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Sectoral composition of GDP and greenhouse gas emissions: an empirical analysis in EU27

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Abstract

Understanding the relationship between economic growth and GHG emissions is crucial for achieving sustainable development and the Paris Agreement decarbonization goals. The objective of this paper is to analyse the long-term relationship between sectoral Gross Domestic Product (GDP) and greenhouse gas (GHG) emissions in the EU27 under the framework of the Environmental Kuznets Curve (EKC) theory. Previous research has yielded inconclusive results and presented various drawbacks, such as the omission of sectoral economic growth, poor data quality, and the use of methods that did not enable hypothesis testing. In contrast, this research applies the Autoregressive Distributed Lag (ARDL) method to assess the EKC in the long-term for the industrial, service, and agriculture components of GDP for EU27 countries from 1990 to 2018 using audited data from the United Nations Framework Convention on Climate Change. Despite a wide body of literature, this is the first research to investigate the EKC's nature in sectoral GDP in the EU-27. The EKC theory has been confirmed statistically in only five countries. Nevertheless, the results imply that economic growth has a lowering impact on the environment in more than half of the EU-27, as the EKC theorizes. A high impact on GHG emissions is observed in the service sector of those countries that combined a high share of services in the national economy with weak energy efficiency performance in the transport and building sectors. Likewise, countries with major employment in carbon-intensive industry branches tend to show a long-term impact on GHG emissions.

Keywords Environmental Kuznets curve · Autoregressive distributed lag (ARDL) · Greenhouse gas emissions · European Union · Climate change mitigation

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1 Introduction

Economic activity and the emission of greenhouse gases (GHG) are intrinsically connected. The use of the combustion engine and the extensive consumption of fossil fuels has allowed for expansive economic growth at the global level, linked to an increase in GHG emissions and increased pressure on the environment (Stearns, 2020). Global GHG emissions have risen since the industrial revolution, following a similar pattern to the Gross Domestic Product (GDP) (EEA, 2022). GHG produce the greenhouse effect, so their accumulation in the atmosphere increases the surface temperature. Thus, the literature defines anthropogenic climate change as that produced by the effect of human beings through GHG emissions linked to economic and industrial activity (Asplund, 2016). The Climate Change issue has led countries to design policies and undertake actions to reduce the GHG emissions associated with the economic activity. The ratification of the United Nations Framework Convention of Climate Change, the Kyoto Protocol, and the Paris Agreement define the level of commitment of countries around the world to reduce the GHG emissions associated with the economic activity to limit the future impacts of climate change (Leggett, 2020).

The effect of the mitigation efforts made so far for lowering the GHG emission impact of economic growth is inconclusive. Various studies found complete or partial dissociation between GHG emissions and GDP in several economies, allowing economic development with reduced GHG emissions (Chen et al., 2018; Haberl et al., 2020; Tenaw & Hawitibo, 2021). Conversely, relevant research suggests that the impact in developed economies continues to rise, attributing the observed GHG emission reductions to circumstantial reasons and industrial relocation to third countries (Koch & Mama, 2019; Mardani et al., 2019). Countries with policy frameworks more conducive to renewable energy and climate change mitigation tend to exhibit a more substantial decoupling between emissions and GDP (Cohen et al., 2018), and technological innovation lessens the impact of economic expansion in growing economies (Jahanger et al., 2022). European Union countries are often identified as example of successful GHG emission reductions due to the intensive mitigation policies implemented since the ’90 s (Papież et al., 2021; Piłatowska & Włodarczyk, 2018), but the disassociation between the economic activity and GHG emissions is not yet fully reached (Vadén et al., 2020), and the GHG emission impact of different EU countries is uneven (González-Sánchez & Martín-Ortega, 2020).

An improved understanding of the link between economic activity and GHG emissions is essential to incentivise sustainable economic growth, especially in the context of the implementation of the Paris Agreement, which aims to limit global warming through extensive mitigation interventions in developed and developing countries. An underlying objective of the Paris Agreement is to allow developing countries to grow their economies in a low-carbon manner, which implies economic growth with a reduced GHG emission impact (Kobayakawa, 2021). Extracting lessons from developed economies, especially those that have implemented substantial efforts to limit climate change, is essential to identify the reasons and drivers of low carbon economic development. This study contributes to this by undertaking a comprehensive analysis of the relationship between sectoral economic growth and the GHG emissions of the EU-27 countries with the final objective of identifying if the economic structure of the European economy is behind the potential decoupling between GHG emissions and economic growth, identifying policy implications for both developed and developing countries in view of the full implementation of the Paris Agreement. The analysis is developed at GDP component level to assess the impact of sectoral economic growth and GHG emissions. This allows assessing if the economic structure of the European countries affects the relationship between GHG emissions and economic growth and provides insights contributing to the discussion on the decoupling between sectoral economic growth and GHG emissions.

This study is framed under the theoretical framework of the Environmental Kuznets Curve (EKC), which provides a basic framework for linking economic growth with environmental impacts (Lapinskienė et al., 2014). The EKC theory set that economic growth gradually reduces the environmental degradation created in the early stages of development, mainly due to changes in the economic structure in favour of services and knowledge-based industries (Panayotou, 2003). Despite the extensive literature on the connection between GHG emissions and economic development according to the EKC theory, less attention has been paid to the relationship between economic structure and GHG emissions. Previous research highlighted as a critical limitation of the EKC literature whether the GDP-series captures the transition of production to the three productive sectors in empirical estimations and whether services are less polluting than industry activities (Kaika & Zervas, 2013). Additionally, previous studies suggest that considering sectoral GDP results in different EKC implications compared to aggregated GDP (Dogan & Inglesi-Lotz, 2020), with few studies examining the EKC in different economic structures and its implications for the relationship between GHG emissions and economic growth. These studies fit into two categories based on their results: the first group of studies ascertains that developed economies increase their GHG emissions in the long run, forming curves that fit into N and U EKC shapes (Mamun et al., 2014; Sohag et al., 2017, 2019; Savona & Ciarli, 2019; Mardani et al., 2019); and the second group validates the EKC theory with mature economies having lower GHG emissions in the long term, shaping inverted U curves (Cohen et al., 2018; Dogan & Inglesi-Lotz, 2020; Okamoto, 2013).

Several limitations of earlier studies may have led to erroneous conclusions. Numerous research studies have as primary purpose the investigation of the EKC shape, however their methodologies do not always allow hypothesis testing. Therefore, the EKC shapes obtained in these investigations may be based on an erroneous association between factors. Relevant examples of this type of studies are Diakoulaki and Mandaraka (2007), Okamoto (2013), Luo et al. (2017), Wu et al. (2018), Chen et al. (2018), Wang and Su (2019), and Wang and Wang (2020). Some studies employ CO_2 instead of GHG (Al Mamun et al., 2014; Isik et al., 2021; Leal et al., 2019; Yang et al., 2018), while others use unaudited data sources (Cohen et al., 2018; Dogan & Inglesi-Lotz, 2020), casting doubt on the reliability of the time series used as the foundation for the research.

This paper overcomes the shortcomings found in the literature and contributes to the EKC literature by further exploring the EKC theory using the sectoral breakdown of GDP and GHG emissions. This is the first study analysing the EKC theory in terms of sectoral GDP in each EU-27 country. The Autoregressive Distributed Lag (ARDL) method is used for the years 1990–2018 in EU27 countries using data from Eurostat (2021) and the United Nations Framework Convention of Climate Change (2021). In addition, we check for structural breaks in the parameters representing the EKC curve.

This paper is organized into several sections. A review of the literature on the relationship between sectoral GDP and GHG emissions within the EKC framework is presented in the second section. Building from the main findings of previous research, the materials and methods of the study are covered in the third section. Results and discussion are found in section four, and the main conclusions are provided in section five.

2 Literature review

The roots of EKC are encountered in the original study of Kuznets (1955), where the author found that inequality tends to increase with economic growth to decline at mature development stages, shaping an inverted U relationship between these variables. Following the rationale set by Kuznets (1955), the EKC hypothesis states that after a certain amount of economic growth, its effect on the environment decreases.

Grossman and Krueger (1991) was the first empirical study testing the EKC hypothesis, confirming the EKC for two pollutants in a broader analysis on the relationship between air quality and economic growth for the North American free trade agreement. Following its first use, other relevant studies used the EKC framework, such as Panayotou (1993) and Selden and Song (1994). In these first studies of the EKC, the relationship between economic growth and environmental degradation has been theorized through the evolution of developing economies. Panayotou (2003) described three stages of economic development: pre-industrial economies (limited impacts of economic growth on the environment), industrial economies (impacts accelerate), and post-industrial economies (service economies where the impacts are reduced).

The three stages of economic development described in Panayotou (2003) have been consistently used in later studies under the EKC framework. The EKC literature has suggested different types of effects on the environment depending on the stage of economic development: a proportional effect in pre-industrial economies, an increased effect in industrial economies, and a lessening effect in post-industrial economies. Different reasons have been identified for the lower impact on the environment in post-industrial economies, such as technologic modernization (Bagliani et al., 2008), changes in the economic structure in favour of services and knowledge-based industries (Panayotou, 2003), and more demanding environmental regulation (Dietz et al., 2012), among other reasons. Additional studies identified that the lessening effect in post-industrial economies might be just temporary (Halkos, 2011). The results of Grossman and Krueger (1995) suggest that at high development levels, the intensive use of materials increases environmental impact leading to an N-shape EKC specification. The existence of an N-shaped relationship between economic growth and environmental impact was confirmed by different studies, such as Friedl and Getzner (2003), Akbostanci et al. (2009), and Lorente and Alvarez-Herranz (2016).

Because of the ease with which data are available and the importance of climate change in the international agenda, GHG emissions have been chosen as the primary proxy for environmental degradation in the bibliography (Özcan & Öztürk, 2019). Extensive bibliography reviews of the relationship between GHG emissions and economic growth under the EKC framework are provided in several studies, such as Özcan and Öztürk (2019) and Mardani et al. (2019), and are thus not reproduced in this paper. Despite the broad literature available on the link between GHG emissions and GDP under the EKC theory, the analysis of the economic structure and its links with GHG emissions has received less attention. A few studies analysed the EKC in different economic structures and its implications for the relationship between GHG emissions and economic growth.

Al Mamun et al. (2014) explored the impact of agriculture, industrial, and service added value to CO_2 emissions and the impacts on the transformation of different economies for the period 1980–2009 using panel data models and cointegration techniques. The study found that service value addition increases more GHG emissions compared to industrial and agriculture value addition in high-income countries in the long run, proving the non-existence of the EKC in countries with service-oriented economic structures empirically.

Sohag et al. (2017) analysed the effect of the agriculture, industry, and services sectors on GHG emissions in middle-income countries using a panel data model. The authors found that industrial GDP is more responsible for CO_2 emissions than service GDP across middle-income countries. Furthermore, the authors confirmed that service value addition increases more CO_2 emissions compared to industrial and agriculture value addition in high-income countries in the long run. The findings of this study suggest the existence of an inverted U-shape relation between CO_2 emissions and economic growth in the long run, that is, the validity of EKC in middle-income industry-oriented economies. Nonetheless, the results of this study pointed to an N-shaped EKC in high-income countries, suggesting that the original EKC hypothesis will not hold in the long run.

Sohag et al. (2019) assessed the EKC in OECD countries for the years 1980–2017, finding a U-shaped relationship contrary to the EKC hypothesis. Savona and Ciarli (2019) found that the long-term shift from manufacturing to services has not led, in all cases, to the de-materialization of economies and a lower environmental burden. Similarly, in its comprehensive literature review, Mardani et al. (2019) concluded that emissions are either increasing or stabilizing, the primary trend in most "tertiarised" economies.

In contrast, numerous authors have found that service-oriented countries have lower GHG emissions, in line with the EKC theory. Okamoto (2013) analysed the GHG emissions in Japan for the years 1990–2005, finding that the GHG reduction owing to the transition to a service economy was not negligible, and the structural shift to a service economy was far more important than service sectors' material dependency. Cohen et al. (2018) found that countries with a high share of services in value-added relative to that of industry or agriculture consistently show low elasticities of GHG emissions with economic growth. In an analysis of the existence of the EKC for industry and national economy for the years 1980–2014 in EU countries, Dogan and Inglesi-Lotz (2020) verified the EKC hypotesis for the aggregate GDP growth but it was not supported for the industry sector. This study failed to consider other sectoral components of economic growth essential to understanding the EKC theory, such as the service and the agriculture sectors. In a recent study, Balsalobre-Lorente et al. (2022) found that economic complexity is linked to CO_2 emissions, validating the EKC theory for Portugal, Ireland, Italy, Greece, and Spain.

Table 1 summarizes the coverage and results of a selection of studies analysing the relationship between economic growth and GHG emissions under different economic structures.

As observed in Table 1, previous studies produced inconclusive results regarding the relationship between GDP growth and GHG emissions at the sectoral level and the existence of the EKC curve either for the national economy or its sectors. Further, the studies present limitations on the sectoral scope considered, as not all economic sectors are empirically tested in all studies. Only Al Mamun et al. (2014) analysed the EKC for the main economic sectors; however, this study failed to analyse the EKC by country (panel model estimation techniques were used) and did not include EU-27 countries in the empirical testing. The analysis of the literature also show that the scope of gases is limited to CO_2 emissions in numerous studies. This omits the contribution of CH_4, N_2O and fluorinated gases to total GHG emissions (Harmsen et al., 2020), failing to consider all emissions generated by the economic activity.

Table 1 Summary of results for a selection of studies

Study	Geographical scope	Sector and gas coverage	Results
Diakoulaki and Mandaraka (2007)	14 EU countries	Manufacturing sector; CO_2	There is no significant change in the relationship between GHG emissions and economic growth in 1990–1997 and 1997–2003, implying the EKC does not hold for industrial economic growth
Okamoto (2013)	Japan	Service sector; CO_2	The existence of EKC was not tested. The author found a GHG emission reduction due to the shift to the service economy in 1990–2005
Al Mamun et al. (2014)	136 countries dived into five groups: lower-income countries, lower-middle-income countries, upper-middle-income countries, high-income OECD countries, and high-income non-OECD countries	Agriculture, industrial, and service sectors; CO_2	The EKC curve was not found in high-income countries for any sector
Luo et al. (2017)	30 Chinese provinces	Agriculture; CO_2	The existence of EKC was not tested. Evidence consistent with the EKC hypothesis
Yang et al. (2018)	China	Manufacturing, construction, transportation, and commercial sectors; CO_2	The existence of EKC was not tested. Evidence consistent with the EKC hypothesis in the energy and heavy industries
Leal et al. (2019)	Australia	Agriculture, industry, construction, commercial services, transport and residential sectors; GHG	The existence of EKC was not tested. Evidence consistent with the EKC hypothesis, particularly for the agriculture and commercial sectors
Wang and Su (2019)	Beijin and Shangai	Construction, transport, industry, agriculture, and trade; CO_2	The existence of EKC was not tested. Evidence consistent with the EKC hypothesis in agriculture and industry in Beijing
Hashmi et al. (2020)	Pakistan	Service sector; CO_2	The existence of EKC was not tested. Evidence consistent with the EKC hypothesis
Su et al. (2020)	Beijing	Construction, transport, industry, agriculture, and trade; CO_2	The existence of EKC was not tested. Evidence consistent with the EKC hypothesis for the agriculture and industry sectors

Table 1 (continued)

Study	Geographical scope	Sector and gas coverage	Results
Dogan and Inglesi-Lotz (2020)	7 EU countries	National economy and industry; CO_2	EKC hypothesis is confirmed when the aggregate GDP growth is considered, while the EKC hypothesis is not confirmed for the industry sector
Isik et al. (2021)	8 OCDE countries	National economy; CO_2	The EKC curve was not found using decomposed per capita GDP series
Simionescu et al. (2021)	Four Central and Eastern European countries	National economy; GHG	An N-shaped EKC was found with increases in emissions in the latter period

3 Materials and methods

3.1 Methodology

The methodology selection for empirical testing builds from the revision of EKC literature. Table 2 shows the methods followed by a selection of studies of similar nature.

According to Andres and Padilla (2018) and González-Sánchez and Martín-Ortega (2020), decomposition analysis, Tapio model, and Logarithmic Mean Divisia Index present several limitations, as they do not allow hypothesis testing, and they assume the functional relationship between factors are proportional. Therefore, these methods are not considered for this study. The use of the Autoregressive distributive lag (ARDL) model by Pesaran et al. (2001) is widespread in the analysis of the EKC, allows to fulfil the objectives of the research and avoids the limitations identified for the other methods.

EKC shows the relationship between greenhouse gases emissions per capita (GHG) and gross product per capita (GDP):

$$\mathrm{GHG}_t = f\left(\mathrm{GDP}_t, \mathrm{GDP}_t^2\right) \tag{1}$$

Usually, the literature (Ahmad et al., 2017; Liobikien and Butkus, 2017) express this relationship in linear form and take the log of the variable to avoid potential negative values:

$$\ln\left(\mathrm{GHG}_t\right) = \alpha_0 + \alpha_1 \cdot \ln\left(\mathrm{GDP}_t\right) + \alpha_2 \cdot \left[\ln\left(\mathrm{GDP}_t\right)\right]^2 \tag{2}$$

A drawback with the estimation of expression (2) is that variables in level are not stationary, so we have to use cointegration methodologies. Our aim is to test changes in this relationship which has U form when $\alpha_2 > 0$ and invert-U if $\alpha_2 < 0$. For that, we consider sensibility or derivative expression:

$$\frac{\partial \ln\left(\mathrm{GHG}_t\right)}{\partial \ln\left(\mathrm{GDP}_t\right)} = \alpha_1 + 2 \cdot \alpha_2 \cdot \ln\left(\mathrm{GDP}_t\right) \tag{3}$$

In expression (3), note that:

- If $\alpha_2 > 0$ (U-form), then $\frac{-\alpha_1}{2\cdot\alpha_2}$ is the vertex of parabolic function or minium.
- Else if $\alpha_2 < 0$ ($\cap$ form), then $\frac{-\alpha_1}{2\cdot\alpha_2}$ is a maximum.

Thus, our objective is to study changes in these values, and we express discrete form Eq. (3):

$$\frac{\Delta \ln\left(\mathrm{GHG}_t\right)}{\Delta \ln\left(\mathrm{GDP}_t\right)} = a_1 + 2 \cdot a_2 \cdot \ln\left(\mathrm{GDP}_{t-1}\right) + u_t \tag{4}$$

And then for econometric estimation (u_t is error term):

$$\Delta \ln\left(\mathrm{GHG}_t\right) = a_1 \cdot \Delta \ln\left(\mathrm{GDP}_t\right) + 2 \cdot a_2 \cdot \ln\left(\mathrm{GDP}_{t-1}\right) \cdot \Delta \ln\left(\mathrm{GDP}_t\right) + u_t \tag{5}$$

Note that a_1 and a_2 are estimates of α_1 and α_2, respectively.

Table 2 Methodological approach for a selection of recent studies on EKC

Study	Methodology	Data
Diakoulaki and Mandaraka (2007)	Decomposition analysis	1990–2003. EU countries
Okamoto (2013)	Additive decomposition method	1990–2005
Al Mamun et al. (2014)	Panel data model	1980 to 2012. 136 countries
Sohag et al. (2017)	Panel data model	1980 to 2012. 82 middle-income countries
Luo et al. (2017)	Decomposition analysis	1997–2014 30 Chinese provinces
Liobikien and Butkus (2017)	Generalized Method of Moments approach	180 countries covering the period from 1990 to 2011
Ahmad et al. (2017)	Autoregressive Distributed Lag (ARDL) and VECM method	Croatia for the period of 1992Q1–2011Q1
Mikayilov et al. (2018)	A time-varying cointegration approach	1861–2014 in 12 Western European countries
Wu et al. (2018)	OECD decoupling factor model, Tapio elastic analysis (TEA) method, and the IGTX decoupling model	1965–2015. The research period is divided into five sub-periods: 1965–1975, 1976–1985, 1986–1995, 1996–2005, and 2006–2015 8 countries
Chen et al. (2018)	Logarithmic Mean Divisia Index (LMDI) decomposition method and the Tapio decoupling analysis	2001–2015 in OECD countries
Cohen et al. (2018)	Trend/cycle decomposition in time series regression analysis	1990–2014 20 countries (20 largest emitters)
Wang and Su (2019)	Tapio model, the Johansen cointegration theory, and the Granger causality test	1990–2015 in China
Engo (2019)	Log-Mean Divisia Index and Tapio models	1971–2014 in Cameroon
Leal et al. (2019)	Logarithmic Mean Divisia Index	1990–2014 for Australis
Song et al. (2019)	Tapio decoupling index	1965–2016 for China and USA
Wang and Wang (2020)	Decoupling index model and decomposition approach	1990–2014 in 186 countries
Piłatowska et al. (2020)	Granger causality and the threshold vector autoregression (TVAR) model	1970–2018 in Spain
Destek et al. (2020)	Time-varying cointegration and bootstrap-rolling window estimation approach	1800–2010 in G-7 countries
Pao and Chen (2020)	Multivariate nonlinear and univariate linear ARIMA models	1987–2016 in France, Belgium, Sweden, Switzerland and USA
Yang et al. (2018)	LMDI and Tapio index	1996–2015. China
Wang et al. (2019)	Tapio decoupling elasticity and the logarithmic mean Divisia index (LMDI) model	2000–2015 for Beijin and Sangai

Table 2 (continued)

Study	Methodology	Data
Hashmi et al. (2020)	Autoregressive distributive lag (ARDL) model with structural break analysis	1971–2014 in Pakistan
Wang and Su (2019)	Tapio model and Logarithmic Mean Divisia Index (LMDI)	2000–2016 six provinces in China
Su et al. (2020)	Tapio model and Logarithmic Mean Divisia Index (LMDI)	2000–2015 for Beijin
Wang and Su (2020)	Tapio indicator and Extended LMDI technique	2000–2014 in 192 countries
Dogan and Inglesi-Lotz (2020)	Fully modified OLS (FMOLS) long-run estimators	1980 to 2014 in seven European countries
Isik et al. (2021)	Cross-sectional-autoregressive distributed lags (CS-ARDL)	1980 to 2017 in OECD
Simionescu et al. (2021)	Dynamic Autoregressive distributive lag (ARDL) panel	1996–2019 in four Central and Eastern European countries

Now, we consider the sectoral decomposition of GDP per capita, substituting GDP for Agriculture (A), Industry (I), and Services (S) per capita and as a consequence expression (5) is:

$$\Delta \ln \left(\mathrm{GHG}_t\right) = \beta_0 + \beta_1 \cdot \Delta \ln \left(A_t\right) + \beta_2 \cdot \ln \left(A_t\right) \cdot \Delta \ln \left(A_t\right) + \beta_3 \cdot \partial \ln \left(I_t\right) + \beta_4 \cdot \ln \left(I_t\right) \cdot \Delta \ln \left(I_t\right) + \beta_5 \cdot \Delta \ln \left(S_t\right) + \beta_6 \cdot \ln \left(S_t\right) \cdot \Delta \ln \left(S_t\right) + u_t \quad (6)$$

where $y_t = \Delta \ln \left(\mathrm{GHG}_t\right) = \ln \left(\mathrm{GHG}_t\right) - \ln \left(\mathrm{GHG}_{t-1}\right)$, $x_{A,t} = \Delta \ln \left(A_t\right) = \ln \left(A_t\right) - \ln \left(A_{t-1}\right)$, $x_{I,t} = \Delta \ln \left(I_t\right) = \ln \left(I_t\right) - \ln \left(I_{t-1}\right)$ and $x_{S,t} = \Delta \ln \left(S_t\right) = \ln \left(S_t\right) - \ln \left(S_{t-1}\right)$. Note that these variables are in first log-difference and as consequence they are stationary, but the question is that $z_{A,t} = \ln \left(A_{t-1}\right) \cdot \Delta \ln \left(A_t\right)$, $z_{I,t} = \ln \left(I_{t-1}\right) \cdot \Delta \ln \left(I_t\right)$ and $z_{S,t} = \ln \left(S_{t-1}\right) \cdot \Delta \ln \left(S_t\right)$ are not stationary. As a result, there might be problems with the consistency of the results as well as possible cointegration between regressors. Furthermore, it is not possible to accurately determine the long-term equilibrium relationship between variables in the presence of more than one cointegration relationship and more than two regressors.

As a consequence, we use the ARDL approach to test EKC, but it does not explain causality between variables. In the presence of cointegration, we take the difference of the variables to make them stationary. Then we use the vector error correction model (VECM) by country, similarly to Ahmad et al. (2017). We test the short and long-run estimates using the following VECM model by country:

$$\begin{bmatrix} \Delta\ln(\mathrm{GHG_t}) \\ \Delta\ln(A_t) \\ \Delta\ln(I_t) \\ \Delta\ln(S_t) \\ \Delta\ln(A_t)^2 \\ \Delta\ln(I_t)^2 \\ \Delta\ln(S_t)^2 \end{bmatrix} = \begin{bmatrix} \beta_{0,\mathrm{GHG}} \\ \beta_{0,A} \\ \beta_{0,I} \\ \beta_{0,S} \\ \beta_{0,A^2} \\ \beta_{0,I^2} \\ \beta_{0,S^2} \end{bmatrix} + \begin{bmatrix} \beta_{\mathrm{GHG,GHG}} & \cdots & \beta_{\mathrm{GHG},S^2} \\ \beta_{A,\mathrm{GHG}} & \cdots & \beta_{A,S^2} \\ \beta_{I,\mathrm{GHG}} & \cdots & \beta_{I,S^2} \\ \beta_{S,\mathrm{GHG}} & \cdots & \beta_{S,S^2} \\ \beta_{A^2,\mathrm{GHG}} & \cdots & \beta_{A^2,S^2} \\ \beta_{I^2,\mathrm{GHG}} & \cdots & \beta_{I^2,S^2} \\ \beta_{S^2,\mathrm{GHG}} & \cdots & \beta_{S^2,S^2} \end{bmatrix} \cdot \begin{bmatrix} \Delta\ln(\mathrm{GHG}_{t-1}) \\ \Delta\ln(A_{t-1}) \\ \Delta\ln(I_{t-1}) \\ \Delta\ln(S_{t-1}) \\ \Delta\ln(A_{t-1})^2 \\ \Delta\ln(I_{t-1})^2 \\ \Delta\ln(S_{t-1})^2 \end{bmatrix} + \begin{bmatrix} \alpha_{\mathrm{GHG,GHG}} & \cdots & \alpha_{\mathrm{GHG},S^2} \\ \alpha_{A,\mathrm{GHG}} & \cdots & \alpha_{A,S^2} \\ \alpha_{I,\mathrm{GHG}} & \cdots & \alpha_{I,S^2} \\ \alpha_{S,\mathrm{GHG}} & \cdots & \alpha_{S,S^2} \\ \alpha_{A^2,\mathrm{GHG}} & \cdots & \alpha_{A^2,S^2} \\ \alpha_{I^2,\mathrm{GHG}} & \cdots & \alpha_{I^2,S^2} \\ \alpha_{S^2,\mathrm{GHG}} & \cdots & \alpha_{S^2,S^2} \end{bmatrix} \cdot \begin{bmatrix} \ln(\mathrm{GHG}_{t-1}) \\ \ln(A_{t-1}) \\ \ln(I_{t-1}) \\ \ln(S_{t-1}) \\ \ln(A_{t-1})^2 \\ \ln(I_{t-1})^2 \\ \ln(S_{t-1})^2 \end{bmatrix} + \begin{bmatrix} u_{\mathrm{GHG},t} \\ u_{A,t} \\ u_{I,t} \\ u_{S,t} \\ u_{A^2,t} \\ u_{I^2,t} \\ u_{S^2,t} \end{bmatrix} \quad (7)$$

In expression (7) β represent short-run coefficients, illustrating the relationship between variables in the short term. Conversely, α represent the relationship between variables in the long term. We use the VECM to assess the impact of sectoral GDP on GHG emissions, as represented in the first row of the vector.

To test the cointegration between variables, we use the maximum eigenvalue and trace test of Johansen, similar to Nasir and Rehman (2011) and Wang and Su (2019). Before applying the cointegration test, however, an important step is to select the optimal lag length of underlying VAR using the conventional model selection criteria (AIC). These criteria establishes that the optimal lag length is two. After the lag length of the VAR is selected, the Johansen test is applied to identify the cointegration relationships between the dependent variable and regressors. The application of the Johansen methodology involves several drawbacks to be considered. Firstly, the number of cointegration relationships can be different by country; consequently, the results would not be comparable among countries. Secondly, given the number of variables (more than two) that intervene in the model and the absence of earlier hypotheses on the cointegration parameters, there is no single expression for such long-term relationships. For these reasons, we apply the ARDL approach to estimate expression (7).

3.2 Data

This empirical research focuses on the EU-27 countries, years 1990–2018. EU-27 countries have a homogeneous level of policy implementation, and the sample contains countries with heterogeneous economic structures. The selection of the EU-27 thus allows fulfilling the objectives of the study. Furthermore, it ensures the comparability of data, as the data for all countries is extracted from the same source.

For GHG emissions, we use the data from national GHG emission inventories submitted to the United Nations Convention on Climate Change (UNFCCC, 2021). By utilizing this data, we ensured that GHG emissions were calculated in accordance with specific quality standards, based on a standardized methodological framework, the 2006 IPCC Guidelines (IPCC, 2006), and annual audits (Pulles, 2017). This overcomes two deficiencies found by the authors in the literature i) the use of CO_2 emissions instead of GHG (Ahmad et al., 2017; Al Mamun et al., 2014; Chen et al., 2018; Cohen et al., 2018; Hashmi et al., 2020), and ii) the use of data sources which are not audited (Destek et al., 2020; Dogan & Inglesi-Lotz, 2020; Cohen et al., 2018).

Specifically, we use national total GHG emissions without land use, land-use change, and forestry, extracted from the Common Reporting Framework (CRF) Table 10S1. For the sectoral GDP components, i.e. GDP Agriculture, Industry, and Services, we use the gross added value from Eurostat (2021). GHG emissions and sectoral GDP are transformed into per capita indexes using the population data from Eurostat (2021). Using the data sources listed above, we obtain one dependent variable: GHG emissions per capita (GHG), and three potential regressors: GDP Agriculture per capita (A), GDP Industry per capita (I), and GDP Services per capita (S). The data used in the empirical research consisted of the log variable of GHG emissions, the log variable, and the squared log variable on the level and first difference for the regressors. We contrast cointegration between sectoral GDP per capita and GHG per capita since a single relationship involving a few variables is a condition for using the Johansen methodology for estimating the long-run relationship between variables. Table 3 shows the results obtained.

The number of cointegration relationships varies from country to country, as shown in the parameter "rank" in the previous table. Moreover, the large number of regressors makes long-term equilibrium relationships unfeasible to determine if considered as a whole. As a result, the use of ADRL by country is justified.

Table 3 Cointegration results

Country	Rank (cointegration relationships)	Trace test	*t*-prob > 0.05
Austria	2	65.028	0.112
Belgium	4	24.076	0.204
Finland	3	42.691	0.140
France	3	39.201	0.255
Germany	4	28.201	0.077
Ireland	4	28.805	0.065
Italy	1	94.731	0.057
Netherlands	2	60.713	0.215
Portugal	4	26.107	0.129
Spain	5	11.334	0.195
Bulgaria	1	91.027	0.100
Croatia	3	41.218	0.183
Cyprus	3	39.502	0.243
Czechia	3	46.232	0.069
Denmark	1	95.078	0.054
Estonia	2	64.821	0.116
Greece	2	66.053	0.095
Hungary	4	23.224	0.243
Latvia	6	0.747	0.387
Lithuania	3	44.367	0.102
Luxembourg	3	41.557	0.172
Malta	5	10.565	0.244
Poland	4	25.090	0.163
Romania	1	90.803	0.103
Slovakia	1	85.917	0.196
Slovenia	3	41.674	0.169
Sweeden	3	41.674	0.169

4 Results and discussion

4.1 Estimation results

This section presents a description and a thorough analysis of short- and long-term results. Based on these findings, an evaluation of the validation of the EKC theory for the EU-27 member states is provided.

Table 4 shows the short-term results (β) using expression (7).

From Table 4, we observe that 10 of the 27 countries analysed had statistically significant coefficients in the short term for any of the tested variables. The short-term relationship between sectoral economic growth and GHG emissions evidence the uneven impact in GHG emissions in EU-27 countries. Notably, sectoral economic growth was not significant for explaining the evolution of GHG emissions in the short term in 17 countries analysed, pointing out the potential lessening effect of economic growth in most EU-27 countries' economic development stage.

Table 4 Short-term estimation results

Country	dif_lnIND_1		dif_lnIND²_1		dif_lnAGRI_1		dif_lnAGRI²_1		dif_lnSERV_1		dif_lnSERV²_1	
	Coeff	tvalue	Coeff	tvalue	Coeff	tvalue	Coeff	tvalue	Coeff	Tvalue	Coeff	tvalue
Austria	−0.1	−0.470	0.18	0.068	−0.01	−0.108	1.25	0.440	−0.05	−0.050	−33.71	−0.979
Belgium	0.19	0.740	2.69	0.612	0.16	1.530	0.45	0.458	0.14	0.175	25.03	0.734
Finland	0.01	−0.030	1.23	0.590	0.54	1.450	3.12	0.590	−0.94	−1.280	−10	−0.354
France	0.31	1.160	8.1	1.230	−0.001	−0.012	−0.48	−0.715	0.28	0.560	−15.18	−0.600
Germany	0.12	1.100	0.84	1.000	−0.06	−1.700	−0.08	−0.540	−0.02	−0.043	5399	0.470
Ireland	**0.37****	3.230	**−0.46***	−2.270	−0.048	−0.702	0.21	0.608	**0.56***	2.410	7.26	1.800
Italy	−0.05	−0.133	2.51	1.250	−0.18	−0.632	2.7	0.640	1.46	1.480	−33.13	−0.980
The Netherlands	**−0.68****	−3.170	−0.99	−0.370	**0.49***	2.240	0.43	0.077	**−0.97***	−2.050	27.16	1.870
Portugal	**0.87***	2.590	−5.9	−0.528	−0.53	−2.020	−0.34	−0.067	1.62	1.750	−6.05	−0.202
Spain	**1.12***	2.930	7.58	1.520	0.16	0.562	0.42	0.167	**2.64****	3.030	**−45.49***	−2.090
Bulgaria	−0.21	−0.611	3.54	0.894	0.027	0.278	−0.44	−0.720	0.026	0.134	1.98	2.010
Croatia	0.44	1.360	1.85	0.649	0.11	0.740	0.66	0.547	0.65	1.140	−0.78	−0.133
Cyprus	0.44	2.770	0.63	0.435	−0.025	−0.225	0.63	0.490	0.097	0.220	4.18	0.530
Czechia	0.19	1.840	1.78	1.970	−0.06	−0.684	−0.04	−0.119	0.23	0.570	14.86	1.720
Denmark	−0.03	−0.082	1.17	0.215	0.11	0.714	−0.56	−0.720	−0.15	−0.121	20	0.545
Estonia	−0.29	−1.020	2.58	1.400	−0.14	−0.960	−0.25	−0.300	−0.28	−0.640	7.56	1.370
Greece	0.21	0.970	0.28	0.130	**−0.36****	−3.150	−0.81	−0.650	0.48	1.750	2.47	0.551
Hungary	0.26	1.450	2.17	1.330	**0.029***	0.526	−0.41	−2.090	−0.15	−0.350	**19.71***	2.140
Latvia	**−0.27***	−2.120	**4.3****	3.380	−0.01	−0.105	2.14	1.180	**−0.42***	−2.620	**6.34***	2.930
Lithuania	−0.39	−0.985	2.42	1.030	0.059	0.231	−2.37	−1.010	−0.24	−0.560	**9.33***	2.320
Luxembourg	−0.07	−0.520	1	1.090	0.01	0.312	0.24	1.710	−0.29	−0.820	7.72	0.970
Malta	−0.37	−0.440	−1.76	−0.240	−0.005	−0.020	0.33	0.670	1.16	0.652	−28.05	−1.280
Poland	−0.28	−0.510	−0.47	−0.080	−0.0074	−0.058	0.026	0.016	1.9	0.578	−17.9	−0.520
Romania	0.068	0.800	**−4.36****	−5.640	−0.11	−0.920	−0.99	−1.810	−0.02	−0.105	2.31	0.855
Slovakia	0.17	1.700	0.41	0.720	0.03	−1.010	−0.08	−0.419	−0.04	−0.130	7.01	1.530

Table 4 (continued)

Country	dif_lnIND_1		dif_lnIND^2_1		dif_lnAGRI_1		dif_lnAGRI^2_1		dif_lnSERV_1		dif_lnSERV^2_1	
	Coeff	tvalue	Coeff	tvalue	Coeff	tvalue	Coeff	tvalue	Coeff	Tvalue	Coeff	tvalue
Slovenia	**0.7****	3.180	**4.7***	2.570	0.63	2.090	−1.23	−1.110	−0.09	−0.108	10.26	0.504
Sweeden	−0.06	−0.391	3.43	1.610	0.02	0.080	−1.74	−0.362	−2.1	−0.970	40.73	0.750

The table shows the coefficient and below in parentheses standard error. (**) is significant at 1% and (*) at 5%. Dif represents the first difference; ^{2} the squared variable; _1 represents the number of lags considered by the variables

Industry gross value added was significant for explaining GHG emissions in 7 countries: Ireland, the Netherlands, Portugal, Spain, Latvia, Romania, and Slovenia. These countries experienced a decreasing trend followed by a rise in the impact of sectoral economic growth in GHG emissions. This indicates an increment in the carbon intensity of the industry in the latter period, which is not necessarily motivated by a structural change in the industry. The weight of industry in the national economy is heterogeneous in these countries, ranging from 19 per cent of GDP in Portugal and Spain to 30 per cent in Romania in 2018. However, these countries show an increase in the weight of industry in the national economy since approximately 2013 (Eurostat, 2021), which is likely to drive the observed short term impact on national total GHG emissions.

Service value added was significant in 6 countries: Ireland, the Netherlands, Spain, Hungary, Latvia, and Lithuania. The major contribution of the service sector to some of these economies (Eurostat, 2021), together with the high energy intensity of the tourism sector (Pablo-Romero et al., 2021), might explain this relationship in the short term.

Agriculture value additions were significant in only three countries: Greece, Hungary, and the Netherlands. The significant weight of agriculture in the economy of these three countries is the only common ground for this relationship. The increasing agriculture emissions intensity after 2009 (Roinioti & Koroneos, 2017) could explain this relationship in the short term.

Table 5 shows the long-term results (α) using expression (7).

Long-term results were significant for any tested variable for 12 countries under study (Table 5). Short-term results were only confirmed in the long term for Romania (industry), Latvia (industry and service), and Spain (service). Therefore, the implications described below for the short-term relationship for the remaining countries can only be attributed to circumstantial factors. This points out the importance of considering the evolution of the economy as a basis for designing longstanding policies and plans aimed at reducing anthropogenic GHG emissions.

The study results indicate that sectoral economic growth is not significant in the long run for more than 50% of EU Member States. This suggests that most EU countries' economic characteristics, behavioural patterns, and mitigation efforts have drastically reduced the influence of sectoral economic growth on national GHG emissions. This finding is in line with Cohen et al. (2018), which found that EU countries tend to show a significant decoupling between trend emissions and trend GDP and for both production (industry-related emissions) and consumption (service-related emissions) activities. The author attributed this fact to the presence of underlying policy frameworks more supportive of renewable energy and climate change mitigation efforts.

Conversely, the results of our research contradict the findings of Sohag et al. (2019), Savona and Ciarli (2019), and Mardani et al. (2019), which pointed those mature economies (primarily service-oriented countries) had a more significant impact on GHG emissions with increasing temporal trends. Relevant exceptions consistent with these authors are identified in our study for several countries and economic sectors. The analysis by economic sector shows that the service and industry sectors, in this order, are the main ones responsible for the economic growth impact of GHG emissions in the long term in those countries where sectoral GDP is found to be significant.

Industry value added was significant for explaining GHG emissions in the long run in 6 EU-27 countries: Austria, Croatia, Czechia, Latvia, Luxembourg, and Romania. Overall, after the 2009 economic crisis, the EU industry has shown a smaller weight of energy-intensive branches and relevant energy efficiency improvements that have allowed a structural decoupling of energy consumption from production (Altdorfer,

Table 5 Long-term estimation results

Country	lnIND_1		$lnIND^2$_1		lnAGRI_1		$lnAGRI^2$_1		lnSERV_1		$lnSERV^2$_1	
	Coeff	t value	Coeff	t value	Coeff	t value	Coeff	t value	Coeff	t value	Coeff	t value
Austria	**−15.68***	−2.240	**−1.55***	−2.220	−56.07	−1.290	−3.61	−1.280	**−31.95****	−3.790	**−4.15****	−3.740
Belgium	−18.11	−1.080	−1.69	−1.080	−27.18	−1.450	−1.62	−1.430	−25.02	−1.810	−3.25	−1.790
Finland	−1.86	−0.730	−0.17	−0.710	−93.96	−1.410	−6.46	−1.400	−23.92	−1.820	−3.05	−1.800
France	1.25	0.080	0.11	0.099	63.21	1.470	2.82	1.470	**−43.39****	−3.230	**−5.5****	−3.220
Germany	4.45	0.660	0.45	0.670	−7.41	−1.430	−0.44	−1.420	0.49	0.118	0.11	0.220
Ireland	0.35	0.712	0.04	0.782	1.46	0.586	0.08	0.523	−2.02	−1.120	−0.25	−1.030
Italy	18.73	0.730	1.76	0.730	112.72	1.230	7.54	1.230	−75.64	−1.580	−9.36	−1.570
The Netherlands	−9.18	−0.604	−0.89	−0.605	24.63	1.060	1.69	1.070	−5.48	−1.170	−0.69	−1.120
Portugal	−42	−0.399	−3.59	−0.394	−89.21	−1.420	−5.65	−1.430	−24.56	−1.520	−2.64	−1.500
Spain	35.68	1.250	3.2	1.260	−13.49	−0.239	−0.91	−0.241	**−18.65***	−2.460	**−2.13***	−2.430
Bulgaria	−2.72	−1.020	−0.19	−1.050	7.66	0.688	0.47	0.696	**−7.73***	−2.880	**−0.66***	−2.920
Croatia	**−3.6****	−0.658	**−0.27****	−0.641	2.89	0.254	0.17	0.244	−8.26	−1.600	−0.77	−1.580
Cyprus	15.43	4.670	1.19	4.620	1.51	0.369	0.096	0.349	**−8.93***	−2.050	−1.02	−2.020
Czechia	**−4.11***	−2.890	**−0.35***	−2.810	−10	−1.080	−0.66	−1.100	−7.89	−1.590	−0.77	−1.550
Denmark	33.46	0.936	3.47	0.938	−10	−0.711	−0.69	−0.706	−11.82	−0.643	−1.57	−0.622
Estonia	3.25	1.020	0.24	0.975	0.38	0.060	0.015	0.046	3.89	0.800	0.37	0.764
Greece	−2.9	−0.390	−0.24	−0.390	2.98	0.196	0.18	0.184	−1.34	−0.260	−0.12	−0.226
Hungary	−2.09	−0.747	−0.16	−0.739	8.76	1.330	0.55	1.340	1.1	0.279	0.11	0.308
Latvia	**9.16***	2.570	**0.67***	2.520	−0.49	−0.213	−0.042	−0.293	**3.04***	2.190	**0.27***	2.120
Lithuania	0.87	0.550	0.058	0.480	7.03	0.467	0.44	0.464	1.22	0.791	0.1	0.694
Luxembourg	**8.74***	2.090	**0.85***	2.060	−2.43	−2.350	−0.15	−2.380	**−10.95***	−2.520	**−1.94***	−2.510
Malta	−14	−0.380	−3	−0.380	−2.71	−0.150	−0.17	−0.160	**−15.45 ***	−2.390	**−1.7***	−2.370
Poland	−3.87	−1.710	−0.3	−1.710	3.64	0.369	0.21	0.356	4.03	0.820	0.37	0.820
Romania	**−6.87****	−3.450	**−0.52****	−3.430	7.48	0.600	0.45	0.590	**−14.3***	−2.830	**−1.2***	−2.820
Slovakia	−1.44	−1.680	−0.1	−1.630	**−3.17****	−3.590	**−0.17****	−3.520	−5.57	−0.792	−0.51	−0.734

Table 5 (continued)

Country	lnIND_1		$lnIND^2$_1		lnAGRI_1		$lnAGRI^2$_1		lnSERV_1		$lnSERV^2$_1	
	Coeff	t value	Coeff	t value	Coeff	t value	Coeff	t value	Coeff	t value	Coeff	t value
Slovenia	−3.1	−1.070	−0.27	1.060	50.48	1.050	3.25	1.060	−7.58	−1.350	−0.79	−1.340
Sweeden	−0.72	−0.235	−0.08	−0.276	−44.64	−1.770	−2.96	−1.760	−14.65	−1.460	−1.9	−1.440

The table shows the coefficient and below in parentheses standard error. (**) is significant at 1% and (*) at 5%. Dif represents the first difference; ^{2} the squared variable; _1 represents the number of lags considered by the variables

2017). However, this is not the case for Austria, Croatia, Czechia, Latvia, and Romania, which show relevant changes in the composition of the industry towards more energy-intensive branches such as the food industry and the production of non-metallic minerals or primary metals (Eurostat, 2022). Carbon-intensive industry branches show employment levels well above the EU average in Austria, Croatia, Romania, and Czechia (Bissinger & Goosse, 2020; Eurostat, 2022). This also seems the reason for Luxembourg, with significant economic activity in those industrial branches. Nevertheless, the confidentiality of the data provided in its national statistics prevents a more detailed analysis of the structural drivers behind the impact of industrial value-added in Luxembourg. At the EU level, Industrial relocation to third countries is suggested as one of the main reasons behind the decoupling between energy consumption and industrial production in central European countries (Fan & Liu, 2021). Nevertheless, industrial relocation would not explain the results for the industry sector of countries such as Italy or Germany, with very significant activity levels for high carbon-intensive industries. Therefore, further research would be required to fully understand the GHG emission impact of industrial GDP in EU-27 countries.

Service value addition was significant in 9 countries: Austria, France, Spain, Bulgaria, Latvia, Luxembourg, Malta, and Romania. The economies of these countries have a major contribution from the service sector, and a significant increase in the contribution of the service sector to the total economy is observed in the period analysed (Luxembourg, Malta, and Latvia had the most significant increase in the contribution of the service sector of the countries analysed). Despite the improvement experienced in the last decade, the energy efficiency performance of these countries is weak compared to the EU average, especially in the transport sector (Odyssee-Mure, 2022). This, together with the rising contribution of the emissions of the transport and the building sectors, which are highly associated with the service sector, could also explain the high impact of service value added in these countries (UNFCCC, 2015). Future mitigation actions focussed on energy efficiency interventions in the transport and the buildings sector could provide the highest benefits in terms of GHG emission reduction in these countries.

Agriculture was tested positive in only one country, Slovakia. Overall, this indicates the reduced influence of agriculture GDP on the GHG emissions of the EU-27 countries. Agriculture is not, from a structural point of view, of the drivers of the long-term contribution from the EU to global GHG emissions.

Based on the results shown in Table 5, Fig. 1 shows the EKC shape in the EU-27 using long-term empirical results. The EKC showed various shapes for countries where the relationship between variables has been proved significant.

The results for Croatia (Industry), Cyprus (Service), Romania (Service), and Latvia (Industry and Service) confirmed the EKC theory, as the EKC formed inverted U shapes. Furthermore, despite not illustrating this pattern, the results obtained for Austria (Service), Czechia (Industry), and Luxembourg (Service) also validated the EKC theory, as economic growth shows a decreasing impact in the long term.

For those countries where sectoral GDP is not significant for explaining GHG emissions, we derive that sectoral GDP has been dissociated from GHG emissions, as it is not found to be statistically significant in the long term. For those countries, the EKC theory is indirectly confirmed, as the impact of sectoral GDP is not significant to explain the evolution of GHG emissions in the mature European economies, as theorized in the EKC framework. This finding is in line with the results of Dogan and Inglesi-Lotz (2020), which found that the EKC theory was confirmed at the aggregate level for EU countries but not when the different GDP components were analysed separately.

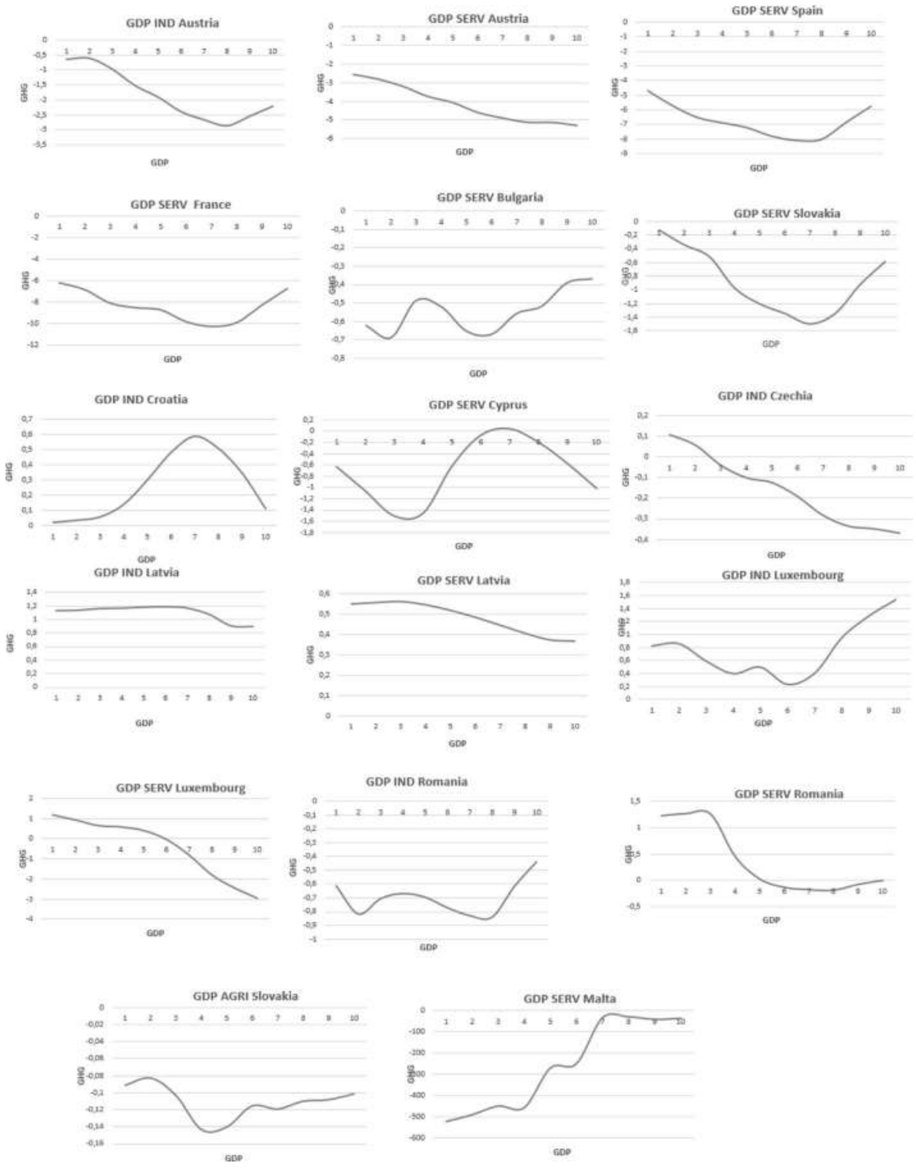

Fig. 1 Long-run Environmental Kuznets curve

The EKC shape obtained in this study for those countries not testing significant coefficients in the long-term show a relationship that is not statistically confirmed and therefore have not been reproduced in this paper. The below paragraphs provide a description of the various EKC shapes that have been confirmed empirically in the study, shown in Fig. 1. The description of the EKC shape is provided for comparative purposes, as the shape of the EKC is the object of study in numerous previous studies.

France had a significant relationship between service and GHG emissions that fitted into a U shape, with an increasing impact in the last three years of the sample. Equivalently, Austria (Industry and services), Romania (industry and services), and Slovakia (agriculture) showed U-shapes for the EKC relationship, displaying increasing trends in the last years of the sample.

Spain showed an N-shaped relationship for Industrial GDP and a U curve for services. Bulgaria's results for industry added value shaped an N curve with an increasing impact on GHG emissions in the latest period. Luxembourg showed an N-shaped relationship for Industrial GDP, while its services sector revealed a decreasing impact of added value in GHG emissions.

Croatia shaped an inverted U relationship for industry GDP, with a decreasing impact on economic growth after a period of incremental influence. Similarly, the EKC shapes for Cyprus's industry and services GDP could fit into an inverted U relationship.

The cases of Czechia (industry) and Latvia (industry and services) do not fit into EKC shapes but evidence an overall decreasing impact in terms of GHG emissions.

4.2 Robustness analysis

We analyse the robustness of the results by checking possible breaks in the time series used using the breakpoint Chow test. The estimate is performed through a bootstrap Chow test (Diebold & Chen, 1996) based on Eq. (7) starting in 1995, adding one additional year and contrasting significant variations in any year in estimated parameters for the sample.

The following Fig. 2 shows the bootstrap estimation against the 1 per cent critical value of the chow test finding potential breaks in the time series of France (GDP Industry in 2009 and GDP service 2009–2011) and Cyprus (GDP Agri 2015).

The break observed for Cyprus (GDP agriculture) is attributed to the short time series available for the country, as previously highlighted by Candelon and Lütkepohl (2001). To ascertain the existence of breaks in the two identified cases for France, we adjust the model used in our experiment, including a dummy representing the potential structural break identified in the Chow test. As shown in Table 6, this model's results are insignificant, proving the nonexistence of structural breaks in the time series.

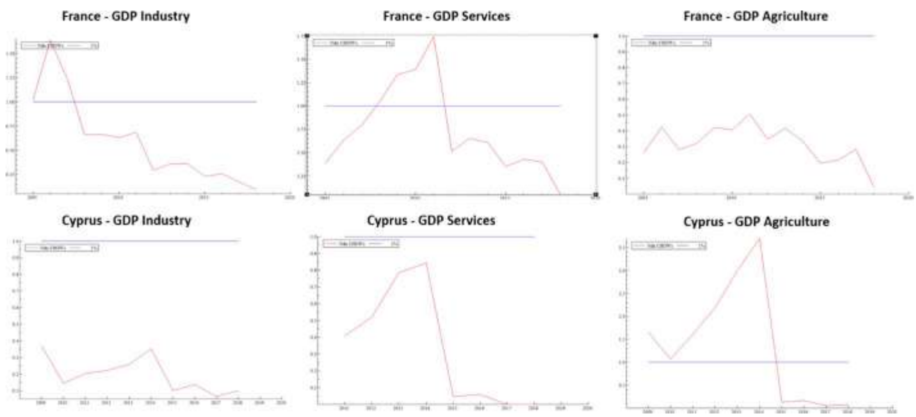

Fig. 2 Breakpoint Chow test results

Table 6 Results of parameters with dummy estimate (GDP industry and services per capita France)

Variable	Coefficient	SE	t-value	t-prob
Panel A. Industry				
Constant	14.36	34.69	0.00	0.000
lnGHG_1	0.98	0.06	14.90	0.683
lnIND_1	5.30	12.61	0.42	0.678
lnIND2_1	0.48	1.14	0.42	0.674
dif_lnIND_1	0.13	0.28	0.47	0.637
dif_lnIND^2_1	6.74	6.35	1.06	0.302
Dummy	0.005	0.005	0.98	0.339
Panel B. Services				
Constant	−53.40	20.12	−2.65	0.001
lnGHG_1	−0.41	0.14	−2.78	0.012
lnServ_1	−26.01	9.90	−2.63	0.016
lnSERV^2_1	−3.28	1.25	−2.61	0.017
Diff_lnSERV_1	−0.054	0.54	−0.10	0.921
Diff_lnSERV^2_1	14.73	23.47	0.62	0.537
Dummy	−0.011	0.01	−0.81	0.424

5 Conclusions

Economic activity and GHG emissions are intrinsically connected. Understanding the nature of this relationship is essential to ensure sustainable development and meet the decarbonization objectives of the Paris Agreement. This article explores the relationship between economic growth and GHG emissions in the EU-27 using the sectoral composition of GDP and national total GHG emissions for 1990–2018. The analysis is framed under the EKC theory, which states that after a certain amount of economic growth, its effect on the environment decreases. This study is the first to analyse the EKC for each of the EU-27 countries, taking into account the sectoral GDP for the industry, service, and agricultural components of the economy in a comprehensive manner, overcoming one of the main limitations identified in the bibliography, related to the use of total GDP series that do not consider the evolution of the three productive sectors. Furthermore, this study employed audited GHG data from the UNFCCC on national total GHG emissions, providing an added value to the analysis compared to other studies that limited the analysis to CO_2 data derived from unreviewed sources.

The EKC theory has been only confirmed statistically in 5 countries. However, more than half of the EU-27 countries do not have a statistically significant relationship between sectoral GDP and GHG emissions, implying that economic growth in those mature economies has a lowering impact on the environment, as theorized by the EKC. The assessment of this study's short- and long-term findings indicates that short-term analysis could lead to inaccurate findings and conclusions. The findings obtained in the short-term analysis were not confirmed in the long term, suggesting that non-structural drivers drove the impact of sectoral economic growth. Using extended periods in analysing the impact of economic growth is recommended to avoid biased conclusions driven by circumstantial factors and to design longstanding policies and plans aimed at reducing anthropogenic GHG emissions.

The analysis by economic sector reveals that the service and industry sectors, in this order, are primarily responsible for the impact of economic growth in GHG emissions in the long term in those countries where sectoral GDP is found significant. For the industry sector, a composition that favoured carbon-intensive industry branches, such as the production of non-metallic minerals or primary metals, is the fundamental cause of industrial GDP's observed high impact on national total GHG emissions. A high impact on GHG emissions has been observed in the service sector of those countries that combined a high share of services in the national economy and a combination of high GHG emissions and weak energy efficiency performance in the transport and building sectors. In terms of the agricultural sector, the analysis of economic growth in the sector showed impact on GHG emissions in only one country, indicating a weakened correlation between agricultural GDP and GHG emissions across EU-27 countries. From a structural standpoint, agriculture is not identified as a significant driver behind the EU's ongoing contribution to global GHG emissions. In view of these findings, countries that are dedicated to aligning with the objectives of the Paris Agreement would be wise to integrate these insights into their policy frameworks. An essential policy implication of this study is that EU-27 countries should conscientiously assess the specific national impact of sectoral economic growth on their national total GHG emissions. This consideration is pivotal for countries aiming to implement highly efficient GHG mitigation strategies that simultaneously foster sectoral economic growth. Accordingly, placing primary emphasis on mitigation measures in the agriculture sector would prove to be the less efficient approach—resulting in a lower impact on economic growth's influence on GHG emissions—for most EU-27 nations. Turning to the service sector, sectoral economic growth necessitates concomitant deployment of robust energy efficiency measures in transportation and building sectors to avoid increasing GHG emissions in the long term. This approach is imperative to counteract the substantial GHG emission impact observed in this study. For EU countries pursuing industrial development policies, the implementation of incentives aimed at promoting the adoption of low-carbon technologies or engagement in less carbon-intensive industrial sectors is highly recommended.

One limitation of the current study is the time sample that could be expanded in the future to include more years in the analysis. The current sample covers 1990–2018, the most extensive data available that met the criteria of consistency of time series, ensuring the data were derived using the same methodology and nomenclature. The conclusions obtained in the current analysis should be ascertained in the future when extended time series are available. Another limitation of the study was the data confidentiality for disaggregated economic indicators at the country level, which has prevented obtaining homogenous information for all countries under analysis. Previous research highlighted one fundamental limitation in the EKC framework whether the GDP-series captures the transition of production to the three productive sectors in empirical estimations and whether services are less polluting compared to industry activities. This study has overcome this limitation by considering the three GDP components separately. However, the industrial relocation of industries is not captured under the analysis and could be one of the drivers of the EU industry reducing its GHG emissions. Further research in this area could enhance the understanding of the role of industrial relocation in the evolution of the GHG emission of EU-27 countries.

The dissociation between GHG emissions and sectoral economic growth found in this study requires future analysis at the country and sector level to ascertain the decoupling between variables and the detailed reasons for such deviation. Further analysis could also be envisaged to explore further the reasons for the high impact encountered in the industry sector of Austria, Croatia, Czechia, Latvia, Luxembourg, and Romania. The composition of the industry of these countries could be reasons for such impact; however, a cross-country comparison with other neighbouring countries also having high energy-intensive industry branches (such as Italy or Germany) could provide further clarity on the reasons for such impact. Likewise, further analysis could be also envisaged to explore the reasons for the high GHG emission intensity in the service sector of Austria, France, Spain, Bulgaria, Latvia, Luxembourg, Malta, and Romania.

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Declarations

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