005)						
imports						-0.0001***					
						(1.1593)					
urbanisation							-0.0001				
							(0.0001)				
density								-0.0001***			
								(1.9299)			
industry									0.0013***		
									(0.0004)		
transport										0.0012***	
										(0.0003)	
household											0.0013**
											(0.0006)

Notes: Robust (HAC) standard errors between brackets. Column (1) reports fixed-effects panel estimates for baseline model. Columns (2) to (11) reports estimates for each of the covariates. See Table 1 for a definition of each variable. *, **, *** Indicate statistical significance at the 10%, 5%, and 1% level respectively.

When evaluating the independent effect of each of the ten variables introduced as controls, it is found that increases in the use of renewables, particularly ‘solar’ energy, ‘imports’ and ‘density’ are associated with reductions of GHG emissions per capita. López-Menéndez et al. (2014) found similar evidence regarding the positive impact of RES on CO_2 emissions reduction for a panel of 27 EU countries during the period 1996–2010, and Zoundi (2017) for a selection of 25 African countries. In this specification, it is obtained that increases in energy independence are not necessarily associated with lower GHG emissions.

By substituting the per capita income variable for economic complexity, equivalent signs are obtained for the coefficients, suggesting again an *N*-shaped relationship, although not always statistically significant. The differences in the estimates obtained for economic growth and the proxy variable for development using the economic complexity indicator somehow reflect the mixed evidence collected on this issue in the literature. While Frodyma et al. (2022) and Tchapchet Tchouto (2023) did not find evidence in favour of the EKC hypothesis, other authors do, especially when analysing countries independently (e.g., Jóźwik et al., 2021). This somehow points to the existing heterogeneity in the implementation of measures to reduce de carbon footprint between the different European countries.

Regarding the control variables, energy ‘imports’ and ‘density’ once again show a significant and negative impact on GHG emissions per capita. The deployment of wind and solar energy—measured as the relative weight of their consumption among renewables—also show a significant and negative association, suggesting that increased consumption of wind and solar energy may lead to a reduction in environmental degradation. This result would be in line with those obtained by Bölük and Mert (2014), Carty and Claveria (2024), Grodzicki and Jankiewicz (2022) and Magazzino et al. (2022), In contrast, energy consumption, both in industry, transportation and in homes, shows a significant and direct impact on environmental degradation, indicating that higher levels of energy consumption are associated with higher GHG emissions per capita.

NARDL results are presented in Tables 4-5. All estimated models are tested for the conventional error term assumptions. We applied the Engle’s ARCH test and the Ljung-Box autocorrelation test, both of fourth order. All specifications passed both tests, so the details are suppressed for the purpose of brevity. We also tested for Granger causality from economic growth and complexity to emissions per capita, i.e. we perform a joint test of significance of all development lags in equation (2): $\sum_{j=0}^{q_1^+-1} \pi_{1,j}^+ = \sum_{j=0}^{q_1^--1} \pi_{1,j}^- = 0$.

Overall, the results presented in Tables 4 and 5 show that the relationship between income and economic complexity and environmental pollution is mostly linear. Only a fraction of the assessed countries exhibits significant short-run and/or long-run asymmetries, although non-linearity is somewhat more present for economic complexity than for income. We also find cointegration for a majority of the observed economies. This finding is line with panel cointegration results obtained by Mohammed et al. (2024) for the EU and by Jóźwik et al. (2021) for Central Europe. Similarly, for a sample of developing countries, Li et al. (2023) found significant long-term and short-term effects of economic expansions on CO_2 emissions.

Table 4. NARDL results – Emissions and economic growth

Country	Type of asymmetry		LR coefficients		Cointegration	Granger causality
	Short run	Long run	θ_1^+	θ_1^-		
Austria	N	N	0.0129		4.99	4.41**
Belgium	N	N	0.0784***		14.47***	39.59***
Bulgaria	Y	N	0.0223		10.51***	38.37***
Croatia	N	N	0.0194**		3.39	32.16***
Czechia	N	N	-0.0034		2.08	118.83***
Denmark	N	Y	-0.0696**	0.0741**	6.67**	10.17***
Finland	N	N	0.2650***		12.50***	31.20***
France	N	N	0.0148		7.75**	54.67***
Germany	Y	N	-O.0226**		6.49**	35.84***
Greece	N	Y	-0.0159	0.0088	3.11	55.78***
Hungary	N	N	-0.0071		6.62**	60.49***
Ireland	N	N	0.0181***		10.32***	33.58***
Italy	N	N	-0.0053		5.02	64.40***
Netherlands	Y	N	-0.0068		11.74***	41.39***
Poland	N	N	0.0006		4.53	22.63***
Portugal	N	N	-0.0104		3.99	7.97***
Slovakia	N	N	0.0016		0.12	60.35***
Slovenia	Y	Y	0.0517	-0.0475	5.88***	11.41***
Spain	N	N	-0.0052		1.86	111.95***
Sweden	N	N	0.1893***		6.43***	60.91***

Notes. *, **, *** Indicate statistical significance at the 10%, 5%, and 1% level respectively. Entries in the "Granger causality" column are the corresponding F test statistics for the null hypothesis of all lags of emissions per capita being insignificant. Entries in the "Cointegration" row are the corresponding F test statistics of the NARDL cointegration test.

Our NARDL estimates for income and for complexity generate very similar results. In Table 4, a negative and significant long-run relationship between income per capita and environmental degradation is found in Denmark, Germany, Hungary, and the Netherlands, suggesting that these countries may be either in the phase of composition effect or the technique effect. The second group of countries—Belgium, Bulgaria, Croatia, Finland, France, Ireland, and Sweden—exhibits a positive long-run relationship. Using a NARDL analysis, Ben Saad et al. (2024) recently found evidence of significant asymmetries in the relationship between GDP per capita and renewable energy in the long term for most North African countries.

Table 5. NARDL results – Emissions and economic complexity

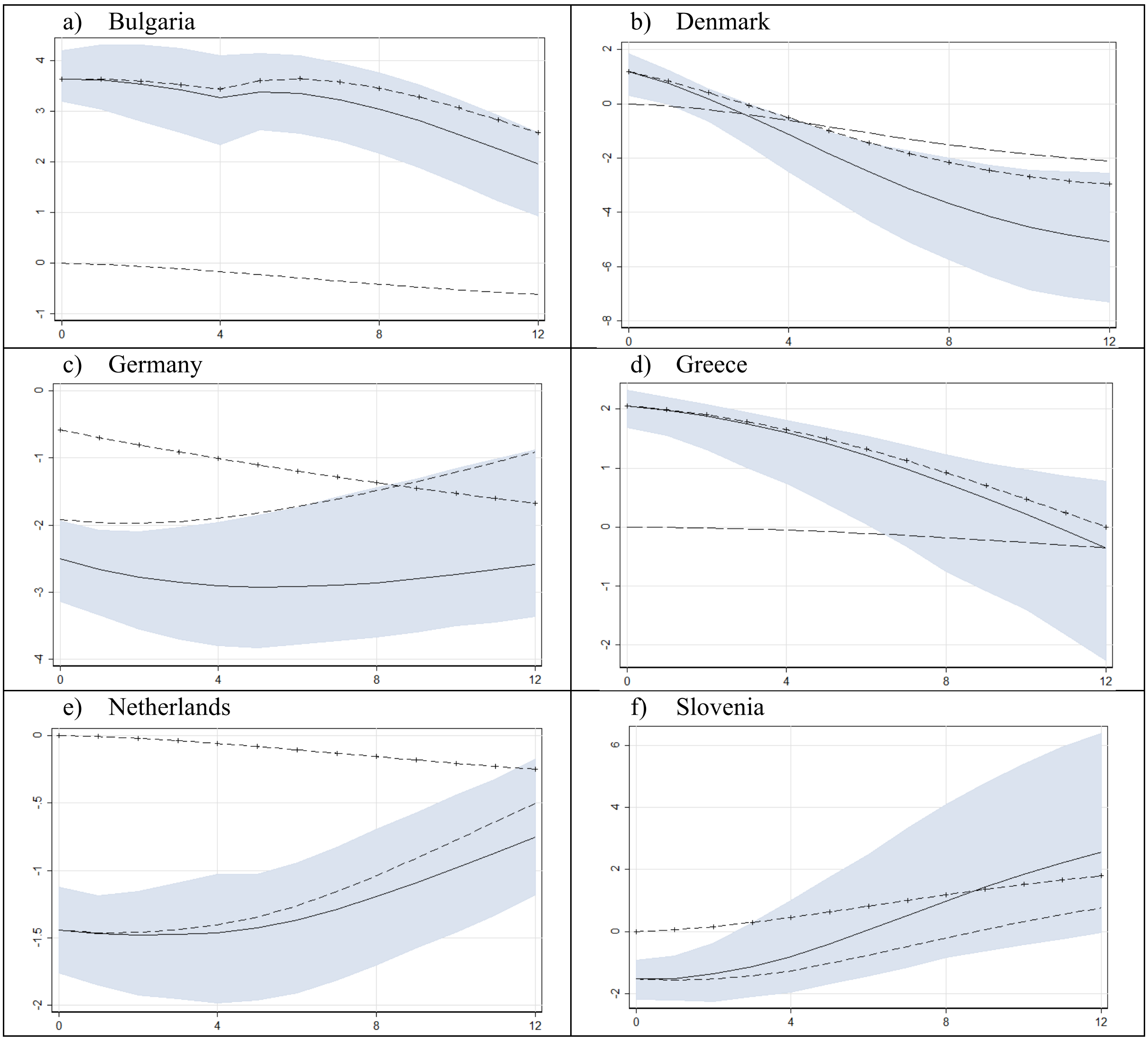
Country	Type of asymmetry		LR coefficients		Cointegration	Granger causality
	Short run	Long run	θ_1^+	θ_1^-		
Austria	N	Y	-0.0114	0.0039	3.20	2.11
Belgium	Y	N	0.0080**		15.16***	8.08***
Bulgaria	Y	Y	0.0611***	-0.0400***	8.53***	14.69***
Croatia	Y	Y	0.0119*	-0.0012	1.75	6.05**
Czechia	N	N	0.0017		5.90**	24.94***
Denmark	N	N	0.0010		2.91	66.12***
Finland	N	N	0.0383		12.38***	8.25***
France	N	N	0.0067		5.16*	17.64***
Germany	Y	N	0.0089**		5.31*	16.79***
Greece	N	N	0.0003		2.56	2.82*
Hungary	N	N	-0.0016		1.32	39.10***
Ireland	N	N	0.0009	6.72**	58.32***	123.76***
Italy	N	Y	0.0294	0.0446**	5.25	8.71***
Netherlands	N	Y	-0.0086	0.0031	6.53**	-
Poland	Y	N	0.0100***		7.84***	38.83***
Portugal	Y	N	-0.0244***		7.94***	42.39***
Slovakia	N	N	0.0043		1.65	25.90***
Slovenia	N	N	0.0310		5.72*	-
Spain	N	Y	-0.0114	0.0039	3.20	2.11*
Sweden	N	N	0.055		7.61***	-

Notes. *, **, *** Indicate statistical significance at the 10%, 5%, and 1% level respectively. Entries in the "Granger causality" column are the corresponding F test statistics for the null hypothesis of all lags of emissions per capita being insignificant. Entries in the "Cointegration" row are the corresponding F test statistics of the NARDL cointegration test.

Similar results are obtained when assessing the relationship between economic complexity and environmental degradation (Table 5). As noted by Nguyen and Kakinaka (2019), this finding suggests that the long-run nexus among renewable energy consumption, output, and carbon emissions is dependent on a country's development stage. And in the case of the EU, it is also linked to the level of compliance with energy policy targets (Śmiech and Papież, 2014).

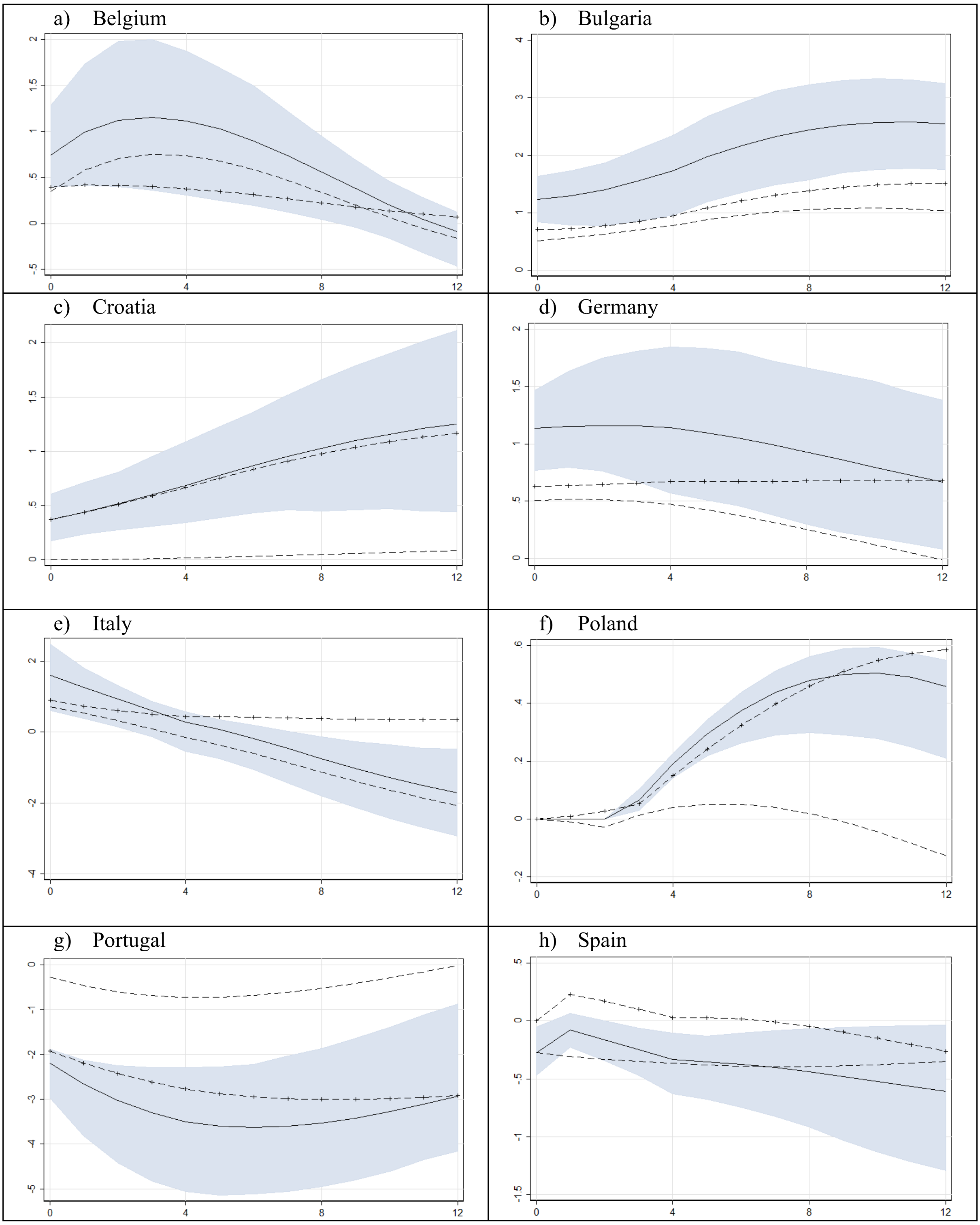
The corresponding dynamic multipliers are depicted in Figures 5 and 6, where the dynamic adjustment of environmental pollution to positive and negative income or economic complexity shocks is examined in Figure 4 and Figure 5.

Figure 4. NARDL dynamic multipliers – Emissions and economic growth including controls



Notes. Dashed lines represent the impact of negative changes in emissions. Lines marked with plus signs capture the impact of positive changes in emissions. Full lines are differences between the two (asymmetry). Shaded areas correspond to 95% confidence intervals.

Figure 5. NARDL dynamic multipliers – Emissions and development including controls



Notes. Dashed lines represent the impact of negative changes in emissions. Lines marked with plus signs capture the impact of positive changes in emissions. Full lines are differences between the two (asymmetry). Shaded areas correspond to 95% confidence intervals.

We graph the dynamic multipliers only in case there is significant asymmetry and the corresponding 95% asymmetric confidence interval does not comprise zero. As it can be observed, more asymmetric relationships are found for the second specification of the EKC (Figure 5), where economic complexity is used as a proxy for development. For example, the last panel in Figure 5 reveals that Spanish pollution reacts positively to increases in economic complexity, indicating that increases in economic development are associated with increased GHG emissions caused, among other reasons, by the added pressure on the extraction of natural resources (Andriamahery and Qamruzzaman, 2021). On the contrary, environmental degradation diminishes when income falls. For a vast majority of countries in Figures 4 and 5, negative economic changes have a considerably greater impact on GHG emissions than positive shocks, so the 95% confidence interval of asymmetry is mostly below the abscissa.

The intensity of the asymmetries found in Figures 4 and 5 may be directly conditioned by the efficiency of supranational initiatives such as the European Green Deal and the European Climate Law, aimed at transforming the EU into a net-zero emitter of greenhouse gases by 2050. Namely, the more these strategies become efficient in securing a climate-neutral paradigm of economic growth, the closer will positive economic multipliers get to the abscissa or even fall below it into the negative domain. In other words, it is the potential success of such policy initiatives that drives the observed asymmetries. Finally, some of the found asymmetry in the EKC could be attributed to the increasing deployment of RES in Europe (Al-Mulali et al., 2016; Carty and Claveria, 2024; Ng et al., 2020; Qalati et al., 2023).

Another finding worth of further elaboration is that economic complexity determines GHG emissions both in the long and the short run (Table 5). This result is in line with the evidence obtained by Marinas et al. (2018), who validated the hypothesis of bi-directional causality between renewable energy consumption and economic growth in the long run. Utilizing and ARDL model, Shahabadi and Heidarian (2024) recently found evidence of a *U*-shaped relationship between human development and long-term environmental quality. Given that complexity is recognised as a potential driver of environmental pollution only recently (e.g., Alola et al., 2023; Balsalobre-Lorente et al., 2022; Yilanci and Pata, 2020), this finding is a vital contribution of this study. When interpreting this result, it should be born in mind that economic complexity is driven by different socio-economic factors such as education (Gomez-Lievano and Patterson-Lomba, 2021) and demographic factors (Nguyen et al., 2020), that until recently had not been taken into consideration, but that have recently been linked to environmental degradation—either through the role of a growing environmental awareness promoted from the educational field (Yin et al., 2021)—, or the growing impact that pollution is having on health and life expectancy (Li et al., 2023)—. In this regard, as suggested by Panayotou (1997), further research is needed to fully grasp the role of socio-economic factors in the nexus between development and environmental degradation.

5. Concluding remarks

Leveraging panel data spanning 20 European countries from 2007 to 2021, this study examines the dynamics among the economy and the environment, with a particular emphasis on validating the EKC hypothesis. To do so, we link per capita greenhouse gas emissions with income and development, proxied by an index of economic complexity, additionally incorporating a wide range of socio-political and energy factors. The analysis combines two time series approaches with the aim of delving deeper into the relationship between environmental degradation and development. On the one hand, we used fixed effects panel models to test the EKC hypothesis. Overall, the obtained results suggest the existence of a *N*-shaped nexus between emissions and income per capita. We iteratively incorporate each control variable independently, finding that energy imports and density, and renewable energy consumption have a significant impact on emissions per capita, suggesting that increases in all four variables have a positive effect on environmental degradation. When replicating the exercise for economic complexity, the signs of the coefficients also showed the existence of an *N*-shaped relationship, although not always statistically significant. However, the estimated coefficients for the variables that capture the deployment of wind and solar energy show that increases in their relative consumption are associated with a reduction in emissions.

On the other hand, we evaluated stability of the link between environmental degradation and development, and the potential existence of an asymmetric adjustment at a country level. In most countries we found significant asymmetries in the adjustment of emissions to positive and negative changes in income, but not so much in economic complexity. In spite of the differences among countries, for most economies, negative shocks in income have a considerably greater impact on environmental degradation than positive ones. The estimations also show the existence of cointegration between emissions and income and economic complexity. These findings have important implications in terms of the design of energy policies, highlighting the need of implementing sector-specific measures.

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