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INVESTIGATING THE RELATIONSHIPS BETWEEN ECONOMIC GROWTH AND ENVIRONMENTAL DEGRADATION: EVIDENCE FROM EU15 COUNTRIES

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Abstract. The Environmental Kuznets Curve (EKC) hypothesis has become a centre of interest for empirical research, as it serves to identify the relationships between economic growth and environmental degradation that will lead to a sustainable development path. The aim of the paper is to investigate these relationships for each of the EU15 countries, which are responsible for the largest amount of carbon dioxide emissions in Europe. Based on the results of the analysis of ARDL bounds cointegration approach, for the 1960–2019 period, it was found that there is a great diversity between the countries in the EU15 regarding the existence and shape of EKC, from the identification of N shape, Inverted U-shape or monotonic relationships to the absence of statistically significant relationships. Thus, there are countries that have managed to implement environmental protection measures early and now ensure GDP growth while significantly reducing CO2 emissions. The similarities and differences identified among EU15 countries can serve as a guide for EU policymakers in developing recommendations adapted to specific situations in order to facilitate economic growth taking into consideration environmental protection.

Keywords: CO2 emissions, economic growth, environmental Kuznets curve, ARDL bounds cointegration approach, error correction models, EU15 countries.

JEL Classification: C32, C52, O44, Q53.

Introduction

Starting with the early 1970s, when the "Limits of Growth" Report brought to light that levels of resources and materials used and the resulted pollution will grow exponentially and then collapse in the next century (Tahvonen, 2000), the environmental quality has been seen as a prerequisite for economic growth. Over time, various international conferences

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concentrated specifically on putting the environmental degradation on the global agenda of the key stakeholders. Therefore, the concept of "environmental degradation" appeared to refer to the deterioration of environmental quality and pollution of the ecosystems. This study views environmental degradation from the idea of air pollution through greenhouse gas (GHG) emissions.

The Kyoto Protocol (United Nations, 1997) is the main international agreement stating that the industrialized countries should reduce their GHG emissions. In particular, the Europe 2020 and 2030 strategies set for the EU states a reduction target of 20% and 40% compared to the levels recorded in 1990. Thus, the success of the EU efforts in reducing the carbon dioxide (CO2) emissions, which amounts 76% of GHG (Oliver & Peters, 2020) in the region, is mainly dependent on the commitment of these countries to the compliance with the imposed regulations.

However, there may appear various challenges if the emissions are mostly generated from energy production, which is the engine of economic growth. In this context, curbing CO2 emissions would determine the reduction of economic growth in the end, which states are very reticent to achieve (Shahbaz et al., 2013). Thus, each country has to face the challenge of finding ways of reaching both high levels of economic growth, and low levels of CO2 emissions.

In Europe, special attention is being paid to reaching these goals by the EU15 countries. According to the author's own calculations, using data available on Global Carbon Project website, the EU15 countries emit approximately 85% of the CO2 emissions in the EU between 1960 and 2019. In addition, significant disparities among the EU15 countries are expected to appear in maintaining the equilibrium between the rates of economic growth and the ones of CO2 emissions reduction.

According to data for 2019, the EU15 countries with comparable levels of economic growth rates in relation with the levels reached in 1990 varied significantly in terms of CO2 emissions reduction rates. Thus, countries such as Portugal, Austria, and Spain had managed until 2019 to reduce CO2 emissions to a level below 20% of the level reached in 1990, while others (e.g., Denmark and United Kingdom) had already met the target set for 2030 (see Figure 1). Along with the last two countries with CO2 emissions reduction rate of over 40%, Luxembourg stands out by its very high rate of economic growth. In contrast, Italy and Greece had low rates of economic growth, accompanied by satisfactory rates of more than 20% reduction in CO2 emissions, similar to the levels in such countries as France and Belgium.

To identify the specific measures to be taken in each country for reaching the objectives set by the EU strategies, we need to know how the dynamics of CO2 emissions follow the dynamics of economic growth, seen as the main responsible factor for the degradation of environment. In this context, the purpose of the study is to analyse the behaviour of CO2 emissions in relation to economic growth for each of the EU15 countries. The research will be conducted using the Environmental Kuznets curve (EKC) framework. Following the model of the Kuznets curve (Kuznets, 1955) which focuses on the income-inequality relationship, the authors Grossman and Krueger (1991) discovered that between the income level and the environmental degradation exists a relationship having the same form of inverted U. They

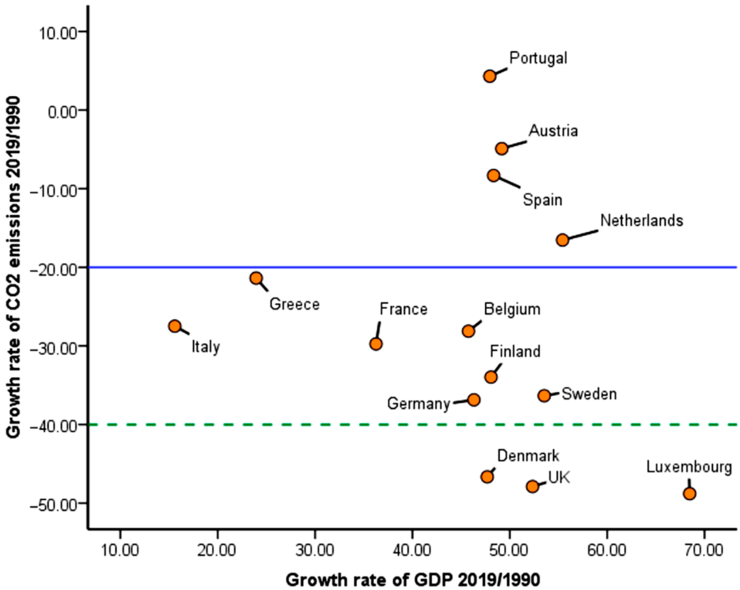


Figure 1. Growth rates of CO2 emissions per capita and GDP per capita in 2019 reported to 1990 levels in the EU15 countries

suggested that the increase of income level determines the environmental degradation until a turning point, when continuous income increase does not lead anymore to environmental deterioration. However, although the inverted U is the desired form of EKC, the actual one which fits a country depends on its particularities of economic development in relation to environmental issue. In this respect, the authors identified, among the possible forms of EKC (linear, quadratic, and cubic), the one specific to each of the countries analysed.

To carry out the study, the following three objectives were established: i) to identify the nature of the relationship between the variables in each of the EU15 countries; ii) to develop an econometric model for the relationship, including a significant shape of EKC for each of the EU15 countries; iii) to make a comparative analysis of the shape of EKC among the EU15 countries.

The results emphasize that the GDP-CO2 emissions relationship in the countries from EU15 takes very different shapes. For example, the traditional EKC assumption of the inverted U-shape relationship was validated for Finland, Germany and Ireland, indicating that CO2 emissions reach a maximum level, and then begin to decrease. The relationship between the analysed variables is monotonically increasing for Austria, Finland and Greece, while monotonically decreasing for Luxembourg. In Sweden, the relationship is N-shaped, with two extreme points of CO2 emissions. For such countries as Belgium, Italy, the Netherlands and Spain, long-term relationships show the following statistically significant shapes: monotonic increasing, inverted N and inverted U, respectively, while for Denmark, France, Portugal and the United Kingdom, there is no statistically significant relationship between economic growth and CO2 emissions. This important diversity (from a lack of a statistically significant relationship to the identification of multiple thresholds) should guide the development and implementation of environmental policies in the EU15 countries, especially in the present context regarding the environmental EU goals which hardly seem to incorporate the specific characteristics of the countries (Lazăr et al., 2019).

The economic growth – CO2 emissions relationship, known as EKC, has been intensely studied in the literature in the field. The present study will contribute to the knowledge in this area by addressing the aggregation bias of the data and using time series in order to examine the existence and shape of EKC for each of the EU15 countries. The few empirical studies conducted on the EU15 countries have applied panel data analysis methods, considered other indicators for measuring the environmental degradation or covered shorter periods (e.g., Madaleno & Mountinho, 2021; Altıntaş & Kassouri, 2020; Destek et al., 2018; Dogan & Seker, 2016).

The paper is structured in four sections. After the introductory section, the second section contains the main directions outlined in the literature on the relationship between economic growth and environmental degradation. The empirical data and the methodology are described in the third section, while the representative results are shown in section four. The paper ends with conclusions and discuses policy implications.

1. Literature review

In recent years, climate change, generally assumed to be caused by human activity, has been a widely discussed issue in the context of environmental degradation. In this respect, environmental degradation through great amounts of CO2 emissions and other greenhouse gases has consequences affecting both developing and developed nations across the world, irrespective of who is held accountable. Researchers worldwide examine the economic growth-environmental degradation relationship to find ways in which both high levels of economic growth and low levels of CO2 emissions could be reached. This relationship is mostly analysed by checking if the EKC hypothesis is valid.

The concept of EKC hypothesis has become interesting for empirical research due to its theory supporting sustainability. It was developed by the authors Grossman and Krueger (1991) and proposed a relationship between economic growth (usually quantified using income per capita) and environmental degradation (usually measured through emissions per capita) which can be represented as an inverted U. This means that, in the early stages of economic growth, the degradation of environment increases until a point in the evolution of income per capita is reached, which varies from a country to another, when the trend is reversing, high income levels determine environmental improvement. The authors also show that the curve with the shape of inverted U is a result from the action of three effects: the scale effect, the composition effect and the technological effect. The first of the effects (i.e., scale effect) appears in the initial stage of development of a country when the acceleration of economic growth produces an inevitable increase in environmental degradation due to economy's transition from an agricultural to an industrial profile. After a specific level of the income, the pressure of an increasing economic growth on the degradation of the environmental tends to slow down, the composition effect (manifested when economy makes a transition from a resource-intensive to a service-and-knowledge-based economy) and the technological effect (manifested through technological progress and adequate R&D investments) being present. In the end, the last two effects have a positive influence on environment, compensating the negative impact of the scale effect (Dinda, 2004).

The EKCs can be used as analytical tools for addressing the questions of effectiveness of the measures taken in each country or region to reduce the environmental degradation through greenhouse gas emissions, especially CO2. Moreover, they can explain the likely trends in carbon emissions of a country and region, shedding light on their position in international negotiations focused on environmental issues. Such insights can reveal whether the international regulations could be accomplished, and how each country or region is likely to achieve any other proposals regarding reduction of emissions (Lipford & Yandle, 2010).

Most of the researches referring to the existence of the EKC adopted the cross-sectional or panel data analysis for a group of countries (Dogan & Seker, 2016 – in OECD; Destek et al., 2018, and Ketenci, 2021 – in EU15; Lazăr et al., 2019 – in CEE). The findings of these studies indicate different shapes of the income per capita-CO2 emissions per capita relationship. In the case of Dogan and Seker (2016), the inverted U-shape was verified, while in the Destek et al. (2018), Lazăr et al. (2019) and Ketenci (2021) studies, other two shapes were present, U and N, respectively. However, the studies conducted for a group of countries reveal only general inferences regarding EKC, which may disregard the distinctive complexity and historical experience of the individual economic environments (Sugiawan & Managi, 2016). For instance, a not significant income effect of one country could be offset by the significant income effects of others, thus concluding in the existence of a shape of EKC for a specific pollutant (Baek, 2015).

In order to avoid issues related to the aggregation bias, recent studies have concentrated on the use of time series data at country level (Acaravci & Ozturk, 2010 – in 19 European countries; Iwata et al., 2010 – in France; Balaguer & Catavella, 2016 – in Spain; Lazăr et al., 2019 – in CEE countries; Kotroni et al., 2020 – Greece; Hatmanu et al., 2021 – in Bulgaria and Romania). The results of these studies emphasize diverse shapes of EKC depending on each country's specificity. In the paper conducted by Lazăr et al. (2019), some of the countries validate the classical shape of U inverted EKC (Czech Republic and Hungary), while others reveal that it has a different shape: U shape (Bulgaria and Latvia), N shape (Croatia and Estonia), inverted-N shape (Poland and Slovakia). In the studies of Iwata et al. (2010); Balaguer and Catavella (2016) and Hatmanu et al. (2021), the analysed countries fulfil the requirements of the EKC hypothesis, while in Kotroni et al. (2020), Greece revealed a U shape relationship. Finally, Acaravci and Ozturk (2010) indicate that for the 19 considered European countries, only Denmark and Ireland reported an income per capita-CO2 emissions significant relationship in terms of EKC.

The existing studies report various findings, starting from no statistically significant relationship between economic growth and environmental degradation to the identification of multiple thresholds. Thus, there is no consensus on the economic growth-environmental degradation relationship within the EKC framework for a specific country or region. The results depend mostly on the analysed period, the indicators used as proxies for the two variables and the methodology applied.

Following the arguments mentioned above and available in the existing literature, in the present study the following research hypotheses will be verified:

H1: Economic growth is a significant determinant of CO2 emissions in each of the EU15 countries.

H2: Developed countries do not share a unique functional form of the economic growth-CO2 emissions relationship.

2. Data and methodology

2.1. Data

In the present paper, CO2 emissions are quantified as metric tons of carbon per capita, and economic growth as GDP per capita in constant prices (2017 dollars). The data regarding the considered indicators were collected from the websites of the International Monetary Fund (IMF) and the Global Carbon Project. Data availability for the following 13 of the EU15 countries covered the 1960–2019 period: Austria, Belgium, Denmark, Finland, France, Greece, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and United Kingdom. For Germany and Ireland, the period 1970–2019 was considered. The transformation of the analyzed variables with a natural logarithm was applied, thus obtaining advantages regarding the attenuation of the hypotheses of homoscedasticity and normality of the residuals and facilitating the interpretation of the difference of first order in terms of growth rate.

2.2. Methodology

The purpose of this study consists in analysing the CO2 emissions – economic growth relationship, considering the basic shapes of EKC, with the following equations:

Linear: $$lnCO2_t = \alpha_0 + \beta_1 lnGDP_t + \varepsilon_t; \quad (1)$$

Quadratic: $$lnCO2_t = \alpha_0 + \beta_1 lnGDP_t + \beta_2 lnGDP_t^2 + \varepsilon_t; \quad (2)$$

Cubic: $$lnCO2_t = \alpha_0 + \beta_1 lnGDP_t + \beta_2 lnGDP_t^2 + \beta_3 lnGDP_t^3 + \varepsilon_t, \quad (3)$$

where *ln* is the natural log, ε_t – the error term which validates the classical hypotheses of a regression model (mean equal to zero, normal distributed, homoscedastic and not autocorrelated) and t represents a time index.

The regression coefficients β_1, β_2 and β_3 are important in the determination of the EKC shape, thus: for example, in the case of the quadratic model, if $\beta_1 > 0$ and $\beta_2 < 0$, then there exists an inverted U-shaped relationship; otherwise, if $\beta_1 < 0$ and $\beta_2 > 0$, then there exists an U-shaped relationship; in the case of the cubic model, if $\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 > 0$, then there exists a N-shaped relationship, but, if $\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 < 0$, then there exists an inverted N-shaped relationship.

For identifying the type of CO2 emissions-GDP relationships, ARDL bounds testing approach of cointegration was applied. Next, taking into consideration the results, the relationships were modelled. In the end, the best econometric model for each country was identified.

Below are presented the stages of the empirical research, considering the case of quadratic specification of EKC (Eq. (2)). The ARDL approach requires to perform unit root tests on analysed variables, which must have the integration order lower than 2 (Jóźwik et al., 2021). In order to verify the robustness of the findings, three specific tests were applied: the Augmented Dicky-Fuller (ADF) test, the Phillips-Perron (PP) test, and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test (Arltová & Fedorová, 2016; Gagea, 2009). In order to avoid spurious results, the classical tests were completed with those of Zivot and Andrews, which includes a break-point at an unknown time (Zivot & Andrews, 1992).

Identification of the existence of the long-run relationship between the considered variables is based on the analysis of the ARDL model which, for the case of the parabolic EKC shape, may be expressed as follows:

$$\Delta lnCO2_t = \alpha_0 + \sum_{i=1}^{a} \alpha_{1i} \Delta lnCO2_{t-i} + \sum_{j=0}^{b} \beta_{1j} \Delta lnGDP_{t-j} + \sum_{k=0}^{c} \beta_{2k} \Delta lnGDP_{t-k}^2 + \theta_1 lnCO2_{t-1} + \theta_2 lnGDP_{t-1} + \theta_3 lnGDP_{t-1}^2 + u_t, \quad (4)$$

where Δ represents the first difference operator; u_t represents the error term; α_1, β_1, β_2 are the short-run coefficients; $\theta_k, k = 1,2,3$, the long-run coefficients; and a, b, c are the optimal number of lags for each of the corresponding variables.

The null hypothesis of the bounds test assumes the lack of a long-run relationship among the variables analysed. In order to verify this hypothesis, Fisher statistics is applied (Adebayo et al., 2021; Hatmanu et al., 2020).

If the results of the Bounds cointegration test show that there exist long-run relationships among the variables considered, this being the most frequent case occurred in the present study, then the error correction model (ECM) will be applied, its equation being the following one:

$$\Delta lnCO2_t = \alpha_0^{'} + \sum_{i=1}^{a} \alpha_{1i}^{'} \Delta lnCO2_{t-i} + \sum_{j=0}^{b} \beta_{1j}^{'} \Delta lnGDP_{t-j} + \sum_{k=0}^{c} \beta_{2k}^{'} \Delta lnGDP_{t-k}^2 + \delta ECT_{t-1} + u_t^{'}, \quad (5)$$

where δ represent the coefficient of error correction term (ECT). This coefficient must be statistically significant and with the value negative and less than 1. It indicates the speed at which, the dependent variable is back to balance following the shock produced within the system. It represents the residual component in the Eq. (2), being determined as difference between the CO2 emissions observed variable and the deterministic component from the long-run model, as follows:

$$ECT_{t-1} = lnCO2_{t-1} - \left(\alpha_0 + \beta_1 lnGDP_{t-1} + \beta_2 lnGDP_{t-1}^2\right). \quad (6)$$

For validating the ECM, the hypotheses formulated on the residuals and the stability of the coefficients should be verified using specific tests.

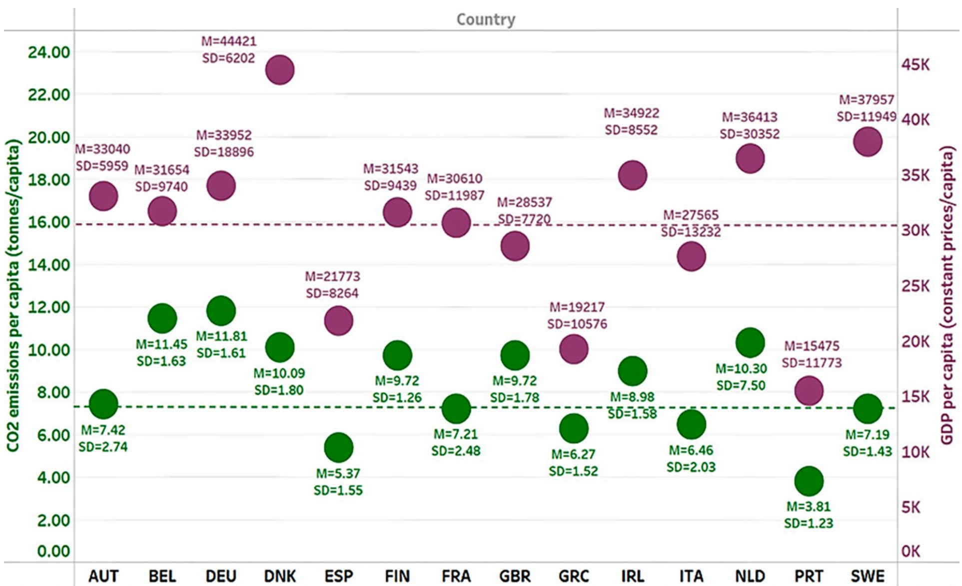
3. Results

This section starts with a descriptive analysis of the CO2 emissions and GDP. Next, the finding regarding the ARDL-Bounds cointegration methodology are presented, alongside with the ones referring to the econometric modelling of the CO2 emissions in relation to GDP considering the three functional forms (i.e., linear, quadratic and cubic) used in the literature focused on the EKC framework.

The descriptive statistics included in Figure 2 show the position of each country in relation with the average levels of CO2 emissions and GDP at the EU15 aggregate level. For each of the series considered, we used the coefficient of variation at the EU15 level, determined as a ratio between the standard deviation and the mean, in order to analyse the degree of variability, as well as the representativeness of the mean. The findings revealed that both CO2 emissions and GDP had a representative mean, the coefficient of variation being less than the threshold of 30% (28.65% and 25.16%, respectively).

In addition, analysing the range of variation for the two variables, significant differences were observed. The lowest variations for CO2 emissions were identified in the case of France and Austria (4.98 and 5.24), while the higher ones characterized Denmark and Finland (8.69 and 19.56). Regarding the variable GDP, the countries which had the lowest range were Portugal and Greece (20158 and 23795). In contrast, Denmark and Ireland registered the highest distances between the minimum and maximum values (45282 and 66958).

There can be distinguished four categories of countries. The first category contains 6 countries (Belgium, Denmark, Finland, Germany, Ireland and Netherlands) that have both average values of GDP and CO2 emissions above the average of the EU15 level. These countries are characterized by a continuous process of economic growth and, given their level of development, even if most of them succeeded in achieving the Europe 2020 targets, their level



		AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	NLD	PRT	SWE
CO2	Min	4.35	8.62	8.40	5.55	1.60	3.34	4.97	5.47	1.13	6.66	2.19	6.41	0.92	4.18
	Max	9.59	14.26	14.25	14.24	8.39	13.90	9.95	11.84	10.30	12.39	8.62	13.29	6.69	11.45
	Skew	-0.71	-0.25	-0.22	-0.65	-0.50	-0.96	0.44	-1.10	-0.36	0.57	-0.90	-0.74	-0.05	0.50
	Kurt	-0.11	2.20	1.83	2.59	2.67	3.41	2.68	3.50	1.98	2.02	3.38	3.51	1.62	2.36
GDP	Min	13031	13022	19681	20538	7376	12185	12744	13934	6260	12745	10879	16220	4501	18062
	Max	50553	47618	47447	65820	33393	49441	44317	43712	30055	79703	38272	55489	24659	58013
	Skew	-0.11	-0.13	-0.06	-0.12	-0.11	0.02	-0.31	0.09	-0.39	0.61	-0.49	0.01	-0.23	0.19
	Kurt	1.72	1.76	1.82	1.72	1.75	1.68	1.87	1.57	2.71	2.29	1.85	1.72	1.70	1.84

CO2 Emissions per capita — Average of CO2 Emissions per capita in EU15 (M=8.27, SD=2.37)
GDP per capita — Average of GDP per capita in EU15 (M=30505, SD=7678)

Figure 2. Descriptive statistics of CO2 emissions per capita and GDP per capita in the EU15 countries

of CO2 emissions still remains high and further investments are needed to reduce emissions. In this sense, such countries as Denmark and Ireland mainly invested in solutions to increase the energy efficiency, used renewable energy sources in a significant proportion of energy use and implemented carbon-abatement programs (World Economic Forum, 2014).

The second category of countries (Austria, France, Sweden) are the countries with average values of GDP above the EU15 level and with average values of CO2 emissions below the level of the group. Sweden, for instance, managed to identify an appropriate equilibrium in the environmental quality-real economy relationship, and more than 50% of its energy consumption is dependent on the renewable sources. In the third category is included only the United Kingdom, which has average CO2 emissions above the average of the EU15 level, and the average GDP below the EU15 level. The United Kingdom is one of the countries, where CO2 emissions reduction determined a decline in economic activity, and which had to adjust its economic structure in such a way as to favour the sectors with less production of such emissions. Finally, in the last category, Greece, Italy, Portugal and Spain are situated below the average values of CO2 emissions and GDP in the EU15. These countries, due to their level of development, were strongly affected by the Global Financial Crisis of 2008–2009 that had a negative influence on all sectors of economy. Thus, the local policymakers had to face both the challenge of stabilizing the economic growth and reaching the Europe 2020 targets (Obradović & Lojanica, 2019).

3.1. The ARDL Bounds cointegration test

The underlying assumption of the ARDL Bounds test is that the order of integration for each of the variables is lower than 2. Therefore, prior to implementing the ARDL models, classical ADF, PP and KPSS unit root tests and Zivot-Andrews unit root with structural break test were applied to ensure that all the variables are not I(2) series. According to the first three tests, variables satisfied this condition, the orders of integration identified being I(0) or I(1). Figure 3 summarises the results of obtained. However, in some cases, the results of these tests were not consistent, indicating different orders of integration, which may be induced by the existence of break points in the evolution of the variable. In those cases, both the graphic representation and the results of Zivot-Andrew's test emphasized the structural breaks which were used in the next stage, the specification of the regression models (e.g., 1991 and 1996 for Denmark; 1979 for Netherlands; 2008 for Spain). Given the final results obtained in the unit root testing, it is suitable to perform the ARDL bounds cointegration approach.

As mentioned above, there were estimated 3 types of models for each of the EU15 countries: linear, quadratic and cubic. The optimal lags lengths among variables in the VAR models was selected taking into consideration the values of the following criteria: FPE, AIC, SC and HQ. The findings regarding the ARDL Bounds testing approach to cointegration are included in Table 1. Taking into consideration that the sample size of the study is relatively small (i.e., $T = 50$ for Germany and Ireland and $T = 60$ for the rest of the countries), critical bounds tabulated by Narayan (2005) were used.

The findings from Table 1 show that in the case of all countries, except Portugal, at least one type of model was found to emphasize that GDP-CO2 emissions relationship exists in the long-run, partially validating the H1 hypothesis. The calculated value of F-statistic were higher than the one of the upper critical bound at various levels of significance. For instance, in the case of Austria, only the linear relationship between variables is significant in the long-run because the calculated value of F-statistic (4.771) is higher than upper critical bound for 5% significance level (4.160), while for quadratic and cubic relationships, the values corresponding to the F-statistics (3.096 and 2.437) are less than the lower critical bound for all of the significance levels considered (e.g., for 1%, 4.558 and 4.118).

In consequence, the study on the relationship between the considered variables will be continued with the estimation of the error correction models (ECM).

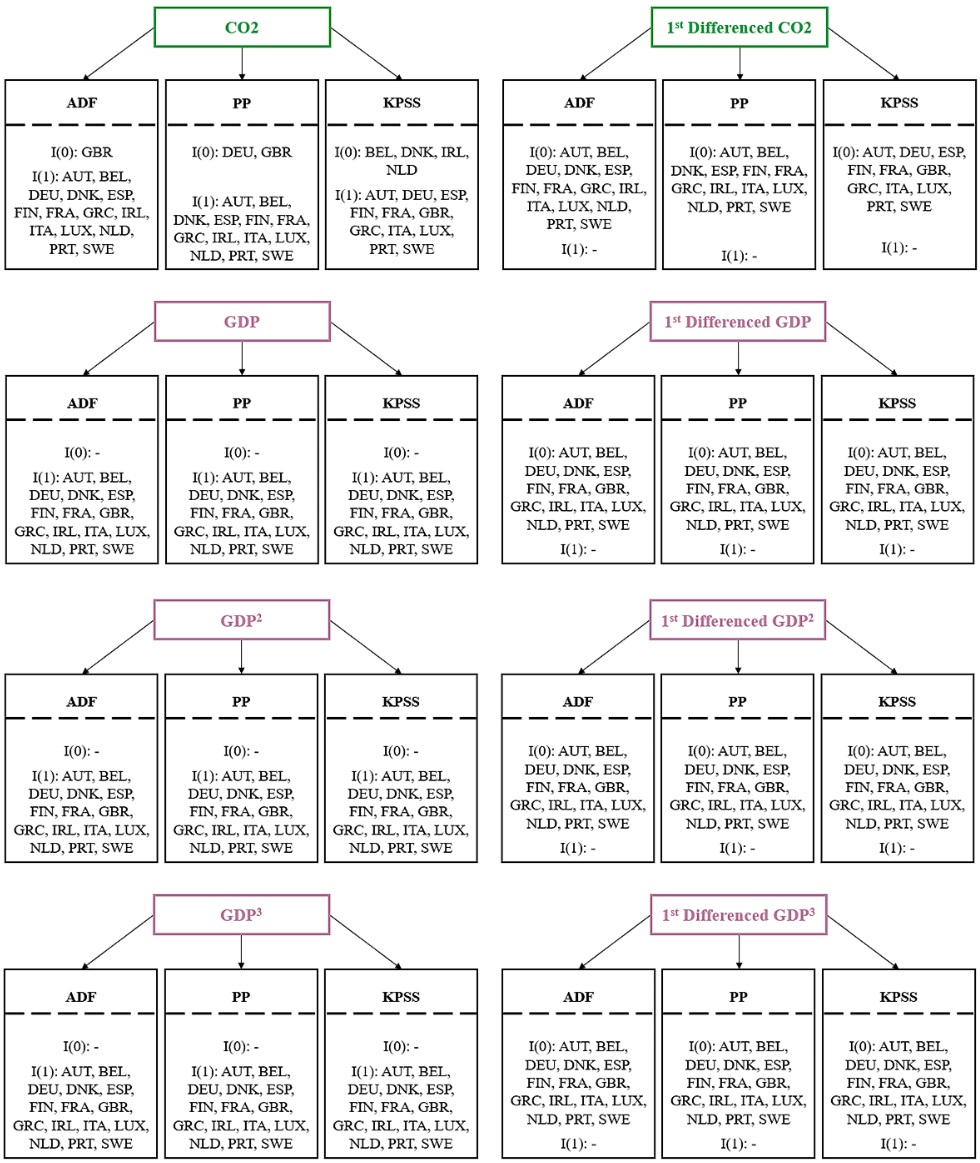


Figure 3. Unit root tests – decision

Table 1. Estimated ARDL models and bounds F-test for cointegration

Country	Linear model		Quadratic model		Cubic model	
	ARDL	F-statistic	ARDL	F-statistic	ARDL	F-statistic
AUT[1]	(1,3)	F = 4.771**	(1,1,0)	F = 3.096	(1,1,0,0)	F = 2.437
BEL[1]	(1,1)	F = 5.980***	(1,0,1)	F = 4.847***	(1,0,1,0)	F = 4.066***
DEU[2]	(1,1)	F = 8.566***	(2,2,2)	F = 5.123***	(1,1,1,0)	F = 10.482***
DNK[1]	(1,1)	F = 6.689***	(1,0,1)	F = 4.448***	(1,0,0,1)	F = 2.896
ESP[1]	(1,1)	F = 1.590	(1,1,1)	F = 3.750*	(1,1,1,0)	F = 4.055**
FIN[1]	(1,2)	F = 6.224***	(1,0,1)	F = 3.629*	(1,0,0,1)	F = 2.963
FRA[1]	(1,1)	F = 8.646***	(1,1,1)	F = 7.469***	(1,1,1,1)	F = 6.040***
GBR[1]	(1,1)	F = 11.257***	(1,0,1)	F = 8.465***	(1,0,0,1)	F = 7.222***
GRC[1]	(1,1)	F = 5.456**	(1,2,2)	F = 1.871	(1,2,2,0)	F = 1.476
IRL[2]	(2,2)	F = 6.718***	(2,2,2)	F = 7.356***	(1,1,1,1)	F = 2.626
ITA[1]	(1,1)	F = 10.827***	(1,0,1)	F = 13.238***	(1,0,0,1)	F = 11.467***
LUX[1]	(2,1)	F = 4.908**	(1,1,1)	F = 5.029**	(1,0,1,1)	F = 4.079**
NLD[1]	(1,1)	F = 3.473	(1,1,0)	F = 4.575***	(2,1,1,1)	F = 4.972***
PRT[1]	(1,1)	F = 1.177	(1,1,1)	F = 2.705	(1,1,1,0)	F = 3.079
SWE[1]	(1,1)	F = 4.385**	(1,0,1)	F = 3.842*	(1,0,0,1)	F = 4.476***

Note: The analysed period is: [1] 1960–2019, [2] 1970–2019. F-statistic is the ARDL cointegration test. The critical values for the lower I(0) and upper I(1) bounds are taken from Narayan (2005, Appendix: Case II). ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively.

3.2. Modelling the relationships between the variables

Further, for the statistically validated models, the estimation results and diagnostic tests are presented. Table 2 comprises two parts: the first part shows the results of estimation of the long-run relationships between CO2 emissions and GDP; the second part displays the results for the coefficient of determination and the tests applied in order to study the residual diagnostics (Jarque-Berra, LM, Breusch-Pagan-Godfrey and ARCH) and stability of the coefficients (RESET).

In studying the linear relationship between CO2 emissions and GDP in the long-run, we identified 7 countries, for which the models were statistically validated. In case of Austria, Greece and Italy, we identified a monotonically increasing shape of EKC, CO2 emissions increasing as GDP increases, implying thus, in the long-run, the environmental quality will deteriorate. In opposition, in Belgium, Finland, Luxembourg and Sweden, the estimated influence of the GDP on CO2 emissions was negative, revealing a monotonically decreasing shape of EKC, which suggests that environment is positively impacted by the evolution of economic growth. Among these findings, the EKC component was significant only for Austria and Greece at a significance level of 1%, and for Luxembourg and Sweden, at a significance level of 5%.

Further, among the long-run quadratic models that were statistically validated, Finland, Germany, Ireland and Sweden confirmed the classical EKC hypothesis of inverted U-shape, while Spain presented a relationship between variables shaped as an U. For the first 4 countries, the CO2 emissions increase as GDP increases up to a point, and, after that, they tend to reduce as it continues to increase. The results emphasize that an equilibrium between the two variables was established, energy consumption in the key sectors of the economies being managed in a way in which low levels of emissions are generated. Regarding Spain, one of the countries which was highly affected by the large fluctuations occurred in the economy due to the Global Financial Crisis, the environment quality still represents an important problem to be dealt with. However, from these results, only the EKC components from the models for Germany, Finland and Ireland were significant at a significance level of 5%.

Finally, in the case of the long-run cubic models that were statistically validated, we identified for Netherlands an inverted N-shape of EKC, and an N-shape for Sweden. In both cases, the shapes of EKC are validated by the confirmation of the condition $\beta_2^2 - 3\beta_1\beta_3 > 0$ but the EKC component was significant only for Sweden.

Table 2 indicates ECT_{t-1} coefficients are significant and have values negative and lower than one, in absolute terms, providing proof in favour of the existence of a cointegration relationship among the variables established by the ARDL Bounds testing approach.

Table 2. Estimated long-run coefficients for the significant ARDL models

Regressor	Linear model						
	AUT	BEL	FIN	GRC	ITA	LUX	SWE
ln GDP	0.465*** [0.094]	−0.014 [0.240]	−0.407 [0.490]	1.104*** [0.344]	0.006 [0.386]	−0.436** [0.180]	−1.431** [0.582]
$(\ln GDP)^2$	–	–	–	–	–	–	–
$(\ln GDP)^3$	–	–	–	–	–	–	–
Constant	−2.974*** [1.018]	2.147 [2.588]	6.535 [5.109]	−8.816** [3.493]	1.578 [3.900]	7.757*** [2.039]	16.814*** [6.046]
ECT_{t-1}	−0.199** [0.089]	−0.082* [0.047]	−0.102* [0.057]	−0.111** [0.053]	−0.060** [0.027]	−0.127** [0.063]	−0.084* [0.045]
Diagnostics							
R^2_{adj}	0.904	0.906	0.915	0.993	0.990	0.951	0.960
F-stat	106.515 (0.000)	178.251 (0.000)	155.323 (0.000)	2068.874 (0.000)	1987.835 (0.000)	283.126 (0.000)	345.828 (0.000)
JB	0.190 (0.909)	0.152 (0.926)	0.004 (0.997)	5.669 (0.058)	1.449 (0.484)	1.138 (0.565)	0.642 (0.725)
LM	0.509 (0.677)	0.450 (0.504)	0.879 (0.421)	0.987 (0.325)	2.246 (0.139)	0.115 (0.891)	0.448 (0.641)
BPG	0.510 (0.766)	0.076 (0.972)	0.705 (0.591)	2.004 (0.106)	0.192 (0.901)	1.191 (0.325)	2.025 (0.104)
ARCH	1.973 (0.165)	0.084 (0.772)	0.386 (0.536)	0.138 (0.710)	0.684 (0.411)	0.500 (0.482)	0.605 (0.440)
RESET	0.625 (0.432)	1.403 (0.241)	0.468 (0.496)	0.305 (0.583)	5.488 (0.023)	0.134 (0.715)	0.200 (0.656)

End of Table 2

Regressor	Quadratic model					Cubic model	
	DEU	ESP	FIN	IRL	SWE	NLD	SWE
ln GDP	18.928*** [3.557]	–8.235 [21.563]	21.196** [8.514]	15.549** [6.335]	21.746 [13.255]	–712.963 [831.240]	1216.730*** [424.967]
(ln GDP)^2	–0.934*** [0.000]	0.398 [1.057]	–1.034** [0.414]	–0.755** [0.314]	–1.092* [0.632]	67.428 [78.701]	–115.668*** [40.770]
(ln GDP)^3	–	–	–	–	–	–2.123 [2.482]	3.660*** [1.303]
Constant	–93.359*** [18.554]	44.257 [109.991]	–106.200** [43.719]	–77.807** [31.921]	–105.978 [69.444]	2512.726 [2924.933]	–4258.647*** [1475.721]
ECT_{t-1}	–0.555*** [0.152]	–0.109* [0.059]	–0.213** [0.085]	–0.289*** [0.082]	–0.101* [0.056]	–0.227** [0.108]	–0.162** [0.072]
Diagnostics							
R_{adj}	0.969	0.987	0.926	0.956	0.961	0.880	0.964
F-stat	216.503 (0.000)	746.502 (0.000)	183.365 (0.000)	116.231 (0.000)	281.328 (0.000)	47.795 (0.000)	255.830 (0.000)
JB	0.623 (0.732)	0.816 (0.664)	0.032 (0.983)	3.905 (0.141)	1.098 (0.577)	2.308 (0.315)	1.147 (0.563)
LM	1.109 (0.340)	0.220 (0.803)	0.001 (0.985)	2.181 (0.127)	1.875 (0.164)	0.902 (0.412)	1.316 (0.277)
BPG	2.180 (0.066)	1.123 (0.362)	0.530 (0.713)	0.869 (0.560)	1.746 (0.140)	0.859 (0.544)	1.187 (0.328)
ARCH	0.004 (0.946)	0.059 (0.808)	0.745 (0.391)	1.155 (0.288)	0.362 (0.549)	0.044 (0.834)	0.150 (0.699)
RESET	0.034 (0.852)	0.387 (0.546)	1.545 (0.219)	0.911 (0.345)	0.228 (0.634)	0.225 (0.637)	2.188 (0.145)

Notes: ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively. Values in [] parentheses are standard errors. Values in () parentheses are p-values for the applied tests. JB, LM, BP, ARCH and RESET stand for Jarque-Bera Normality test, Breusch-Godfrey serial correlation LM test, Breusch-Pagan-Godfrey test of heteroscedasticity, ARCH test of heteroscedasticity and Ramsey Regression Equation Specification Error Test.

The value of the ECT coefficient is equal to the proportion by which the correction of long-run disequilibrium in the CO2 emissions is made in each period. For instance, the deviation from the long-run path of CO2 emissions is corrected each year by 55.5% in Germany, and 28.9%, in Ireland, and by 12.7% in Luxembourg and by 11.1% in Greece.

Regarding the short-run relationships, in Table 3 can be observed that the GDP was significantly related to CO2 emissions in some lags. For instance, in the short-run linear and quadratic models, some of the coefficients were significant up to two lags.

For validating the models presented above, the coefficient stability and the hypotheses formulated on the residuals (hypothesis of normality, hypothesis of lack of autocorrelation and the hypothesis of homoscedasticity) were tested. The results of the tests were presented in Table 2 and Figure 4 and indicate that all the models are valid.

Table 3. Estimated short-run coefficients for the significant ARDL models

Regressor	Linear model						
	AUT	BEL	FIN	GRC	ITA	LUX	SWE
Δln CO2(–1)	–0.116 [0.136]	0.079 [0.134]	0.098 [0.722]	–0.017 [0.132]	0.295** [0.126]	0.324** [0.139]	–0.084 [0.129]
Δln CO2(–2)	–	–	–	–	–	0.151 [0.130]	–
Δln GDP	1.349*** [0.385]	1.447*** [0.318]	1.222*** [0.450]	0.745*** [0.191]	1.481*** [0.177]	0.901*** [0.266]	0.886** [0.360]
Δln GDP(–1)	–0.374 [0.383]	0.033 [0.357]	–0.782 [0.498]	–0.066 [0.217]	–0.219 [0.258]	–0.123 [0.291]	–0.234 [0.367]
Δln GDP(–2)	1.147*** [0.377]	–	0.563 [0.431]	–	–	–	–
Δln GDP(–3)	–0.442 [0.393]	–	–	–	–	–	–
Δ(ln GDP)^2	–	–	–	–	–	–	–
Δ(ln GDP)^2(–1)	–	–	–	–	–	–	–
Δ(ln GDP)^2(–2)	–	–	–	–	–	–	–
Δ(ln GDP)^3	–	–	–	–	–	–	–
Δ(ln GDP)^3(–1)	–	–	–	–	–	–	–
Constant	–0.027** [0.013]	–0.034*** [0.011]	–0.009 [0.017]	0.029*** [0.010]	–0.014** [0.005]	–0.025* [0.063]	–0.013 [0.111]

Regressor	Quadratic model					Cubic model	
	DEU	ESP	FIN	IRL	SWE	NLD	SWE
Δln CO2(–1)	0.049 [0.159]	0.131 [0.141]	0.071 [0.133]	–0.166 [0.138]	–0.152 [0.125]	–0.071 [0.146]	–0.186 [0.120]
Δln CO2(–2)	–	–	–	0.088 [0.119]	–	0.254* [0.137]	–
Δln GDP	16.320** [6.461]	–14.982 [0.979]	22.359*** [7.747]	4.839 [3.042]	21.778*** [7.715]	–698.916* [345.853]	456.542* [275.254]
Δln GDP(–1)	–6.444 [7.957]	10.163 [8.467]	–	2.399 [2.983]	–	307.359 [327.332]	–
Δln GDP(–2)	–4.303 [6.038]	–	–	9.240*** 2.836]	–	–	–
Δln GDP(–3)	–	–	–	–	–	–	–
Δ(ln GDP)^2	–0.740** [0.309]	0.790 [0.495]	–1.034*** [0.374]	–0.219 [0.142]	–0.994*** [0.367]	67.927** [33.386]	–42.901 [26.437]
Δ(ln GDP)^2(–1)	0.307 [0.378]	–0.488 [0.434]	–0.023 [0.019]	–0.093 [0.138]	–0.015 [0.016]	–29.479 [31.754]	–
Δ(ln GDP)^2(–2)	0.236 [0.289]	–	–	–0.420*** [0.132]	–	–	–
Δ(ln GDP)^3	–	–	–	–	–	–2.193** [1.072]	1.344 [0.845]
Δ(ln GDP)^3(–1)	–	–	–	–	–	0.940 [1.025]	–0.001 [0.001]
Constant	–0.034*** [0.006]	–0.008 [0.009]	–0.006 [0.014]	–0.060*** [0.011]	–0.016 [0.010]	–0.022 [0.010]	–0.017* [0.010]

Notes: ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively. Values in [] parentheses are standard errors.

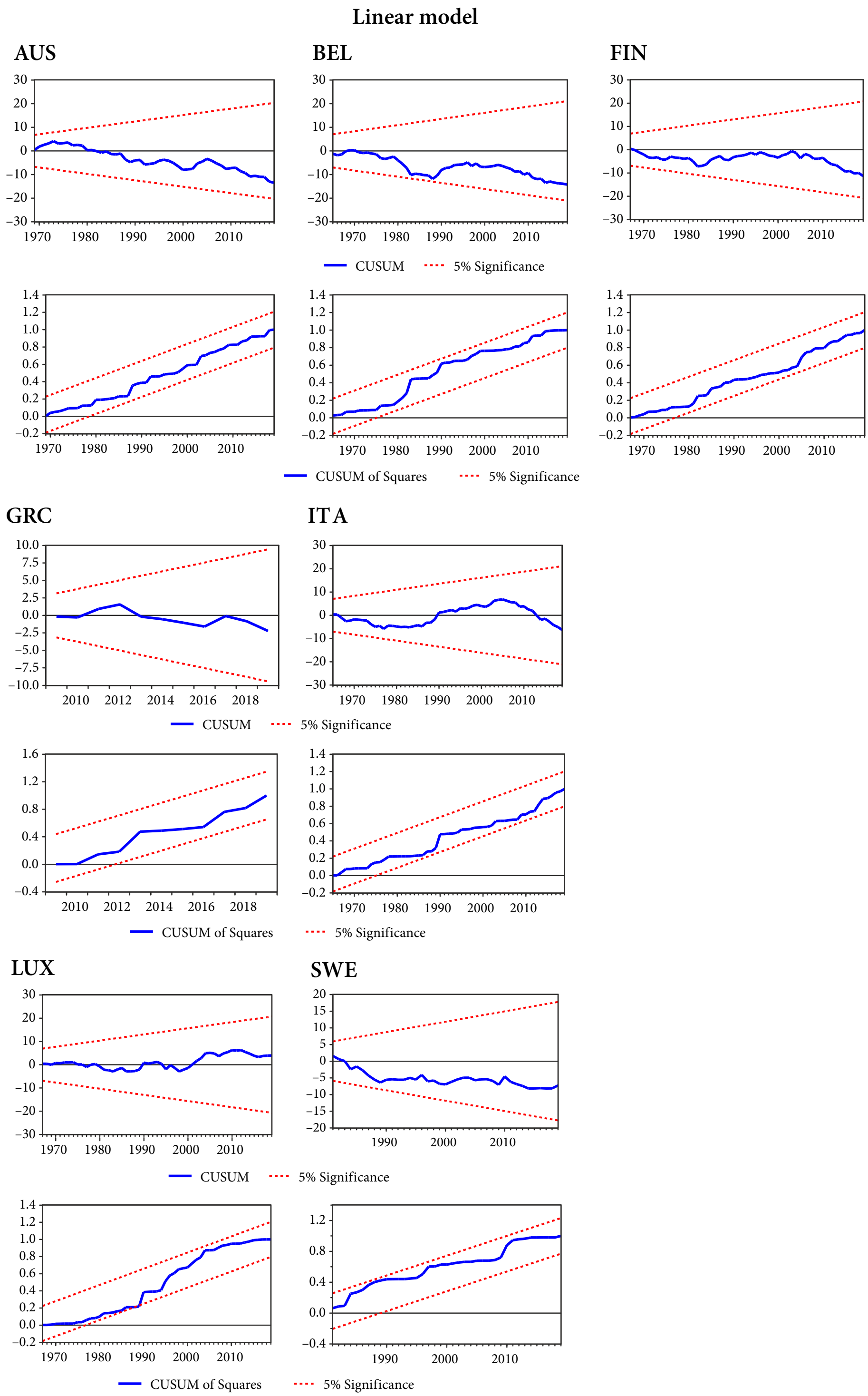


Figure 4. *To be continued*

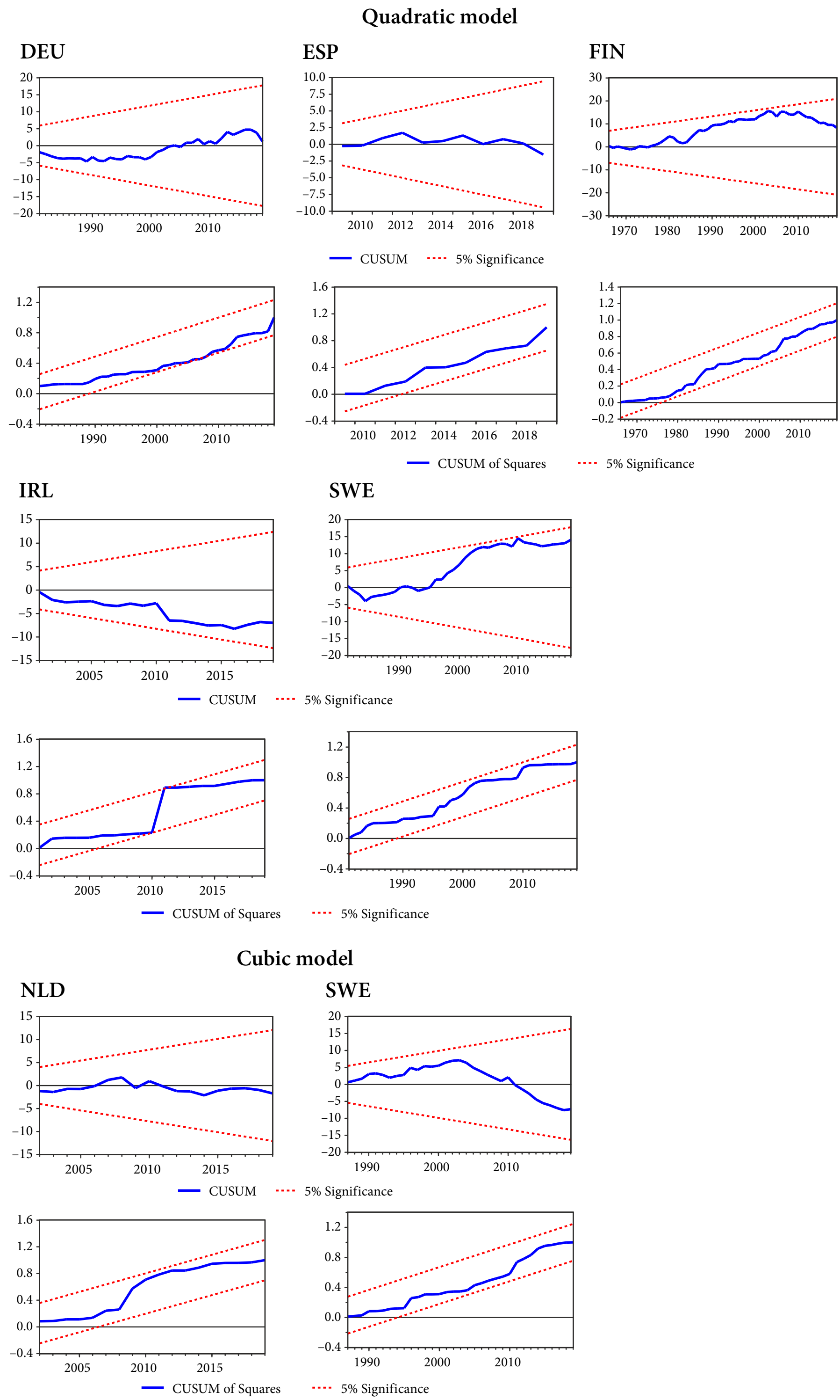
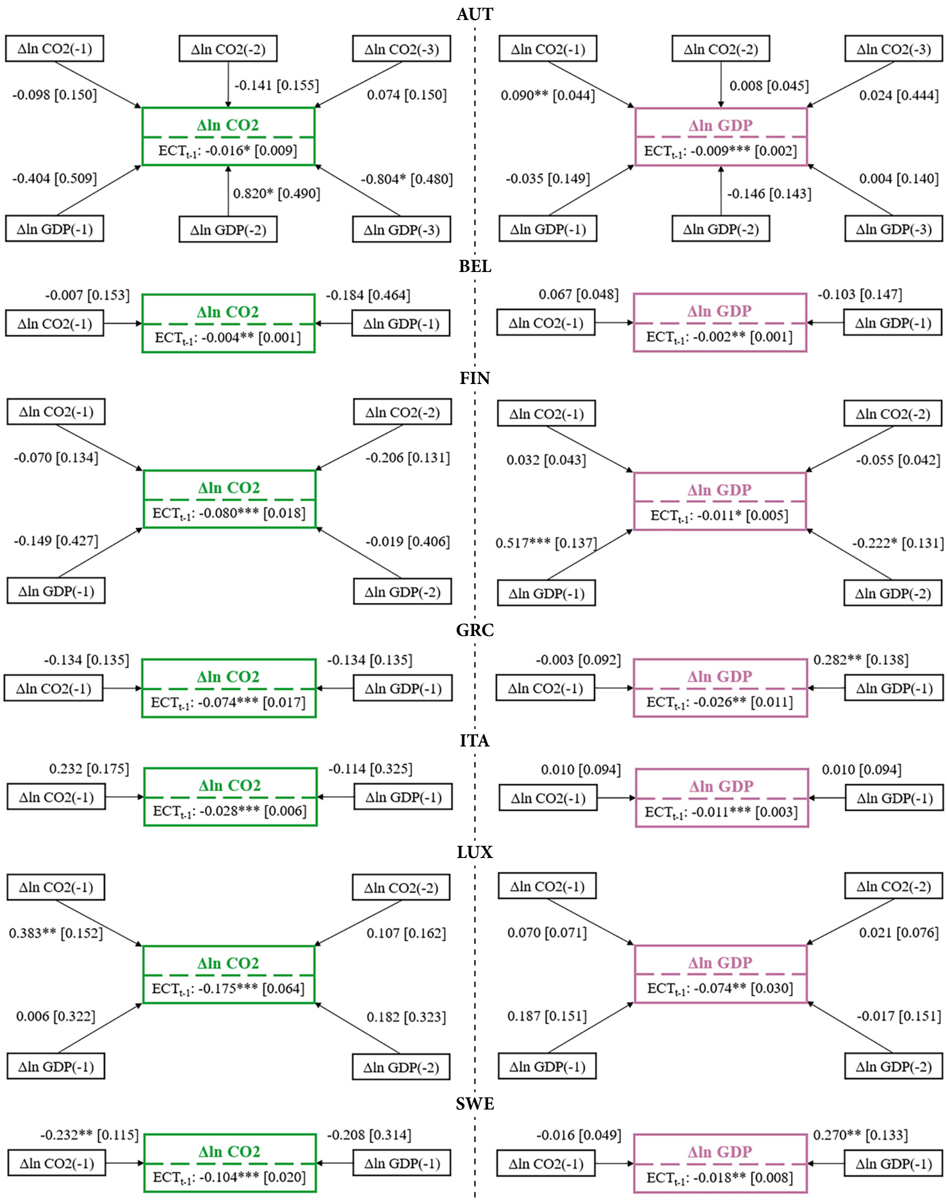


Figure 4. Plots of the CUSUM and CUSUMSQ stability tests statistics

The robustness of results obtained in the validated models was checked through the VEC Granger causality models (Granger, 1969). Figures 5–7 include the linear, quadratic and cubic models, and the VEC Granger causality models containing the variables in the first differences in relation to the ECT terms and the first differenced variables up to a particular lag.



Notes: ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively. Values in [] parentheses are standard errors.

Figure 5. Granger causality test results – linear models

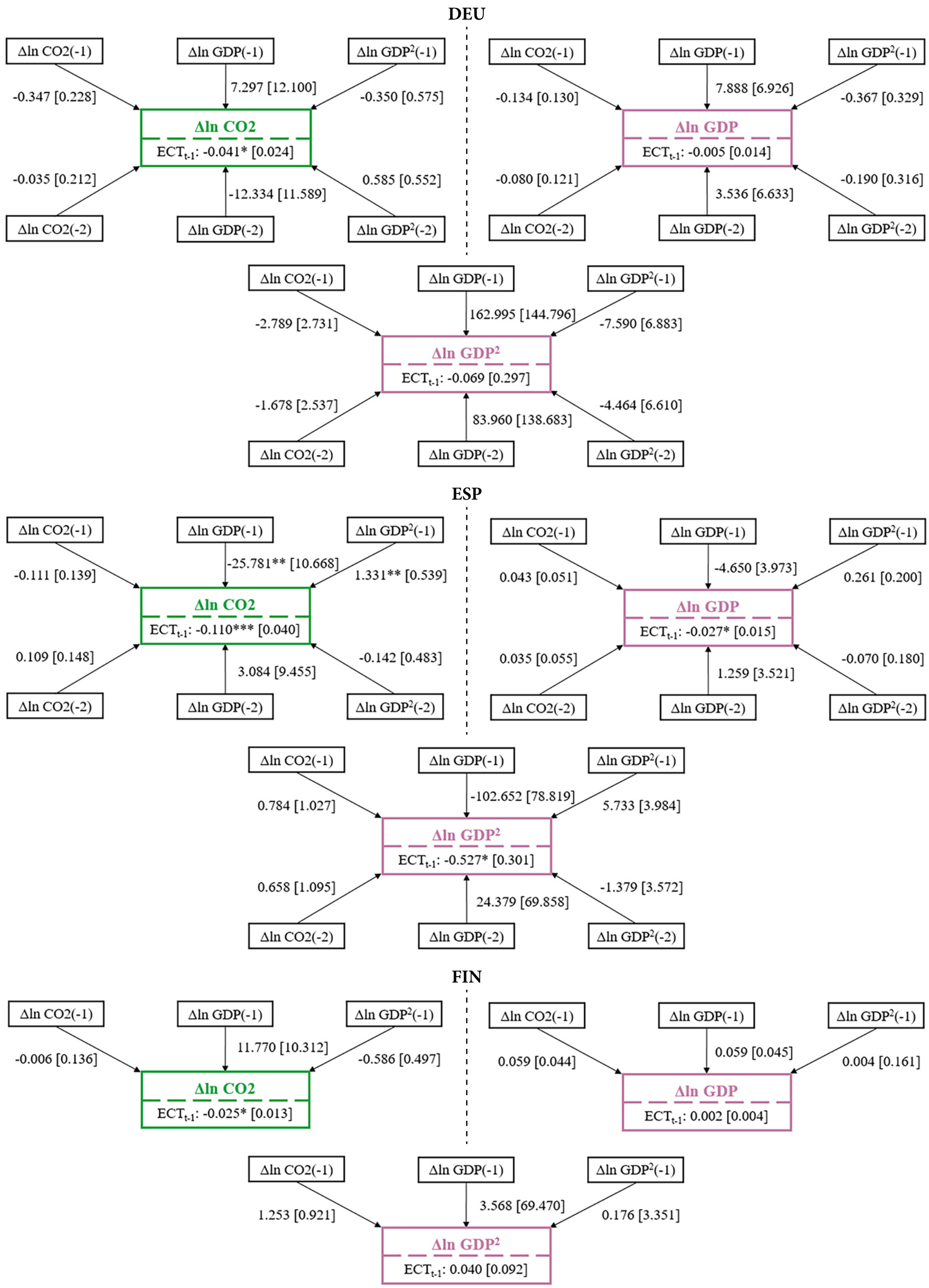
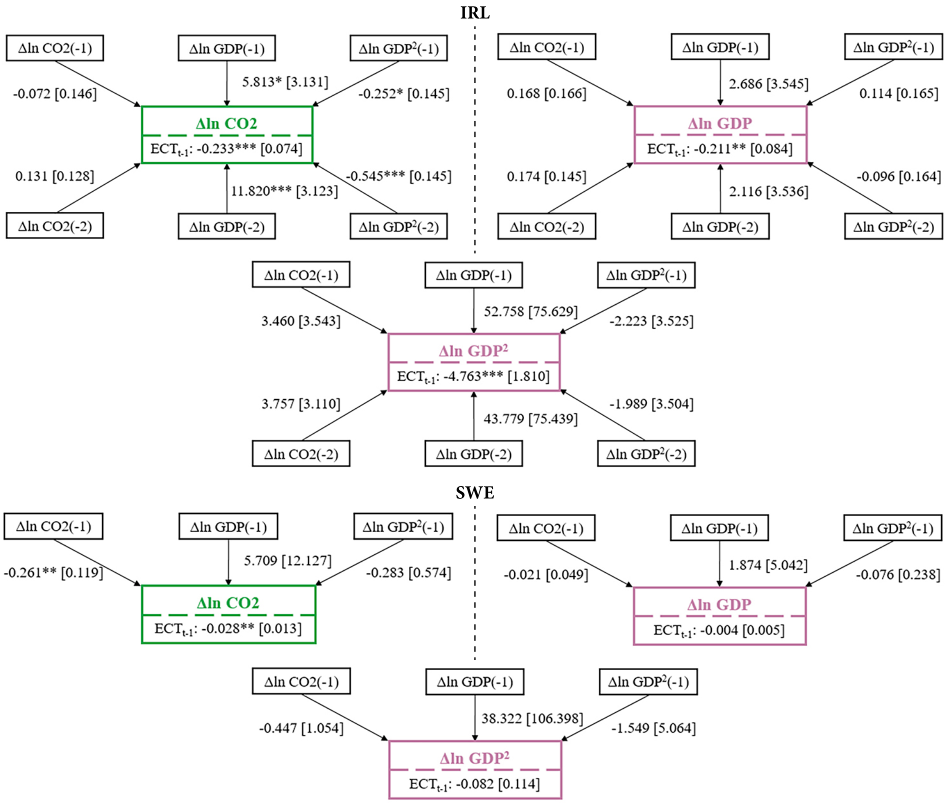


Figure 6. *To be continued*



Notes: ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively. Values in [] parentheses are standard errors.

Figure 6. Granger causality test results – quadratic models

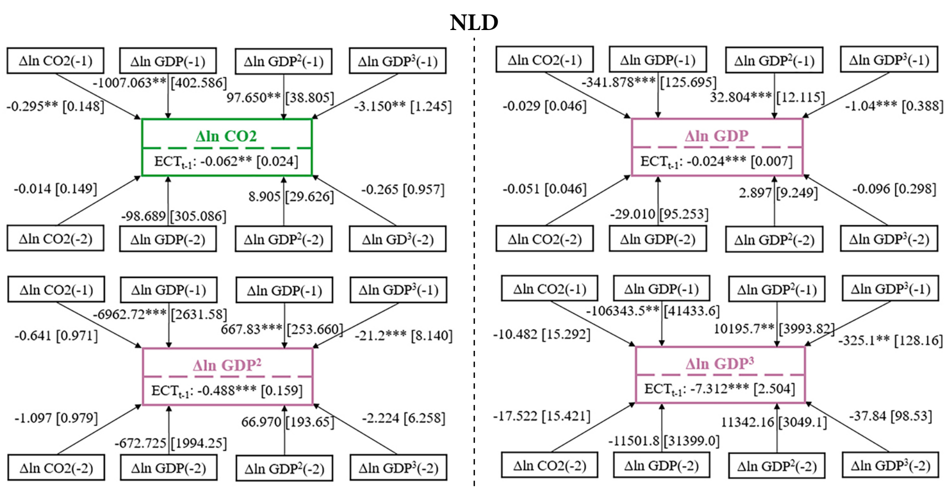
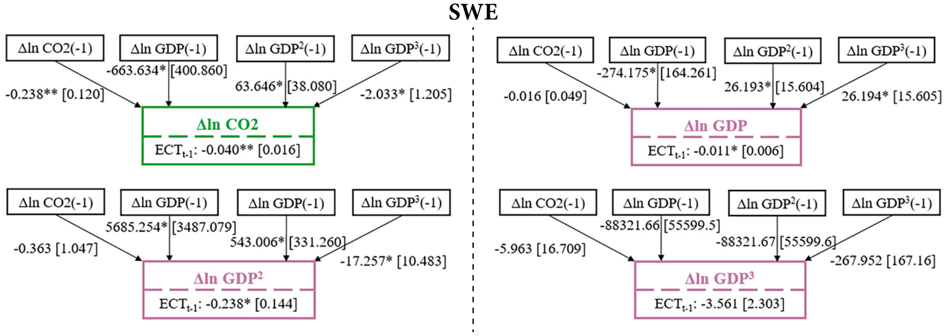


Figure 7. *To be continued*



Notes: ***, ** and * denote statistical significance at the 1%, 5% and 10% levels, respectively. Values in [] parentheses are standard errors.

Figure 7. Granger causality test results – cubic models

In the long-run, the CO2 emissions are Granger caused by the GDP in the countries where cointegration has been previously identified. Regarding the short-run, the results revealed that each country has a specific behaviour and that GDP has significant influences on CO2 emissions but at different lags. Therefore, the result of the VEC Granger causality models are in line with the ones obtained performing the ARDL cointegration approach.

Overall, the findings indicate that, in the long-run, the following shapes of EKC are significant: monotonically increasing shape – for Austria and Greece; monotonically decreasing shape – for Luxembourg and Sweden; inverted U-shape – for Finland, Germany and Ireland; N-shape – for Sweden. Thus, the H2 hypothesis stating that there isn't a unique functional form describing the economic growth-CO2 emissions relationship is validated. Given that Sweden has two models validated, the best model was selected taking into consideration the information criteria and R^2_{adj}, the results revealing that the cubic model is more suited than the other.

4. Discussions

The four obtained EKC patterns were included in Figure 8, specifying the countries following them. These results are in line with some of the ones obtained in the other previous studies (e.g., Acaravci & Ozturk, 2010; Balaguer & Catavella, 2016; Kotroni et al., 2020). Although the desired EKC pattern is the inverted U one, as Grossman and Krueger (1991) stated, the relationship between economic growth and CO2 emissions proved to be different among the EU15 countries, very few of them validating it (Finland, Germany, and Ireland). These patterns are consistent with the classification made by Lamb et al. (2022) regarding the emissions trends of countries: Greece registering growth in several decades and in the recent period peak followed by a decline in emissions; Germany and Sweden having, since the 1970s, a long and continuous decrease in emissions.

Economic growth is the major phenomena which influenced these trends over time, and in this context, the Global Financial Crisis of 2008–2009 was a major impediment. In the case of Greece, which registered lower levels of GDP for a long period after this shock, the reduction of emissions was mainly based on the fact that the share of renewable energy in electricity production grew, while the share of oil-based power plants dropped. In contrast, Germany quickly stabilized from the effects of the crisis and managed to overachieve the emission reduction targets by implementing such national climate strategies and policies as taxation of energy and emissions and increasing of the nuclear power share in the electricity production. Sweden, which also overachieved the targets, based its emission reduction on the shift in the industry sector from oil to electricity and on a high electricity production resulted from hydropower and nuclear power (Bekaliyev et al., 2021).

Studying the measures implemented by these countries in order to reduce the pressure of economic growth on the environmental degradation through GHG emissions, it can be emphasized that energy is the key factor managed because, on one hand, it represents the main engine of economic growth, and, on the other hand, GHG emissions (mainly CO2) are a direct consequence of the energy used in human activities. In this respect, the source of energy used plays a significant role, and renewable resources represent efficient solutions on

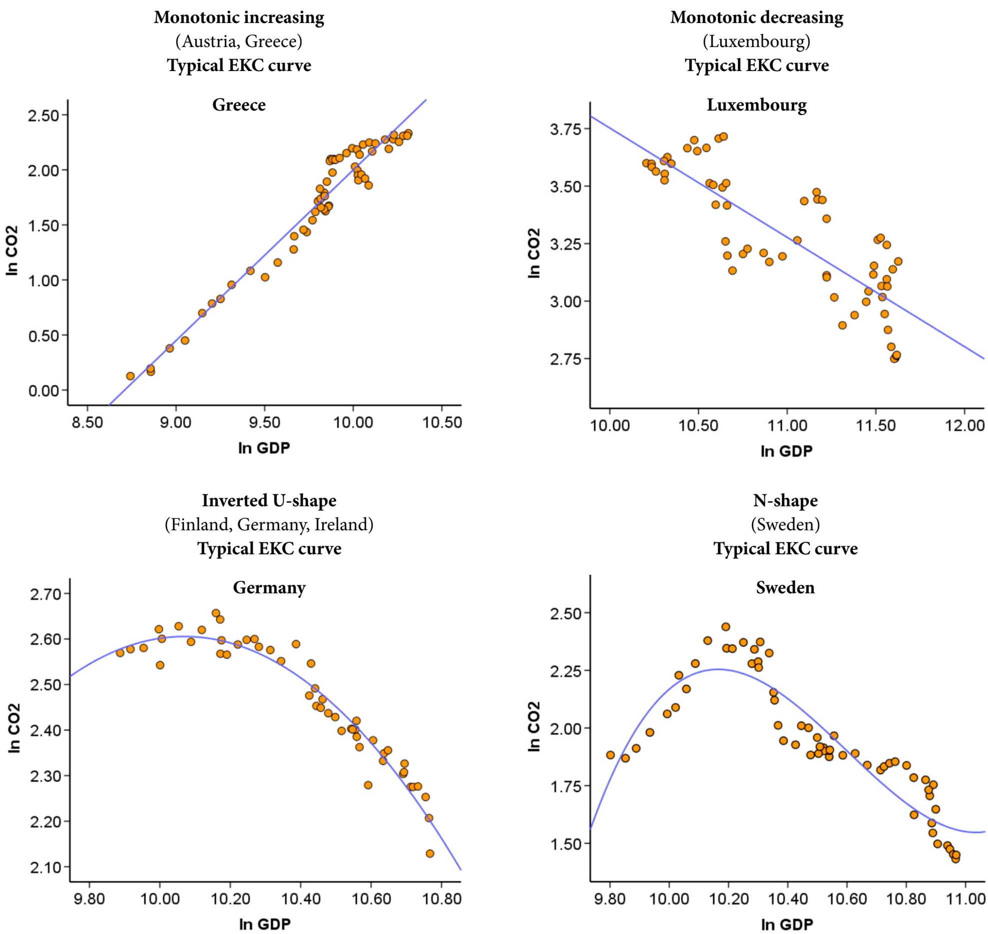


Figure 8. Groups of countries based on the EKC pattern

the long term. This fact can be identified, also, in several recent studies from the academic literature that focus on the impact of renewable resources of energy on the CO2 emissions (Bilgili et al., 2021a; Adebayo et al., 2022). In addition, other factors such as financial development, institutional factors, population density, research and development expenditures, tourism, trade, urbanization could also be responsible for mediating the economic growth-CO2 emissions relationship, reflecting the particularities of the analysed countries (Balaguer & Catavella, 2016; Lazăr et al., 2019; Hatmanu et al., 2021; Bilgili et al., 2021b).

Although, in some countries, a significant path to limiting the CO2 emissions generated in economic activities was to increase the proportion of renewable energy resources in the total energy consumption, there can be identified several limitations in hindering the widespread usage of this type of resources: technical limitations regarding renewable energy availability and technology needed in order to collect it; social limitations referring to awareness and information, public attitude and acceptance; regulatory limitations regarding lack of incentives and rules governing foreign investment; and administrative limitations in terms of bureaucratic licensing and procedures (Olabi & Abdelkareem, 2022). These barriers could represent a significant impediment in the case of the countries that are still facing the challenge of achieving economic growth with low levels of CO2 emissions.

Conclusions

The study focused on the study of the link between economic growth and environmental degradation at the level of the industrialized countries of the EU in the period 1960–2019. For each of these EU15 countries, the three functional forms were considered (i.e., linear, quadratic and cubic) that are used in the specialized literature focused on the EKC framework. The results emphasized various shapes that reflect the relationship between the GDP per capita (used to measure economic growth) and CO2 emissions per capita (used t measure environmental degradation): monotonic increasing shape for Austria and Greece, monotonic decreasing shape for Luxembourg, inverted U-shape for Finland, Germany and Ireland and N shape for Sweden. These relationships were identified on the long-run by applying the ARDL Bounds cointegration approach and error correction models.

Most of the EU15 countries managed to achieve the targets established in the Europe 2020 strategy, some of them (e.g., Germany and Sweden) also exceeding the targets imposed in the Europe 2030 strategy. Assessing the progress in countries with high reduction of emissions is important for the identification of the best practices and for spurring other countries to increase their ambition and action towards sustainability.

Given that economic growth is the main factor influencing the evolution of emissions, all key sectors of the economy, ranging from the energy sector, through industry, transport, construction and agriculture should bear the pressure of reducing emissions. The energy sector, as the engine of economic growth, could lead to important limitations in terms of emissions if such measures as reduction of overall energy use, expanded renewable energy or zero-carbon sources (e.g., solar PV, nuclear or wind) and transition to clearer fuels are implemented.

Further research could emphasize the manner in which economic activities from each of the sectors mentioned above have an impact on the GHG emissions. This way, policymakers could have a more accurate image of the economic activities that should be adjusted to prevent additional emissions. Moreover, in this sense, such additional variables as financial development, measures regarding population structure and energy use could offer further important insights.

Author contributions

Conceptualization, M.H.; methodology, M.H. and C.C.; software, M.H. and C.C.; validation, M.H. and C.C.; formal analysis, M.H. and C.C.; investigation, M.H. and C.C.; resources, M.H. and C.C.; data curation, C.C.; writing – original draft preparation, M.H. and C.C.; writing – review and editing, M.H. and C.C.; visualization, C.C.; supervision, M.H.

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