

# European CO<sub>2</sub> emissions persistence Analysis. A comparative IPCC contributor study with fractional integration

Ana María Molleda<sup>a</sup>, Miguel A. Martín-Valmayor<sup>b,c,\*</sup> , Juan Infante<sup>a</sup>

<sup>a</sup> Universidad Villanueva, Madrid, Spain

<sup>b</sup> Francisco de Vitoria, Madrid, Spain

<sup>c</sup> Universidad Complutense, Madrid, Spain

## ARTICLE INFO

Handling Editor: Mark Howells

JEL classification:

C22

C32

Q01

Q52

Keywords:

Pollutants

Europe

CO<sub>2</sub>

Time trends

Long memory

Fractional integration

## ABSTRACT

This paper investigates the persistence of CO<sub>2</sub> emissions in the largest European economies (Germany, France, Italy, Spain, and the Netherlands) from 1970 to 2023 by using a fractional integration framework. With this purpose, we contribute to the existing literature by investigating two research questions. First, to assess persistence in the specific subsectors, organized by Intergovernmental Panel on Climate Change (IPCC) standard categories; and second, to study their cross-country and cross-sectoral long-term and short-term relationships. The main findings suggest clear evidence of persistent patterns in emissions and their associated components, with a significant negative trend in all cases except France. Regarding the relationship between crossed components, we find evidence that transportation and industry demonstrate a high degree of correlation, yet no evidence of cointegration is observed. Conversely, waste shows a high level of cointegration across countries but no correlation. We find different patterns for the remaining components, with no discernible relationship observed across sectors within a single country or across different countries for the same sector. These findings suggest that despite the EU's substantial commitment to reducing carbon emissions, there appears to be no coordinated strategy across the different countries to fully implement these policies.

## 1. Introduction

Emissions and the resulting greenhouse effect are major drivers of climate change, entailing serious health impacts [1] and extreme events such as heat waves, floods, and wildfires. The global climate crisis has brought greenhouse gas (GHG) emissions to the forefront of environmental and policy concerns, with the European Union (EU) playing a key role in the fight against climate change. As the global community grapples with the urgent need to reduce emissions and mitigate the impacts of global warming, understanding the dynamics of greenhouse gas (GHG) emissions in major European economies has become increasingly crucial. The present study aims to contribute to the existing body of knowledge by focusing on five of the EU's largest economies in terms of GDP: Germany, France, Italy, Spain, and the Netherlands, spanning from 1970 to 2023.

The trajectory of climate change mitigation efforts in Europe can be traced back to the 1997 Kyoto Protocol, a significant milestone in the international climate policy. Since then, the EU has implemented a series of ambitious climate initiatives, including the European Climate Change Program (ECCP) in 2000 and the European Emissions Trading Scheme (ETS) in 2003 with national emission caps from power and industry sectors (Directive 2003/87/EC [2]). The EU's climate ambitions gained further momentum with the 2008 Climate and Energy Package, which introduced the “20-20-20” targets. These aimed for a 20 % reduction in greenhouse gas emissions and a 20 % share of renewable energy usage by 2020 [3]. These measures proved remarkably effective, with the EU achieving a 34 % reduction in GHG emissions by 2023 compared to 1990 levels [4].

The 2015 Paris Agreement further galvanized global climate action, prompting the EU to set even more ambitious targets. The European

Miguel A. Martín-Valmayor and Juan Infante gratefully acknowledge financial support from the Grant UFV 2025–28 funded by the Instituto de Investigaciones Económicas y Sociales (IIES) from the Universidad Francisco de Vitoria (UFV). Comments from the Editor and the five anonymous reviewers are gratefully acknowledged.

\* Corresponding author. Universidad Francisco de Vitoria, Facultad de Derecho, Empresa y Gobierno; Pozuelo de Alarcón, E-28223, Madrid, Spain.

E-mail addresses: [ana.molleda@villanueva.edu](mailto:ana.molleda@villanueva.edu) (A.M. Molleda), [miguel.martin@ufv.es](mailto:miguel.martin@ufv.es), [mamart02@ucm.es](mailto:mamart02@ucm.es) (M.A. Martín-Valmayor), [juan.infante@villanueva.edu](mailto:juan.infante@villanueva.edu) (J. Infante).

<https://doi.org/10.1016/j.esr.2025.101986>

Received 21 April 2025; Received in revised form 23 October 2025; Accepted 17 November 2025

Available online 25 November 2025

2211-467X/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Commission's 2030 framework aimed for a 40 % reduction in greenhouse gas emissions and a 27 % share of renewable energy usage compared to 1990 levels, with the goal of achieving climate neutrality by 2050 [5]. Member States, including Germany, have set even more ambitious targets, aiming for carbon neutrality before 2050 and a 65 % reduction in GHG emissions.

Persistence is a very important topic when evaluating emissions, as the presence of a stable mean or mean reverting behaviour would indicate that short-term measures could be more effective in tackling emissions. However, identifying a persistent behaviour would demonstrate the effectiveness of long-term interventions in reducing such emissions. Furthermore, the persistence pattern would suggest that it would not be possible to make an accurate forecast of the emissions subsequent values by relying solely on previous figures. This fact emphasizes the need for advanced econometric methods when modelling such emissions. For instance, standalone short-term policies may encompass taxes and emissions trading systems, while long-term policies may include the promotion of sustainable practices and energy efficiency, including the introduction of green energy, reforestation, or investment in carbon capture systems [6].

As most of the related studies dealing with the persistence of CO<sub>2</sub> emissions have analyzed data from a country perspective ([7–13] or [14] among others), we aim to contribute to such studies by disaggregating persistence results with a cross-sectorial perspective. Consequently, two research questions can be formulated. First, if the CO<sub>2</sub> emissions disaggregated by Intergovernmental Panel on Climate Change (IPCC) standard categories are persistent or not; and second if there were any form of internal policy coordination and across countries or industries.

Therefore, major conceptual innovations are twofold. First, we focus on a sector-specific framework for diagnosing emissions persistence. This will enable us to identify sector-specific patterns that may be overlooked by country-level analyses. To this end, we will analyze emissions, focusing on their specific impact. Emissions will be categorized according to the IPCC standard. Second, to improve our understanding of the complex emission dynamics and policy effects within the EU, we will analyze potential cross-relationships across countries and sectors to assess internal policy coordination and dependencies. For this study, we will examine short- and long-term relationships between countries and sectors. These empirical results will enable us to evaluate the design and implementation of EU policies in recent years.

For this purpose, we will examine the persistence and mean reversion properties of greenhouse gas (GHG) emissions since 1970 in the largest EU economies, disaggregating such results by IPCC category. From a methodological perspective we will use a fractional integration framework. This is a more general methodology than standard models based on traditional unit root tests. Those tests rely on the dichotomy between stationary and nonstationary series. It allows the integration parameter to take any real value, including fractional ones, as opposed to only integers. Consequently, the integration factor can be utilized as a metric to assess the degree of persistence, thereby providing valuable insights into the mean reversion properties of the series. Additionally, we will examine crossed sectoral relationships, looking for long-term cointegration relationships across different countries and IPCC contributors to evaluate the potential policy relationships.

Therefore, this research is expected to make several important contributions to the field of climate policy and emissions analysis. By examining the persistence and mean reversion properties of CO<sub>2</sub> emissions, the study will provide empirical evidence on the success of different climate policies recently implemented in the EU. The analysis of emissions across different IPCC segments will provide valuable insights into which sectors have been most responsive to policy interventions and which may require additional efforts, while the correlation results will provide additional information on the level of coordination between different countries and sectors. By providing a detailed assessment of sectoral emission trends and policy effectiveness,

the study aims to inform the design of more targeted and effective climate change mitigation strategies. As the EU continues to pursue its ambitious climate change goals, the insights provided by this research will be crucial in guiding future policy decisions and ensuring that emission reduction efforts are consistent with IPCC commitments and long-term sustainability goals. Nevertheless, this paper has some limitations that can guide future research. In particular, we have limited the crossed coordination relationships by groups and studied these relationships in isolation for each group to make the paper easier to understand. Thus, the structure of this paper is as follows: Section 2 presents the literature review; Section 3 is devoted to the methodology; Section 4 describes the data used and the empirical results obtained; and finally, Section 5 concludes the manuscript with the main implications of this study and future lines of research.

## 2. Literature review

Several studies have examined the trends and underlying drivers of greenhouse gas (GHG) emissions in Europe. Bhattacharyya and Matsu-mura [15] used a decomposition analysis approach to examine changes in GHG emission intensity in EU-15 countries, highlighting the role of energy efficiency improvements, structural changes in the economy, and shifts in the energy mix as key determinants of emission intensity. More recent cross-country analyses have further emphasized the impact of economic development, energy efficiency, and trade on national carbon emissions [16,17].

Lapinskiene et al. [18] explored the complex relationship between economic development and GHG emissions in EU countries, shedding light on potential trade-offs and synergies between economic growth and environmental sustainability. They emphasized the need for a balanced approach to address both objectives, a point also made by other global studies underscoring the importance of coordinated policy efforts to meet international climate targets [19]. Andrés and Padilla [20] investigated the drivers of GHG emissions in the EU transport sector. Their findings revealed the impact of factors such as economic growth, population density, and modal shift on transport-related emissions. Similar relationships between economic development and emissions have been observed in other regions, such as South Asia, where green technology and energy efficiency are essential for mitigating climate change [17].

Given the diverse nature of economic activities and their varying contributions to greenhouse gas (GHG) emissions, sectoral analyses have been a focal point in the emissions literature. Lamb et al. [21] conducted a comprehensive review of trends and drivers of GHG emissions by sector and region (1990–2018), providing a very valuable insight into the evolving emission patterns across various economic activities and continents. Focusing on specific sectoral papers in the EU, Robaina-Alves and Moutinho [22] examined energy-related GHG emissions in agriculture (1995–2008) looking for the emission drivers within this sector. Simionescu et al. [23] explored GHG emissions mitigation in the EU based on labour market changes, looking for potential synergies between employment policies and environmental objectives. Mielcarek-Bocheńska and Rzeźnik [24] focused specifically on greenhouse gas emissions from agriculture in EU countries, examining the current state and future perspectives. Parravicini et al. [25] turned their attention to the urban wastewater sector, exploring options for reducing emissions and the potential for implementing targeted mitigation measures. Martín-Ortega and González-Sánchez [26] conducted an empirical analysis of the sectoral composition of GDP, highlighting the varying emission intensities of different economic sectors. The emergence and diffusion of climate-related financial policies, such as those examined by D'Orazio [27] in G20 countries, underscore the importance of policy innovation and diffusion for effective mitigation.

Precisely in terms of mitigation strategies and policy implications for reducing greenhouse gas (GHG) emissions in the European Union (EU), Clarkson et al. [28] examined the valuation framework for GHG

emissions under the EU Emissions Trading Scheme, a key policy for regulating and incentivizing emission reductions. Hof et al. [29] analyzed the EU's 40 % GHG emission reduction target for 2030, considering its implications and feasibility. Moro and Lonza [30] analyzed the impacts of electricity carbon intensity in EU from electric vehicles, providing valuable insights of transitioning to electric mobility and decarbonizing the electricity generation sector. Akdag and Yıldırım [31] explored energy efficiency improvements to curb emissions in European countries. Jäger-Waldau et al. [32] investigated the role of photovoltaics in achieving the EU's ambitious target of reducing greenhouse gas (GHG) emissions by 55 % by 2030, demonstrating the potential of renewables in decarbonizing the energy sector and contributing to emission reductions. Cucchiella et al. [33] offered future estimates of GHG emissions in Europe, emphasizing the need for a co-ordinated approach to effectively mitigate those emissions. Gavurova et al. [34] examined the relationship between greenhouse gas (GHG) emissions and health in the European Union (EU), highlighting the need for a comprehensive approach considering the interconnected nature of environmental, economic, and social factors. Additional policies have also been proposed as part of a broader mitigation portfolio, including innovative carbon removal technologies, such as industrial biochar systems [35], and market integration and price collar proposals [36]. The political economy of climate finance and overseas investments, particularly from emerging economies such as China, is also recognized as a key factor in shaping global mitigation outcomes [37].

Nowadays, persistent sectoral and national disparities, data inconsistencies, and emerging policy and market influences continue to shape European CO<sub>2</sub> emissions. The lack of harmonisation between land use data and Paris-aligned benchmarks not only undermines international stocktakes, but also creates significant discrepancies between national ambitions and modelled climate trajectories [38]. Region-specific factors drive highly differentiated transport emissions pathways in Central Europe, where economic structure and policy both foster progress and perpetuate challenges, particularly in countries such as Austria and Poland [39]. Alongside regional and sectoral divides, energy uncertainty and geopolitical tensions have measurable impacts: energy volatility tends to raise emissions, while major geopolitical rifts can reduce them by restructuring trade and investment flows [40]. The emissions intensity of different energy sources varies widely across EU clusters. Fossil fuels consistently contribute to higher CO<sub>2</sub> output, while biofuels and some renewables show mitigation potential, albeit with mixed effectiveness [41]. At the intersection of innovation and policy, digitalization targeted small and medium enterprises initiatives to drive emission reductions. However, certain research and development and broadband investments paradoxically increase sectoral emissions, illustrating the context-dependent nature of technological progress [42]. Crucially, the persistence of emissions in major EU economies, especially in transport and industry, reflects inadequate long-term policy coordination and limited mean reversion. This signals the need for more integrated mitigation strategies to shift these entrenched trends [43].

Furthermore, other authors have also studied the effect of economic progress, intensified energy use and renewable energy use on the annual growth rates of per capita carbon dioxide emissions in highly polluted economies [44]. This confirms that economic progress deteriorates environmental quality in both the short and long term. However, as the long-term adverse environmental effects of economic growth are relatively lower than the short-term effects, the Environmental Kuznets Curve (EKC) hypothesis can be considered valid. This relationship has also been studied in the context of the Middle East, revealing that trade liberalisation and remittance inflows can support economic growth [45]. Other studies have examined the positive correlation between women's labour participation, income, and energy intensity [46], as well as the beneficial impact of the financial sector on environmental performance [47].

With respect to the persistence study of greenhouse gas (GHG) emissions, some studies used unit root testing. Jaunky [48] conducted

an analysis of 36 high-income countries (1980–2005), employing augmented Dickey–Fuller (ADF) unit root testing [49,50]. The findings indicated that a total of 12 countries were found to be in accordance with non-stationary data. Christidou et al. [7] examined the stationarity of CO<sub>2</sub> emissions per capita for a global sample of 36 countries (1870–2006) using nonlinear unit root tests, concluding that stationarity is more likely in wealthy countries that have outsourced some of the emissions-intensive industries. Li et al. [51] conducted a study of 50 U.S. states (1990–2010) employing the augmented Dickey–Fuller ADF [49, 50], the PP [52] and the KPSS [53] tests. The findings indicated the presence of unit roots in the majority of the 50 U.S. states. Tiwari et al. [54] examined CO<sub>2</sub> emissions per capita for 35 countries in sub-Saharan Africa from 1960 to 2009 using nonlinear unit root tests. Their findings indicated evidence of the stationarity hypothesis for developing countries. Yilanci and Pata [55] used Lagrange multiplier (LM) tests to analyze the ecological balance (1961–2016), finding evidence of mean reversion behaviour in the US, Germany and Italy. Pata and Yilanci [56] used a Fourier quantile test that allows nonlinearities and smooth structural changes for a similar sample, finding now nonstationary behaviour in the US, while confirming stationarity in Germany, Italy, and the Netherlands. Pata and Aydin [13] used a wavelet-based non-linear unit root test to investigate the per capita CO<sub>2</sub> emissions (1868–2014) for the G7 countries, finding evidence of unit roots for all countries. Finally, Solarin et al. [57] investigated the persistence of potential shocks to non-methane volatile organic compounds (NMVOC) between 1820 and 2019, comparing traditional unit root approaches and Fourier quantile unit root test, finding evidence of quite different results between these methods. In particular, empirical results of Fourier tests show stationarity in five additional countries that traditional root tests consider non-stationary. This indicates that non-methane volatile organic compounds (NMVOCs) emissions tend to follow a stationarity process in the long term in developed countries. This result underscores the significance of non-linearities in understanding emissions behaviour when employing linear methods.

In fact, econometric literature has observed that these traditional statistical tests may be unreliable in the range of  $0.5 < d < 1$  [58,59]. More recently, Caporale and Gil-Alana [60,61] proposed that in that range, series might be nonstationary but fractionally integrated  $I(d)$ , exhibiting slow mean reversion properties. In such cases, fractional integration provides a more suitable framework because unit root tests may conclude that these series are non-mean reverting  $I(1)$  when, in reality, they follow a slow mean-reverting pattern as  $0.5 < d < 1$  and is close to one.

In the context of CO<sub>2</sub> emissions studies with a fractional integration framework, Gil-Alana et al. [9] analyzed the BRICS and the G7 over the past 150–250 years, finding evidence of substantial disparities associated with the levels of industrialization. With the exception of Germany, the US and the UK ( $0.5 < d < 1$ ), integration factors observed were equal to or greater than one. Gil-Alana and Trani's [10] study, which focused on the EU, China, and the US from 1960 to 2013, identified unit roots ( $d = 1$ ) or  $d > 1$  behaviour in all countries except the UK. In a subsequent paper, Gil-Alana and Monge [62] examined global CO<sub>2</sub> emissions from 1880 to 2015, finding evidence of a  $d > 1$  value across the entire period. Claudio-Quiroga and Gil-Alana's [63] paper analyzed G7, EU27, and BRICS countries using daily samples during the period of the COVID-19 pandemic, with evidence of slow mean reversion ( $0.5 < d < 1$ ) across all countries. Infante et al. [14] analyzed Europe, the BRICS countries, the US, and Japan with monthly data (2000–2010 and 2010 to 2022 subperiods). The authors found evidence of slow mean reversion across all countries ( $0.5 < d < 1$ ) with lower values in Germany ( $0 < d < 0.5$ ). Finally, Solarin et al. [6] examined long-term black carbon emissions in the EU (1820–2019), finding evidence of high levels of persistence in most countries and slow mean reversion behaviour ( $0.5 < d < 1$ ) in only five out of 27 countries.

Fractional integration methods have also been applied to CO<sub>2</sub> emissions time series in Latin America, revealing similar patterns of

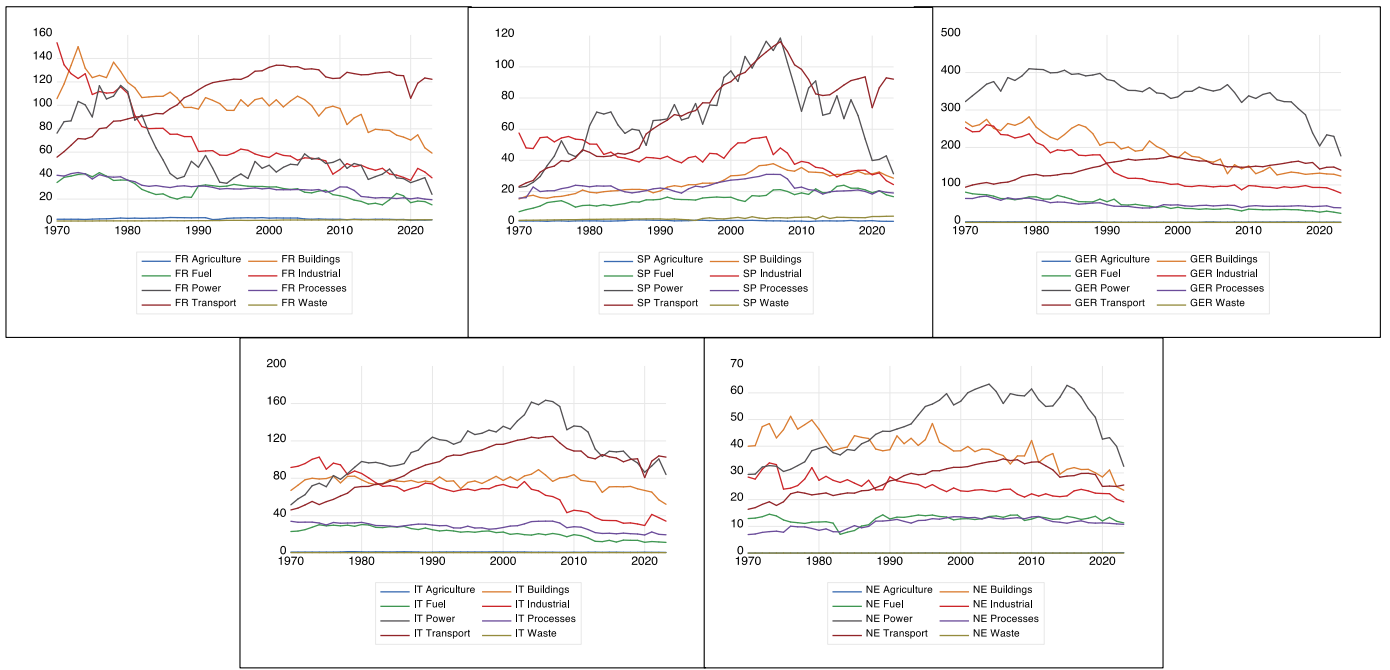


Fig. 1. Descriptive plots of the emissions for the countries and sectors under study.

persistence and mean reversion [64]. Reference forecasts for worldwide CO<sub>2</sub> emissions using ARFIMA models further emphasize the national dimension of policy efforts to meet IPCC targets [19]. The intersection of energy security, poverty alleviation, and climate change is increasingly recognized as a critical policy nexus, particularly in Asian economies [65].

### 3. Methodology

Univariate time-series models are a class of specifications in which we can model and predict variables using only the information contained in their past values, as well as the current and past values of an error term, if applicable [66]. Time series models are typically empirical in nature, aiming to capture the salient features of the observed data. One such feature is stationarity, which is defined as having a constant mean, variance, and autocovariance. Consequently, when a shock arises in a stationary series, its effects gradually dissipate. This is in contrast to non-stationary data, where the effects of shocks persist indefinitely. The aim of analysing the stochastic properties of the time series is to ascertain this duality. One potential method of identifying this duality is through unit root testing ([49,52,53], etc.), in which series are directly tested for stationarity. However, within a fractional integration framework, we are able to estimate the integration factor  $d$  directly. The persistence of the time series is then evaluated depending on its value. Thus, fractional integration provides a more flexible and accurate analysis because it allows  $d$  to take on any real value instead of returning dual results as in unit root testing.

Therefore, a stochastic process  $\{x(t), t = 0, \pm 1, \dots\}$  is defined as a stationary covariance with mean  $\mu$  and integrated of order 0, if the infinite sum of their autocovariances, defined as  $\gamma(u) = E[(x(t) - \mu)(x(t+u) - \mu)]$  are finite. That is,  $\sum_{u=-\infty}^{\infty} |\gamma(u)| < \infty$ . These types of processes, denoted as  $I(0)$  are also known as short memory, and may include white noise processes and also stationary and invertible autoregressive moving average (ARMA) models, which are the most common stationary time series. Conversely, a process exhibits long memory if the infinite sum of its autocovariances is also infinite.  $\sum_{u=-\infty}^{\infty} |\gamma(u)| = \infty$ . In this case, past observations are relevant for future observations, as there is a certain dependence on past observations.

Similarly, a process is said to be integrated of order  $d$  and similarly denoted by  $I(d)$ , if it requires  $d$  time differences to become an  $I(0)$  process, that is  $(1 - B)^d x_t = u_t$ , with  $t = 0, \pm 1, \dots$  and  $B$  the lag or backshift operator with  $B(x_t) = x_{t-1}$ . This  $d$ -value is called the integration factor and can be any integer or fractional value. That's why the estimation of this parameter is called fractional integration.

Therefore, processes that have this  $d$ -value larger than 0 are known as long-memory due to the dependence between distant observations in time. This backshift operator in  $B$  can also be expressed from its binomial expansion, such that, for any real  $d$ :

$$(1 - B)^d = \sum_{j=0}^{\infty} \binom{d}{j} (-1)^j B^j = 1 - dB + \frac{d(d-1)}{2} B^2 - \dots \quad (1)$$

which would mean that in the specific case of  $(1 - B)^d x_t$ , we have

$$(1 - B)^d x_t = x_t - dx_{t-1} + \frac{d(d-1)}{2} x_{t-2} - \dots \quad (2)$$

Consequently, in the context of environmental time series, where policy interventions may result in gradual rather than instantaneous changes in persistence properties, the  $d$ -value may assume a significant role. This is because it can serve as a metric for the degree to which the series exhibits persistence ([67–69], etc.). The larger  $d$  is, the greater the degree of dependence between observations.

- $d = 0$  would imply a short memory process or white noise
- $0 < d < 0.5$  characterizes a long memory process with stationary covariance and mean reversion properties
- $0.5 \leq d < 1$ , the series is non-stationary covariance although it is still mean-reverting but at a shorter pace, with shocks hyperbolically decay to zero
- $d \geq 1$  implies non-stationarity and lack of mean reversion properties

From a historical perspective, although fractional integration was already proposed in the early 1980s by Granger [70,71], Granger and Joyeux [72] and Hosking [73], it only became popular in economics and finance in the late 1990s and early 2000s ([74–76]; etc.). More recently, extensions of this methodology have also been applied in the study of the long-term behaviour of emissions ([9,10,14,62]; etc.). In general, the

**Table 1**  
Descriptive statistics of the countries and sectors under study.

| FRANCE        |             |           |       |            |        |         |           |       |
|---------------|-------------|-----------|-------|------------|--------|---------|-----------|-------|
|               | Agriculture | Buildings | Fuel  | Industrial | Power  | Process | Transport | Waste |
| Mean          | 3.19        | 101.29    | 27.71 | 70.24      | 58.43  | 29.75   | 110.24    | 1.80  |
| Median        | 3.04        | 102.52    | 28.25 | 58.91      | 49.43  | 29.03   | 121.75    | 1.79  |
| Maximum       | 4.19        | 150.09    | 42.53 | 153.41     | 117.02 | 42.60   | 134.22    | 2.48  |
| Minimum       | 1.92        | 59.17     | 15.04 | 35.89      | 23.94  | 19.44   | 55.73     | 1.23  |
| Std. Dev.     | 0.65        | 18.69     | 7.53  | 29.32      | 25.02  | 6.30    | 22.22     | 0.39  |
| Std. Dev/mean | 0.20        | 0.18      | 0.27  | 0.42       | 0.43   | 0.21    | 0.20      | 0.22  |
| Skewness      | −0.06       | 0.07      | 0.12  | 1.09       | 1.07   | 0.29    | −0.87     | 0.11  |
| Kurtosis      | 1.72        | 3.14      | 2.13  | 3.14       | 2.87   | 2.47    | 2.49      | 1.50  |
| Observations  | 54          | 54        | 54    | 54         | 54     | 54      | 54        | 54    |
| GERMANY       |             |           |       |            |        |         |           |       |
|               | Agriculture | Buildings | Fuel  | Industrial | Power  | Process | Transport | Waste |
| GERMANY       |             |           |       |            |        |         |           |       |
| Mean          | 1.05        | 194.56    | 48.03 | 143.96     | 346.67 | 49.23   | 144.82    | 0.17  |
| Median        | 1.09        | 193.34    | 42.85 | 109.36     | 351.31 | 45.36   | 148.70    | 0.18  |
| Maximum       | 1.68        | 281.84    | 80.80 | 261.02     | 410.06 | 70.48   | 177.66    | 0.21  |
| Minimum       | 0.29        | 123.63    | 24.07 | 78.28      | 177.56 | 38.39   | 94.13     | 0.03  |
| Std. Dev.     | 0.47        | 51.03     | 15.81 | 59.37      | 51.01  | 8.86    | 22.14     | 0.04  |
| Std. Dev/mean | 0.45        | 0.26      | 0.33  | 0.41       | 0.15   | 0.18    | 0.15      | 0.22  |
| Skewness      | −0.19       | 0.09      | 0.41  | 0.68       | −1.48  | 0.94    | −0.69     | −2.48 |
| Kurtosis      | 1.50        | 1.60      | 1.79  | 1.87       | 5.24   | 2.61    | 2.45      | 8.93  |
| Observations  | 54          | 54        | 54    | 54         | 54     | 54      | 54        | 54    |
| ITALY         |             |           |       |            |        |         |           |       |
|               | Agriculture | Buildings | Fuel  | Industrial | Power  | Process | Transport | Waste |
| ITALY         |             |           |       |            |        |         |           |       |
| Mean          | 1.07        | 75.90     | 21.90 | 65.27      | 110.68 | 28.24   | 93.42     | 0.45  |
| Median        | 1.04        | 76.98     | 22.76 | 68.85      | 109.00 | 29.22   | 100.82    | 0.45  |
| Maximum       | 1.52        | 89.25     | 30.57 | 102.75     | 163.42 | 34.19   | 124.73    | 0.54  |
| Minimum       | 0.78        | 52.28     | 11.44 | 29.48      | 51.62  | 19.34   | 46.22     | 0.39  |
| Std. Dev.     | 0.19        | 6.60      | 5.91  | 20.38      | 27.35  | 4.46    | 22.83     | 0.03  |
| Std. Dev/mean | 0.17        | 0.09      | 0.27  | 0.31       | 0.25   | 0.16    | 0.24      | 0.08  |
| Skewness      | 0.39        | −1.27     | −0.36 | −0.22      | 0.04   | −0.62   | −0.58     | 0.52  |
| Kurtosis      | 2.32        | 5.52      | 2.00  | 2.14       | 2.46   | 2.26    | 2.19      | 2.71  |
| Observations  | 54.00       | 54.00     | 54.00 | 54.00      | 54.00  | 54.00   | 54.00     | 54.00 |
| NETHERLANDS   |             |           |       |            |        |         |           |       |
|               | Agriculture | Buildings | Fuel  | Industrial | Power  | Process | Transport | Waste |
| NETHERLANDS   |             |           |       |            |        |         |           |       |
| Mean          | 0.03        | 39.05     | 12.60 | 24.87      | 47.79  | 11.15   | 27.24     | 0.01  |
| Median        | 0.03        | 39.04     | 12.91 | 23.94      | 47.83  | 11.64   | 28.63     | 0.01  |
| Maximum       | 0.18        | 51.24     | 14.53 | 33.77      | 63.27  | 13.73   | 35.31     | 0.01  |
| Minimum       | 0.01        | 23.54     | 7.03  | 19.18      | 29.44  | 6.96    | 16.39     | 0.00  |
| Std. Dev.     | 0.04        | 6.18      | 1.56  | 3.17       | 10.98  | 1.96    | 5.36      | 0.00  |
| Std. Dev/mean | 1.14        | 0.16      | 0.12  | 0.13       | 0.23   | 0.18    | 0.20      | 0.30  |
| Skewness      | 2.51        | −0.33     | −1.69 | 0.90       | −0.20  | −0.60   | −0.26     | −2.65 |
| Kurtosis      | 8.65        | 2.87      | 6.18  | 3.63       | 1.59   | 2.16    | 1.92      | 9.10  |
| Observations  | 54.00       | 54.00     | 54.00 | 54.00      | 54.00  | 54.00   | 54.00     | 54.00 |
| SPAIN         |             |           |       |            |        |         |           |       |
|               | Agriculture | Buildings | Fuel  | Industrial | Power  | Process | Transport | Waste |
| SPAIN         |             |           |       |            |        |         |           |       |
| Mean          | 1.24        | 25.92     | 15.75 | 43.07      | 67.59  | 22.58   | 70.87     | 2.68  |
| Median        | 1.18        | 25.35     | 15.52 | 42.35      | 67.05  | 21.76   | 75.32     | 2.45  |
| Maximum       | 1.78        | 37.89     | 24.03 | 57.61      | 118.44 | 31.00   | 116.12    | 4.22  |
| Minimum       | 0.77        | 15.21     | 7.05  | 24.45      | 22.70  | 15.79   | 23.32     | 1.45  |
| Std. Dev.     | 0.23        | 6.65      | 4.04  | 8.31       | 24.19  | 3.64    | 26.21     | 0.76  |
| Std. Dev/mean | 0.19        | 0.26      | 0.26  | 0.19       | 0.36   | 0.16    | 0.37      | 0.28  |
| Skewness      | 0.47        | 0.05      | 0.06  | −0.14      | 0.15   | 0.78    | −0.17     | 0.35  |
| Kurtosis      | 2.54        | 1.66      | 2.30  | 2.20       | 2.47   | 3.07    | 1.78      | 2.16  |
| Observations  | 54          | 54        | 54    | 54         | 54     | 54      | 54        | 54    |

most widely used method in the literature is the linear analysis  $y(t) = \alpha + \beta t + x(t)$ , with  $t = 1, 2, \dots$ , where  $x(t)$  is a process I(d) described as  $(1 - B)^d x_t = u_t$  under the assumption that the error term  $u(t)$  is a white noise process with no autocorrelation. Sowell [77] and Doornik and Ooms [78] provide detailed descriptions of the evaluation of this parameter under a maximum likelihood criterion for these models.

#### 4. Empirical results

The datasheet for this paper is built using data from the European

Commission, Joint Research Centre (EC-JRC)/Netherlands Environmental Assessment Agency (PBL) from the Emissions Database for Global Atmospheric Research (EDGAR) for the year 2024 [79]. Time series for CO<sub>2</sub> with yearly observations for the 1970–2023 period were chosen. The selected countries are the largest European countries in terms of GDP (Germany, France, Italy, Spain, and the Netherlands), and the studied components are IPCC sectors with a minimum weight of 1.5 % for total emissions, namely Agriculture, Buildings, Fuel, Industrial, Power, Processes, Transport, and Waste. Fig. 1 plots the different series under study organized by country, and Table 1 provides some descriptive statistics of the sample. It is evident that the values across the

**Table 2**  
Final estimations of the integration factor (d).

| Integration factor (d) estimations |             |                          |                            |                                                    |                |
|------------------------------------|-------------|--------------------------|----------------------------|----------------------------------------------------|----------------|
| Series                             |             | No terms                 | An intercept (t-statistic) | An intercept and a linear time trend (t-statistic) | Standard error |
| <b>FRANCE</b>                      |             |                          |                            |                                                    |                |
| <b>Total emissions</b>             | <b>I(1)</b> | <b>1.02 (0.81, 1.22)</b> | —                          | —                                                  | <b>0.105</b>   |
| Agriculture                        | I(d)        | 0.63 (0.37, 0.89)MR      | 0.08 (1.69)                | −0.00 (−2.14)                                      | 0.132          |
| Buildings                          | I (1)       | 0.93 (0.76, 1.09)        | —                          | —                                                  | 0.084          |
| Fuel                               | I (1)       | 1.07 (0.76, 1.38)        | —                          | —                                                  | 0.157          |
| Industrial                         | I (1)       | 1.17 (0.95, 1.38)        | —                          | —                                                  | 0.110          |
| Power                              | I (1)       | 0.95 (0.71, 1.19)        | —                          | —                                                  | 0.122          |
| Processes                          | I (1)       | 1.03 (0.84, 1.23)        | —                          | —                                                  | 0.099          |
| Transport                          | I (1)       | 1.11 (0.98, 1.24)        | —                          | —                                                  | 0.065          |
| Waste                              | I (0)       | 0.98 (0.85, 1.11)        | —                          | —                                                  | 0.068          |
| <b>GERMANY</b>                     |             |                          |                            |                                                    |                |
| <b>Total emissions</b>             | <b>I(1)</b> | <b>1.05 (0.86, 1.24)</b> | —                          | —                                                  | <b>0.096</b>   |
| Agriculture                        | I(d)        | 0.84 (0.46, 1.22)        | −0.02 (−0.79)              | —                                                  | 0.194          |
| Buildings                          | I (1)       | 0.49 (0.41, 0.58)MR      | 194.77 (1.04)              | —                                                  | 0.042          |
| Fuel                               | I (1)       | 0.44 (0.23, 0.66)MR      | 74.67 (11.72)              | —                                                  | 0.111          |
| Industrial                         | I (1)       | 1.15 (0.96, 1.34)        | —                          | —                                                  | 0.096          |
| Power                              | I (1)       | 1.10 (0.94, 1.26)        | —                          | —                                                  | 0.080          |
| Processes                          | I (1)       | 0.95 (0.75, 1.16)        | —                          | —                                                  | 0.103          |
| Transport                          | I (1)       | 1.19 (0.98, 1.39)        | —                          | —                                                  | 0.105          |
| Waste                              | I (0)       | 1.18 (0.99, 1.37)        | —                          | —                                                  | 0.096          |
| <b>ITALY</b>                       |             |                          |                            |                                                    |                |
| <b>Total emissions</b>             | <b>I(1)</b> | <b>1.11 (0.93, 1.28)</b> | —                          | —                                                  | <b>0.089</b>   |
| Agriculture                        | I(d)        | 0.93 (0.69, 1.17)        | —                          | —                                                  | 0.121          |
| Buildings                          | I (1)       | 0.85 (0.61, 1.08)        | —                          | —                                                  | 0.121          |
| Fuel                               | I (1)       | 0.98 (0.76, 1.20)        | —                          | —                                                  | 0.112          |
| Industrial                         | I (1)       | 1.02 (0.81, 1.22)        | —                          | —                                                  | 0.104          |
| Power                              | I (1)       | 0.90 (0.66, 1.14)        | 5.64 (2.92)                | −0.18 (−3.29)                                      | 0.122          |
| Processes                          | I (1)       | 1.07 (0.85, 1.28)        | —                          | —                                                  | 0.111          |
| Transport                          | I (1)       | 1.06 (0.91, 1.21)        | —                          | —                                                  | 0.076          |
| Waste                              | I (0)       | 0.47 (0.26, 0.68)MR      | 0.43 (4.09)                | 0.00 (0.47)                                        | 0.106          |
| <b>NETHERLANDS</b>                 |             |                          |                            |                                                    |                |
| <b>Total emissions</b>             | <b>I(1)</b> | <b>1.04 (0.83, 1.25)</b> | —                          | —                                                  | <b>0.108</b>   |
| Agriculture                        | I(d)        | 1.17 (0.96, 1.38)        | —                          | —                                                  | 0.107          |
| Buildings                          | I (1)       | 0.37 (0.16, 0.58)        | 46.95 (18.10)              | −0.33 (−4.50)                                      | 0.108          |
| Fuel                               | I (1)       | 0.85 (0.56, 1.15)        | —                          | —                                                  | 0.152          |
| Industrial                         | I (1)       | 0.47 (0.38, 0.56) MR     | 24.87 (5.03)               | —                                                  | 0.046          |
| Power                              | I (1)       | 1.25 (1.05, 1.45)        | —                          | —                                                  | 0.102          |
| Processes                          | I (1)       | 0.96 (0.68, 1.25)        | —                          | —                                                  | 0.146          |
| Transport                          | I (1)       | 1.17 (0.94, 1.41)        | —                          | —                                                  | 0.119          |
| Waste                              | I (0)       | 1.39 (1.32, 1.46)        | —                          | —                                                  | 0.036          |
| <b>SPAIN</b>                       |             |                          |                            |                                                    |                |
| <b>Total emissions</b>             | <b>I(1)</b> | <b>1.17 (0.98, 1.36)</b> | —                          | —                                                  | <b>0.097</b>   |
| Agriculture                        | I(d)        | 0.82 (0.59, 1.05)        | —                          | —                                                  | 0.116          |
| Buildings                          | I (1)       | 1.11 (0.92, 1.29)        | —                          | —                                                  | 0.096          |
| Fuel                               | I (1)       | 0.93 (0.68, 1.18)        | —                          | —                                                  | 0.128          |
| Industrial                         | I (1)       | 0.93 (0.65, 1.21)        | —                          | —                                                  | 0.144          |
| Power                              | I (1)       | 0.95 (0.71, 1.19)        | —                          | —                                                  | 0.124          |
| Processes                          | I (1)       | 1.01 (0.81, 1.22)        | 0.06 (0.25)                | —                                                  | 0.105          |
| Transport                          | I (1)       | 1.15 (0.98, 1.33)        | —                          | —                                                  | 0.088          |
| Waste                              | I (0)       | 0.47 (0.29, 0.64)MR      | 2.70 (2.92)                | —                                                  | 0.088          |

same country (column) vary significantly in terms of dispersion (standard deviation/mean value), symmetry (skewness) and outliers (kurtosis) when comparing different countries.

$$y(t) = \alpha + \beta t + x(t), (1 - B)^d x(t) = u(t) \quad t = 1, 2, \dots, \quad (3)$$

under the assumption that the error term is a white noise process.  $y(t)$  refers to each of the emission series under study;  $\alpha$  and  $\beta$  are unknown coefficients, referring respectively to a constant and a (linear) time trend;  $x(t)$  is the detrended series; and  $u(t)$  is an I (0) process that in our case is a white noise process. Therefore, no autocorrelation is permitted for  $u(t)$  above. The integration factor  $d$  in (3) has been estimated across three different set-ups. First, we have assumed that both  $\alpha$  and  $\beta$  are equal to zero a priori (i.e. we have assumed the non-existence of deterministic components). Next, we have allowed for an intercept with

no linear time trend. Finally, we have allowed for a linear time trend and both coefficients have been freely estimated from the data. From these three estimations, we have chosen the one with minimum standard error. Estimates of  $d$  and the 95 % confidence intervals are displayed in Table 2.

When considering the results for total emissions, we find evidence of a similar behaviour in all countries, with a non-stationary I (1) pattern in all countries. Such results are in line with previous studies, as Gil-Alana et al. [9] that analyzed G7 over the past 150–250 years; Gil-Alana and Trani [10] regarding EU in a similar large time spans (1960–2013) or Solarin et al. [6] which with black carbon emissions found evidence of unit roots ( $d = 1$ ) or  $d > 1$  behaviour in the same countries under study. Therefore, external shocks are likely to have long-lasting effects on CO<sub>2</sub> emission behaviour. When examining the findings from studies with a

**Table 3**  
Linear time trend analysis for total CO<sub>2</sub> emissions.

| Variable    | Coefficient | Std. Error | t-Statistic | p-value             |
|-------------|-------------|------------|-------------|---------------------|
| France      | −0.09       | 0.11       | −0.8        | 0.4273              |
| Germany     | −0.3        | 0.12       | −2.46       | 0.0172 <sup>a</sup> |
| Italy       | −0.37       | 0.12       | −3.22       | 0.0022 <sup>a</sup> |
| Netherlands | −0.14       | 0.03       | −4.07       | 0.0002 <sup>a</sup> |
| Spain       | −0.3        | 0.17       | −1.73       | 0.0895 <sup>b</sup> |

<sup>a</sup> Significant value at 95 % confidence Interval.

<sup>b</sup> Significant value at 90 % confidence Interval.

**Table 4**  
Estimation of structural break following Bai-Perron (2003).

| Country            | France     | Germany          | Italy      | Netherlands | Spain      |
|--------------------|------------|------------------|------------|-------------|------------|
| <b>Totals</b>      | 1981, 2006 | –                | 2009       | –           | 2008       |
| <b>Agriculture</b> | 1992, 2000 | 1990, 2004, 2014 | 1979       | 2017        | –          |
| <b>Buildings</b>   | 2011       | 2007             | 2003       | –           | 2003       |
| <b>Fuel</b>        | 1990, 2017 | 1992             | –          | –           | –          |
| <b>Industrial</b>  | 1981       | 1982, 1990       | –          | –           | 2006       |
| <b>Power</b>       | 1981       | 2017             | 2009       | 2005, 2015  | 2008       |
| <b>Process</b>     | 1980, 2003 | 1998             | –          | 1988        | 1984, 2009 |
| <b>Transport</b>   | 2017       | 2000, 2017       | 1997, 2017 | 2009        | 2017       |
| <b>Waste</b>       | 2011       | 2017             | 1991, 2004 | 2017        | –          |

broader perspective, such as those focusing on ecological balance [55, 56], we observe a consistent pattern in developed countries, characterized by stationary behaviour despite ecological deficits. Therefore, further measures in the carbon environment are needed to achieve an ecological equilibrium and sustainability that can benefit the persistent profile of CO<sub>2</sub> emissions.

Thus, external shocks are expected to have permanent effects in the CO<sub>2</sub> emission behaviour. When linking with some other studies that have a broader perspective, for instance those studying the ecological balance ([55] or [56]), we find a stationary behaviour in developed countries but with ecological deficits. Therefore, we see that further measures in the carbon environment are still needed to achieve an ecological equilibrium and sustainability that can benefit the persistent profile of the CO<sub>2</sub> emissions.

Focusing now on the time trends from previous calculations (see Table 3), it is noticeable that three of these five countries (Germany, Italy and the Netherlands) have negative slopes at a 95 % confidence level. Similarly, Spain has a negative slope but at a 90 % confidence level while France also has a negative slope, but in this case at a very large p-value (0.427) that is not statistically significant. These findings would suggest a downward trend in the EU emission levels, and due to the persistent nature of such emissions, the likelihood of a future decline, similarly as in Infante et al. [14] but now observed with larger time spans. However, here the question remains again whether this downward trend will be sufficient to meet the established reduction targets.

In terms of the sectorial emission components, we find, in general terms, evidence of non-mean reverting patterns with I (1) results. Exceptions with slow mean-reverting patterns and I(d) behaviour ( $0.5 < d < 1$ ) are in France agriculture, German buildings, German fuel, Italy waste, Netherlands buildings and industrial, and Spanish waste. Therefore, sectorial emissions would also be vulnerable to external shocks that would have permanent effects except in the previously mentioned areas that would experience slow mean reverting patterns. These results align with the observed global emission pattern, indicating a consistent I (1) general behaviour across all countries. The findings are also congruent with the sectorial analysis conducted in Solarin et al.

[57] for NMVOCs emissions in agriculture, buildings, residences, and waste, employing conventional testing methods. However, the conclusions differ when utilizing the Fourier-quantile unit root test that found evidence of stationarity as potential deviations from long-term equilibrium levels are unlikely to have prolonged consequences.

## 5. Discussion of results

To check robustness we have studied structural breaks according to the methodology developed by Bai and Perron [80], confirming the evidence of those breaks, which are summarized in Table 4.

Regarding its possible origin, Stechemesser et al. [81] studied climate policies that achieved major emission reductions, finding evidence that the majority of those breaks are aligned with two or more policies, indicating in the study that complementary combinations of policy instruments vary across sectors and country groups. In developed economies, pricing is the most successful intervention, while subsidies are the most complementary instrument, especially in combination with pricing. Transportation is generally the sector with the most potential for complementarities, while regulation appears to be a potent policy primarily only in developing economies.

In our case, the results appear to align with those of this study. With the exception of transportation in 2017, we observe heterogeneity in the number of breaks and break dates. Therefore, we are unable to identify a single EC policy pattern regarding these breaks. This transportation break may be linked to the EC's new draft proposals for the 2025 and 2030 fleet targets in 2017, which presented the prospect of integrating a fixed quota of zero-emission vehicles (ZEVs) into the new transport directive [82]. Regarding the remaining breaks, economic reasons may be at play in Italy (2009) and Spain (2008), potentially influenced by the financial crisis that particularly impacted southern countries. Germany also experienced significant economic changes in the 1990s due to the reunification of the country. Additionally, France experienced significant economic shifts in 1981, coinciding with the election of Mitterrand.

In terms of the impact of structural breaks within a fractional integration framework, Gil Alana et al. [83] examined precious metals (1972–2013, monthly data) finding evidence that, in most cases, persistence increased over time. Similarly, Yaya et al. [84] analyzed structural breaks in bank share prices from (2001–2013, daily samples) and found an increase in dependence over time. Caporale et al. [85] analyzed major European stock market indexes (2009–2019, weekly samples) and found similar stochastic behaviour properties across the subsamples. However, the degree of persistence may change without clearly identifiable patterns. In all these cases, the authors re-estimated the d-value in the subsamples and compared it with the estimation from the full sample. Finally, Solarin et al. [6] analyzed black carbon emissions over a longer time span (1820–2019) and found similar results in the last subsample compared to the entire sample. The results of a segmented analysis in which the d-value was estimated for each subsample are described in Table 5.

When analyzing the subsamples, we see that similarly to Caporale et al. [85] the subseries' general character remains unchanged although the confidence interval enlarges due to the smaller sample size. In terms of emissions, this result is also aligned with the persistent figures obtained in Solarin et al. [6] for black carbon emissions, and with Solarin et al. [57] for sectoral NMVOCs emissions, which exhibit non-stationary patterns, suggesting a certain robustness of the general findings. However, we must note that a few outliers arise (in bold), particularly when the sample size is small. This occurred in the transportation category after 2017, for which only six samples were available for estimation.

After completing these robustness checks, we have also analyzed potential relationships across countries and industries. For this purpose, we have used first both short-term correlations and long-term cointegration tests [86] between the different components (see Table 6). Starting with the total emissions per country, we observed a strong pair correlation between France and Germany and also between the

**Table 5**Estimates of  $d$  for each country and subsample.

| Breaks             | Series             | Full Sample      | First                    | Second                    | Third                     | Fourth            |
|--------------------|--------------------|------------------|--------------------------|---------------------------|---------------------------|-------------------|
| <b>France</b>      |                    |                  |                          |                           |                           |                   |
| 1981, 2006         | <b>Totals</b>      | 1.02 (0.81,1.22) | <b>0.40 (1.12,1.92)</b>  | 1.31 (1.06,1.57)          | 1.00 (0.67,1.33)          |                   |
| 1992, 2000         | <b>Agriculture</b> | 0.62 (0.37,0.89) | 0.74 (1.22,2.71)         | <b>0.09 (-1.03,1.21)</b>  | 0.31 (0.02,0.61)          |                   |
| 2011               | <b>Buildings</b>   | 0.93 (0.76,1.09) | 0.89 (0.69,1.09)         | 0.93 (-0.13,1.99)         |                           |                   |
| 1990, 2017         | <b>Fuel</b>        | 1.07 (0.76,1.38) | 1.11 (0.34,1.87)         | 0.96 (-1.20,1.12)         | 0.99 (0.39,1.59)          |                   |
| 1981               | <b>Industrial</b>  | 1.17 (0.95,1.38) | 1.24 (0.35,2.14)         | 1.17 (0.95,1.39)          |                           |                   |
| 1981               | <b>Power</b>       | 0.95 (0.71,1.19) | 0.63 (0.85,2.10)         | 1.09 (0.85,1.33)          |                           |                   |
| 1980, 2003         | <b>Process</b>     | 1.03 (0.84,1.23) | 0.46 (0.77,1.69)         | 1.30 (1.09,1.50)          | 1.10 (0.41,1.80)          |                   |
| 2017               | <b>Transport</b>   | 1.11 (0.98,1.24) | 1.35 (1.22,1.48)         | <b>0.40 (-3.24,4.05)</b>  |                           |                   |
| 2011               | <b>Waste</b>       | 0.98 (0.85,1.11) | 1.15 (0.93,1.36)         | <b>-0.20 (1.94,1.54)</b>  |                           |                   |
| <b>Germany</b>     |                    |                  |                          |                           |                           |                   |
| –                  | <b>Totals</b>      | 1.05 (0.86,1.24) |                          |                           |                           |                   |
| 1990, 2004, 2014   | <b>Agriculture</b> | 0.84 (0.46,1.22) | 0.11 (-0.46,0.69)        | 0.60 (-0.38,1.59)         | 0.50 (-0.87,1.87)         | 1.13 (-0.72,2.99) |
| 2007               | <b>Buildings</b>   | 0.49 (0.41,0.58) | 0.97 (-0.40,1.34)        | 0.36 (-1.05,1.77)         |                           |                   |
| 1992               | <b>Fuel</b>        | 0.44 (0.23,0.66) | 0.26 (-0.27,0.78)        | 0.36 (0.07,0.65)          |                           |                   |
| 1982, 1990         | <b>Industrial</b>  | 1.15 (0.96,1.34) | 1.12 (-0.85,1.09)        | 0.94 (-1.51,3.38)         | 1.23 (1.04,1.42)          |                   |
| 2017               | <b>Power</b>       | 1.10 (0.94,1.26) | 0.94 (0.68,1.19)         | 1.24 (0.53,1.94)          |                           |                   |
| 1998               | <b>Process</b>     | 0.95 (0.75,1.16) | 1.00 (0.65,1.34)         | 0.63 (0.12,1.15)          |                           |                   |
| 2000, 2017         | <b>Transport</b>   | 1.19 (0.98,1.39) | 1.31 (1.08,1.54)         | 1.34 (0.99,1.69)          | 0.84 (-2.15,3.84)         |                   |
| 2017               | <b>Waste</b>       | 1.18 (0.99,1.37) | 1.49 (1.44,1.54)         | 1.15 (-0.84,3.13)         |                           |                   |
| <b>Italy</b>       |                    |                  |                          |                           |                           |                   |
| 2009               | <b>Totals</b>      | 1.11 (0.93,1.28) | 1.23 (0.91,1.55)         | 1.08 (0.69,1.48)          |                           |                   |
| 1979               | <b>Agriculture</b> | 0.93 (0.69,1.17) | 1.24 (0.48,2.01)         | 0.94 (0.70,1.18)          |                           |                   |
| 2003               | <b>Buildings</b>   | 0.85 (0.61,1.08) | 0.43 (-0.07,0.94)        | 1.02 (0.64,1.41)          |                           |                   |
| –                  | <b>Fuel</b>        | 0.98 (0.76,1.20) |                          |                           |                           |                   |
| –                  | <b>Industrial</b>  | 1.02 (0.81,1.22) |                          |                           |                           |                   |
| 2009               | <b>Power</b>       | 0.90 (0.66,1.14) | 0.93 (0.42,1.43)         | <b>0.01 (-0.79,0.81)</b>  |                           |                   |
| –                  | <b>Process</b>     | 1.07 (0.85,1.28) |                          |                           |                           |                   |
| 1997, 2017         | <b>Transport</b>   | 1.06 (0.91,1.21) | 1.35 (1.16,1.54)         | 1.25 (0.83,1.68)          | <b>-0.07 (-4.48,4.34)</b> |                   |
| 1991, 2004         | <b>Waste</b>       | 0.47 (0.26,0.68) | <b>1.24 (-1.63,4.11)</b> | 0.31 (-0.33,0.95)         | 0.58 (-0.07,1.24)         |                   |
| <b>Netherlands</b> |                    |                  |                          |                           |                           |                   |
| –                  | <b>Totals</b>      | 1.04 (0.83,1.25) |                          |                           |                           |                   |
| 2017               | <b>Agriculture</b> | 1.17 (0.96,1.38) | 0.77 (0.53,1.01)         | 1.20 (-0.27,2.67)         |                           |                   |
| –                  | <b>Buildings</b>   | 0.37 (0.16,0.58) |                          |                           |                           |                   |
| –                  | <b>Fuel</b>        | 0.85 (0.56,1.15) |                          |                           |                           |                   |
| –                  | <b>Industrial</b>  | 0.47 (0.38,0.56) |                          |                           |                           |                   |
| 2005, 2015         | <b>Power</b>       | 1.25 (1.05,1.45) | 1.19 (0.92,1.46)         | 0.63 (-0.63,1.89)         | 1.31 (0.61,2.00)          |                   |
| 1988               | <b>Process</b>     | 0.96 (0.68,1.25) | 0.95 (0.13,1.77)         | 0.93 (0.52,1.35)          |                           |                   |
| 2009               | <b>Transport</b>   | 1.17 (0.94,1.41) | 1.22 (1.00,1.43)         | 1.12 (0.45,1.79)          |                           |                   |
| 2017               | <b>Waste</b>       | 1.39 (1.32,1.46) | 1.27 (1.11,1.43)         | 1.28 (0.59,1.97)          |                           |                   |
| <b>Spain</b>       |                    |                  |                          |                           |                           |                   |
| 2008               | <b>Totals</b>      | 1.17 (0.98,1.36) | 1.18 (0.91,1.44)         | 1.23 (0.93,1.54)          |                           |                   |
| –                  | <b>Agriculture</b> | 0.82 (0.59,1.05) |                          |                           |                           |                   |
| 2003               | <b>Buildings</b>   | 1.11 (0.92,1.29) | 1.21 (0.95,1.48)         | 0.93 (0.45,1.42)          |                           |                   |
| –                  | <b>Fuel</b>        | 0.93 (0.68,1.18) |                          |                           |                           |                   |
| 2006               | <b>Industrial</b>  | 0.93 (0.65,1.21) | 0.80 (0.37,1.24)         | 1.06 (0.65,1.46)          |                           |                   |
| 2008               | <b>Power</b>       | 0.95 (0.71,1.19) | 0.95 (0.69,1.22)         | 1.07 (0.64,1.51)          |                           |                   |
| 1984, 2009         | <b>Process</b>     | 1.01 (0.81,1.22) | 0.78 (-0.12,1.68)        | 1.43 (1.09,1.77)          | 0.95 (0.24,1.66)          |                   |
| 2017               | <b>Transport</b>   | 1.15 (0.98,1.33) | 1.40 (1.20,1.60)         | <b>-0.11 (-3.72,3.51)</b> |                           |                   |
| –                  | <b>Waste</b>       | 0.47 (0.29,0.64) |                          |                           |                           |                   |

**Note:** Bold values indicate outliers due to the very short size of the subsample.

Netherlands and Spain. However, the Netherlands and Spain exhibited a very negative correlation against France and Germany, and a positive correlation with Italy. Therefore, no common behaviour is seen in the short term. Regarding the cointegration tests, we see no evidence of cointegration between the countries under analysis. Consequently, even though there is evidence of local correlations between some specific countries in the short-term, there is not a long-term pattern that would help to maintain this initial joint behaviour. Series are expected to follow separate paths in the long-term or may not have a persistent link that relates them in a stable way over time in terms of the others.

In order to delve deeper into the sectoral analysis, we have also analyzed the specific distribution of IPCC contributors for each country (Tables 7A and 7Ba and 7b). Again, we do not see a common framework across countries. The correlations do not show a common short-term pattern across industries in a single country, as the cross-correlations

have different breakdowns. On the other hand, the cointegration analysis shows evidence of co-integration only in a limited number of elements and with different distributions across countries. Specifically, we have identified cointegration at the 90 % confidence level for agriculture, buildings, industry, and transport in France; at the 95 % for power and transport and at the 90 % for buildings in Italy; at the 95 % for industry and at the 90 % for waste in the Netherlands; and at the 95 % for processes and waste in Spain. Finally, there is an absence of cointegration evidence between industries in Germany. Therefore, we see some sort of internal long-term relationship in some countries (especially in France), but not a common distribution pattern across the different countries.

Regarding this behaviour, it is important to note that prior to 2005, there was no common emission framework in place. However, in that year, the EU launched the EU Emissions Trading System (EU ETS), which

**Table 6**  
Inter-country total emission relationships.

| CORRELATION MATRIX  |             |                    |             |                    |        |
|---------------------|-------------|--------------------|-------------|--------------------|--------|
|                     | France      | Germany            | Italy       | Netherlands        | Spain  |
| France              | 1.000       | 0.856              | 0.111       | −0.147             | −0.426 |
| Germany             | 0.856       | 1.000              | 0.055       | −0.241             | −0.587 |
| Italy               | 0.111       | 0.055              | 1.000       | 0.801              | 0.713  |
| Netherlands         | −0.147      | −0.241             | 0.801       | 1.000              | 0.782  |
| Spain               | −0.426      | −0.587             | 0.713       | 0.782              | 1.000  |
| COINTEGRATION TESTS |             |                    |             |                    |        |
| Dependent           | t-statistic | Prob. <sup>a</sup> | z-statistic | Prob. <sup>a</sup> |        |
| France              | −2.732      | 0.732              | −15.418     | 0.612              |        |
| Germany             | −2.598      | 0.786              | −27.365     | 0.100              |        |
| Italy               | −2.333      | 0.873              | −20.727     | 0.321              |        |
| Netherlands         | −2.010      | 0.941              | −10.679     | 0.860              |        |
| Spain               | −1.799      | 0.966              | −7.180      | 0.963              |        |

**Note:** Engel & Granger (1987) cointegration results. The null hypothesis is that series are not cointegrated. In bold, confidence level of 90 % or higher.

<sup>a</sup> MacKinnon [87] p-values.

was the world's first carbon market. The purpose of the EU ETS was to reduce overall EU emissions and generate revenues to finance the green transition (EC, 2025). Covered entities are obligated to relinquish allowances for all their covered emissions. The allocation of these allowances is determined through two mechanisms: auctions with minimum and maximum prices, or free allocation [88] assigned by nations to designated installations (Miteco, 2025). Consequently, as each country is able to assign these free rights and protect certain industrial sectors, the emission framework within a single country might differ from that of other ones.

Finally, to complete the analysis and looking for common EU policies, we have searched for relationships within a single sector across the different countries (Table 8A and Table 8B). Here, we observe a strong correlation in the transport sector (average value of crossed correlations 0.91) and a noticeable value in the industrial (0.77) but with no evidence of general cointegration relationships between these sectors. On the other hand, we see a long-term cointegration relationship in the waste sector (99 % confidence level for France and Spain, 95 % for Italy, 90 % for Germany and 85 % for the Netherlands), but curiously, with no short-term correlation (average value of crossed correlations, 0.14). For the remaining sectors, we observe minimal correlation, with occasional cointegration relationships for each sector (Italian agriculture, Spanish power).

Regarding the transport sector, the empirical results clearly show a high correlation, yet a lack of cointegration. This suggests that emissions norms are applied across all countries in the short term. However, the lack of cointegration implies that, in the long term, countries follow different paths since emissions are not coordinated across countries. Some authors such as Lindlof [89] or Haas and Sander [82] point out that, even though several norms were adopted in the EU such as CO<sub>2</sub> emission performance standards for new passenger cars (EC, 2009) or the Roadmap to a Single European Transport Area (EC, 2011), the automotive sector as a whole, and the German companies in particular, influenced those fleet limits to be thoroughly unambitious. Member states were permitted some implementation flexibility, which led to divergent long-term trajectories and a lack of cointegration since national policies were different [90]. For example, over this period, Germany's observed data shows an increase in transport emissions, while other countries, such as France and Italy, have stabilized.

Consequently, the transport sector was the only one in the EU in which emissions increased from 1990 to 2019. In 2019, emissions from the transport sector were over 25 % higher than in 1990, resulting in the sector accounting for nearly 30 % of total EU carbon emissions [91]. Thus, more restrictive limits were adopted in 2019 (EU 2019/631). Our empirical results reveal a common structural break in all countries except the Netherlands in 2017 when the prospect of integrating a fixed

quota of zero-emission vehicles (ZEVs) into the new transport directive and the EC's draft proposals for the 2025 and 2030 fleet targets was presented. Observed data shows some stabilization after 2019, though no clear reduction pattern emerges across the years.

Currently, Member States are pursuing two primary strategies to reduce emissions: increasing advanced biofuel production [92] and promoting electric vehicle adoption [93]. However, the lack of cointegration results suggests that although norms are applied in the short term, there is a clear deficit in terms of the long-term coordination needed to achieve further reductions. The literature confirms that significant regional differences persist in the application of transport policies despite EU directives. This suggests that additional approaches are needed to develop effective sustainability policies for transport that are adapted to the specificities of different EU regions [91,94].

In the context of waste management, the total emissions impact is clearly less significant compared to the transport sector (see Table 1). In this case, country policies appear to be driven by EU directives. EU Member States must implement the directives outlined in EU Directive 2008/98/EC, which requires the adoption of waste management and prevention programs for sustainable development and the reduction of landfill waste through the recycling of waste components (EC, 2008). Conversely, the waste sector shows strong cointegration but low short-term correlation across countries due to the direct and harmonized implementation of this directive. The uniformity of these mandates leads to convergence in long-term emissions trajectories (cointegration), even though short-term fluctuations differ due to local factors. Our empirical findings suggest that all countries adopt these policies similarly, consistent with the study by Marišová and Valenčíková [95] that examined Slovakia, France, and Finland. However, other authors have pointed to regional variations within the EU [96] and have requested a more integrated approach within the EU, with additional efforts from member states to accelerate the transition to a circular economy [97].

In sectors such as industry, power, and agriculture, lack of cointegration and correlation results across countries could be likely due to the structure of the EU Emissions Trading System (ETS). While the ETS provides an overarching framework, it leaves substantial discretion to national governments in allocating allowances and protecting certain sectors. This results in fragmented policy implementation and heterogeneous persistence patterns. Similarly, for the remaining sectors, our empirical findings may potentially reflect the absence of coordinated strategies in how each country implements the EU emission reduction policies.

Therefore, our study may provide empirical evidence for papers that request more coordinated policies across countries to achieve effective emission reductions in the EU, such as Cucchiella et al. [33], Gavurova et al. [34], Parravicini et al. [25], and Tsiminadis and Kyriakopoulos [96]. Others point to the fragmented regulatory approaches that underpin these variations, as highlighted by Brodny and Tutak [98]. Alternatively, Martinez-Zarzoso et al. [99] argue that divergent pollution policies across Central and Eastern European countries may create pollution havens. Recent literature further emphasizes that, despite its cap-and-trade design and declining overall emissions cap, the EU ETS has led to marked disparities in emissions growth rates and volatility across regions, particularly between more and less developed areas [100]. Flexibility in national allocation plans and varying pre-existing climate policy mixes contribute to this institutional misfit, complicating transnational coordination and learning. Consequently, policy incoherence and fragmented governance often undermine the effectiveness of the EU ETS, highlighting the need for clearer, more harmonized implementation and oversight at the EU level.

## 6. Conclusions

In this paper, we have examined the CO<sub>2</sub> emission persistence for the largest EU contributors (France, Italy, Germany, Spain and the Netherlands). For this purpose, we have analyzed emissions for the time

**Table 7A**

Sectorial correlations per specific country.

| FRANCE                          |             |           |       |            |       |           |           |       |
|---------------------------------|-------------|-----------|-------|------------|-------|-----------|-----------|-------|
|                                 | Agriculture | Buildings | Fuel  | Industrial | Power | Processes | Transport | Waste |
| Agriculture                     | 1.00        | 0.41      | 0.27  | 0.16       | 0.07  | 0.30      | −0.01     | −0.48 |
| Buildings                       | 0.41        | 1.00      | 0.84  | 0.81       | 0.80  | 0.92      | −0.67     | −0.82 |
| Fuel                            | 0.27        | 0.84      | 1.00  | 0.76       | 0.74  | 0.86      | −0.60     | −0.73 |
| Industrial                      | 0.16        | 0.81      | 0.76  | 1.00       | 0.84  | 0.92      | −0.93     | −0.85 |
| Power                           | 0.07        | 0.80      | 0.74  | 0.84       | 1.00  | 0.83      | −0.77     | −0.68 |
| Processes                       | 0.30        | 0.92      | 0.86  | 0.92       | 0.83  | 1.00      | −0.80     | −0.86 |
| Transport                       | −0.01       | −0.67     | −0.60 | −0.93      | −0.77 | −0.80     | 1.00      | 0.82  |
| Waste                           | −0.48       | −0.82     | −0.73 | −0.85      | −0.68 | −0.86     | 0.82      | 1.00  |
| Average of crossed correlations |             |           | 0.08  |            |       |           |           |       |
| GERMANY                         |             |           |       |            |       |           |           |       |
|                                 | Agriculture | Buildings | Fuel  | Industrial | Power | Processes | Transport | Waste |
| Agriculture                     | 1.00        | 0.53      | 0.63  | 0.72       | 0.44  | 0.74      | −0.77     | 0.06  |
| Buildings                       | 0.53        | 1.00      | 0.92  | 0.91       | 0.69  | 0.80      | −0.64     | 0.38  |
| Fuel                            | 0.63        | 0.92      | 1.00  | 0.95       | 0.65  | 0.85      | −0.74     | 0.33  |
| Industrial                      | 0.72        | 0.91      | 0.95  | 1.00       | 0.56  | 0.94      | −0.86     | 0.18  |
| Power                           | 0.44        | 0.69      | 0.65  | 0.56       | 1.00  | 0.47      | −0.23     | 0.82  |
| Processes                       | 0.74        | 0.80      | 0.85  | 0.94       | 0.47  | 1.00      | −0.86     | 0.08  |
| Transport                       | −0.77       | −0.64     | −0.74 | −0.86      | −0.23 | −0.86     | 1.00      | 0.21  |
| Waste                           | 0.06        | 0.38      | 0.33  | 0.18       | 0.82  | 0.08      | 0.21      | 1.00  |
| Average of crossed correlations |             |           | 0.31  |            |       |           |           |       |
| ITALY                           |             |           |       |            |       |           |           |       |
|                                 | Agriculture | Buildings | Fuel  | Industrial | Power | Processes | Transport | Waste |
| Agriculture                     | 1.00        | 0.37      | 0.73  | 0.59       | −0.12 | 0.42      | −0.26     | 0.22  |
| Buildings                       | 0.37        | 1.00      | 0.52  | 0.48       | 0.41  | 0.67      | 0.08      | 0.42  |
| Fuel                            | 0.73        | 0.52      | 1.00  | 0.89       | −0.26 | 0.77      | −0.56     | 0.04  |
| Industrial                      | 0.59        | 0.48      | 0.89  | 1.00       | −0.31 | 0.83      | −0.58     | −0.10 |
| Power                           | −0.12       | 0.41      | −0.26 | −0.31      | 1.00  | 0.06      | 0.91      | 0.70  |
| Processes                       | 0.42        | 0.67      | 0.77  | 0.83       | 0.06  | 1.00      | −0.30     | 0.08  |
| Transport                       | −0.26       | 0.08      | −0.56 | −0.58      | 0.91  | −0.30     | 1.00      | 0.60  |
| Waste                           | 0.22        | 0.42      | 0.04  | −0.10      | 0.70  | 0.08      | 0.60      | 1.00  |
| Average of crossed correlations |             |           | 0.26  |            |       |           |           |       |
| NETHERLANDS                     |             |           |       |            |       |           |           |       |
|                                 | Agriculture | Buildings | Fuel  | Industrial | Power | Processes | Transport | Waste |
| Agriculture                     | 1.00        | −0.67     | 0.11  | −0.53      | 0.04  | 0.22      | 0.15      | −0.84 |
| Buildings                       | −0.67       | 1.00      | −0.10 | 0.69       | −0.37 | −0.34     | −0.37     | 0.39  |
| Fuel                            | 0.11        | −0.10     | 1.00  | −0.11      | 0.43  | 0.42      | 0.40      | 0.15  |
| Industrial                      | −0.53       | 0.69      | −0.11 | 1.00       | −0.58 | −0.63     | −0.64     | 0.15  |
| Power                           | 0.04        | −0.37     | 0.43  | −0.58      | 1.00  | 0.87      | 0.93      | 0.45  |
| Processes                       | 0.22        | −0.34     | 0.42  | −0.63      | 0.87  | 1.00      | 0.94      | 0.24  |
| Transport                       | 0.15        | −0.37     | 0.40  | −0.64      | 0.93  | 0.94      | 1.00      | 0.34  |
| Waste                           | −0.84       | 0.39      | 0.15  | 0.15       | 0.45  | 0.24      | 0.34      | 1.00  |
| Average of crossed correlations |             |           | 0.06  |            |       |           |           |       |
| SPAIN                           |             |           |       |            |       |           |           |       |
|                                 | Agriculture | Buildings | Fuel  | Industrial | Power | Processes | Transport | Waste |
| Agriculture                     | 1.00        | −0.07     | −0.07 | 0.07       | 0.21  | 0.17      | 0.02      | −0.13 |
| Buildings                       | −0.07       | 1.00      | 0.83  | −0.41      | 0.69  | 0.46      | 0.95      | 0.79  |
| Fuel                            | −0.07       | 0.83      | 1.00  | −0.63      | 0.50  | 0.17      | 0.82      | 0.74  |
| Industrial                      | 0.07        | −0.41     | −0.63 | 1.00       | 0.05  | 0.43      | −0.39     | −0.62 |
| Power                           | 0.21        | 0.69      | 0.50  | 0.05       | 1.00  | 0.78      | 0.74      | 0.32  |
| Processes                       | 0.17        | 0.46      | 0.17  | 0.43       | 0.78  | 1.00      | 0.53      | 0.11  |
| Transport                       | 0.02        | 0.95      | 0.82  | −0.39      | 0.74  | 0.53      | 1.00      | 0.75  |
| Waste                           | −0.13       | 0.79      | 0.74  | −0.62      | 0.32  | 0.11      | 0.75      | 1.00  |
| Average of crossed correlations |             |           | 0.28  |            |       |           |           |       |

period from 1970 to 2023, using the EDGAR database from Crippa et al. [79], with yearly samples. We have sought to make a valuable contribution to the existing literature by investigating two research questions. First, to assess persistence in the specific IPCC sector contributions; and second, to study their cross-country and cross-sectoral long-term and short-term relationships. To this end, we have employed a linear fractional integration framework and used the integration degree as an indicator of the level of persistence.

To deal with the first research question, we have analyzed global country emissions, finding clear evidence of non-stationary behaviour ( $d = 1$ ), as in previous studies by Gil-Alana et al. [9] and Gil-Alana and Trani [10]. Additionally, we have identified negative slopes in Germany, Italy and the Netherlands at a 95 % confidence level, and in Spain at a

90 % confidence level. This suggests a downward trend in EU emission levels, consistent with the findings of Infante et al. [14], but now observed over a longer time span. Furthermore, we observe strong pair correlation between France and Germany, and between the Netherlands and Spain. However, no evidence of cointegration is seen in the long term.

In terms of the sectorial emission components, evidence of non-mean reverting patterns with I (1) results is found, with very few exceptions being slow mean-reverting patterns with I(d) behaviour ( $0.5 < d < 1$ ). In particular, these exceptions are France agriculture, German buildings, German fuel, Italy waste, Netherlands buildings and industrial, and Spanish waste. In this regard, when studying IPCC components from a single country, we also observe a lack of a general pattern of correlation,

**Table 7B**

Sectorial cointegration tests per specific country.

| FRANCE             |               |                    |                |                    |
|--------------------|---------------|--------------------|----------------|--------------------|
| Dependent          | tau-statistic | prob. <sup>a</sup> | z-statistic    | prob. <sup>a</sup> |
| <b>Agriculture</b> | <b>−5.471</b> | <b>0.074</b>       | <b>−62.796</b> | <b>-</b>           |
| <b>Buildings</b>   | <b>−5.554</b> | <b>0.063</b>       | <b>−38.431</b> | <b>0.072</b>       |
| Fuel               | −3.907        | 0.600              | −23.955        | 0.603              |
| <b>Industrial</b>  | <b>−5.404</b> | <b>0.083</b>       | <b>−31.676</b> | <b>0.244</b>       |
| Power              | −3.247        | 0.861              | −16.557        | 0.907              |
| Processes          | −4.278        | 0.427              | −27.523        | 0.423              |
| <b>Transport</b>   | <b>−5.378</b> | <b>0.087</b>       | <b>−37.247</b> | <b>0.092</b>       |
| Waste              | −4.782        | 0.228              | −32.372        | 0.219              |
| GERMANY            |               |                    |                |                    |
| Dependent          | tau-statistic | prob. <sup>a</sup> | z-statistic    | prob. <sup>a</sup> |
| Agriculture        | −4.293        | 0.420              | −27.594        | 0.419              |
| Buildings          | −4.964        | 0.174              | −33.776        | 0.174              |
| Fuel               | −5.192        | 0.120              | −33.625        | 0.179              |
| Industrial         | −5.149        | 0.129              | −34.133        | 0.164              |
| Power              | −4.731        | 0.245              | −27.723        | 0.413              |
| Processes          | −3.792        | 0.653              | −23.006        | 0.650              |
| Transport          | −3.553        | 0.755              | −18.955        | 0.830              |
| Waste              | −4.651        | 0.275              | −51.155        | 0.002              |
| ITALY              |               |                    |                |                    |
| Dependent          | tau-statistic | prob. <sup>a</sup> | z-statistic    | prob. <sup>a</sup> |
| Agriculture        | −3.924        | 0.592              | −24.345        | 0.583              |
| <b>Buildings</b>   | <b>−5.447</b> | <b>0.077</b>       | <b>−39.241</b> | <b>0.060</b>       |
| Fuel               | −4.684        | 0.262              | −30.241        | 0.300              |
| Industrial         | −3.260        | 0.857              | −18.071        | 0.861              |
| <b>Power</b>       | <b>−7.084</b> | <b>0.002</b>       | <b>−52.971</b> | <b>0.001</b>       |
| Processes          | −4.769        | 0.232              | −29.041        | 0.352              |
| <b>Transport</b>   | <b>−6.736</b> | <b>0.005</b>       | <b>−51.435</b> | <b>0.002</b>       |
| Waste              | −4.880        | 0.198              | −32.800        | 0.204              |
| NETHERLANDS        |               |                    |                |                    |
| Dependent          | tau-statistic | prob. <sup>a</sup> | z-statistic    | prob. <sup>a</sup> |
| Agriculture        | −4.836        | 0.211              | −36.925        | 0.098              |
| Buildings          | −4.733        | 0.244              | −31.889        | 0.236              |
| Fuel               | −3.704        | 0.692              | −21.612        | 0.718              |
| <b>Industrial</b>  | <b>−5.779</b> | <b>0.040</b>       | <b>−41.410</b> | <b>0.037</b>       |
| Power              | −5.258        | 0.117              | 17.844         | 1.000              |
| Processes          | −4.391        | 0.377              | −28.543        | 0.374              |
| Transport          | −3.704        | 0.692              | −22.373        | 0.681              |
| <b>Waste</b>       | <b>−5.434</b> | <b>0.080</b>       | <b>−72.366</b> | <b>-</b>           |
| SPAIN              |               |                    |                |                    |
| Dependent          | tau-statistic | prob. <sup>a</sup> | z-statistic    | prob. <sup>a</sup> |
| Agriculture        | −3.227        | 0.866              | −18.629        | 0.842              |
| Buildings          | −4.060        | 0.528              | −26.457        | 0.475              |
| Fuel               | −3.361        | 0.825              | −20.038        | 0.787              |
| Industrial         | −5.105        | 0.139              | −33.033        | 0.197              |
| Power              | −2.576        | 0.976              | −15.389        | 0.934              |
| <b>Processes</b>   | <b>−5.871</b> | <b>0.033</b>       | <b>−37.092</b> | <b>0.095</b>       |
| Transport          | −3.783        | 0.657              | −24.680        | 0.566              |
| <b>Waste</b>       | <b>−6.583</b> | <b>0.007</b>       | <b>−48.388</b> | <b>0.006</b>       |

Note. Engel & Granger (1987) cointegration results. The null hypothesis is that series are not cointegrated. In bold, confidence level of 90 % or higher.

<sup>a</sup> MacKinnon [87] p-values.

and co-integration is evident in only a limited number of elements (particularly in France), with different distributions across countries.

To analyze the robustness of these results, we studied structural breaks using the Bai-Perron (2003) methodology. We found evidence that the general character of the subseries remains unchanged, though the confidence interval enlarges due to the smaller sample size of the subsamples. This result aligns with previous emission studies, such as those by Solarin et al. [6] on black carbon emissions and Solarin et al. [57] on sectoral non-methane volatile organic compound (NMVOC) emissions. These studies exhibit non-stationary patterns, suggesting the robustness of the general results obtained. Further research could be driven by increasing the frequency of the data sample and comparing these results to improve their accuracy. Moreover, the presence of structural breaks may indicate the need for non-linear models. One

**Table 8A**

Country correlation relationships per specific sector.

| AGRICULTURE                     |        |         |       |             |       |
|---------------------------------|--------|---------|-------|-------------|-------|
|                                 | France | Germany | Italy | Netherlands | Spain |
| France                          | 1.00   | 0.01    | 0.74  | −0.53       | 0.48  |
| Germany                         | 0.01   | 1.00    | 0.14  | −0.45       | 0.52  |
| Italy                           | 0.74   | 0.14    | 1.00  | −0.50       | 0.66  |
| Netherlands                     | −0.53  | −0.45   | −0.50 | 1.00        | −0.66 |
| Spain                           | 0.48   | 0.52    | 0.66  | −0.66       | 1.00  |
| Average of crossed correlations |        | 0.04    |       |             |       |
| BUILDINGS                       |        |         |       |             |       |
|                                 | France | Germany | Italy | Netherlands | Spain |
| France                          | 1.00   | 0.86    | 0.65  | 0.91        | −0.66 |
| Germany                         | 0.86   | 1.00    | 0.35  | 0.85        | −0.89 |
| Italy                           | 0.65   | 0.35    | 1.00  | 0.66        | −0.01 |
| Netherlands                     | 0.91   | 0.85    | 0.66  | 1.00        | −0.64 |
| Spain                           | −0.66  | −0.89   | −0.01 | −0.64       | 1.00  |
| Average of crossed correlations |        | 0.21    |       |             |       |
| FUEL                            |        |         |       |             |       |
|                                 | France | Germany | Italy | Netherlands | Spain |
| France                          | 1.00   | 0.68    | 0.74  | 0.11        | −0.67 |
| Germany                         | 0.68   | 1.00    | 0.84  | −0.32       | −0.86 |
| Italy                           | 0.74   | 0.84    | 1.00  | −0.31       | −0.80 |
| Netherlands                     | 0.11   | −0.32   | −0.31 | 1.00        | 0.38  |
| Spain                           | −0.67  | −0.86   | −0.80 | 0.38        | 1.00  |
| Average of crossed correlations |        | −0.02   |       |             |       |
| INDUSTRIAL                      |        |         |       |             |       |
|                                 | France | Germany | Italy | Netherlands | Spain |
| France                          | 1.00   | 0.95    | 0.86  | 0.78        | 0.71  |
| Germany                         | 0.95   | 1.00    | 0.82  | 0.80        | 0.61  |
| Italy                           | 0.86   | 0.82    | 1.00  | 0.77        | 0.86  |
| Netherlands                     | 0.78   | 0.80    | 0.77  | 1.00        | 0.58  |
| Spain                           | 0.71   | 0.61    | 0.86  | 0.58        | 1.00  |
| Average of crossed correlations |        | 0.77    |       |             |       |
| POWER                           |        |         |       |             |       |
|                                 | France | Germany | Italy | Netherlands | Spain |
| France                          | 1.00   | 0.52    | −0.49 | −0.62       | −0.36 |
| Germany                         | 0.52   | 1.00    | 0.07  | −0.14       | 0.16  |
| Italy                           | −0.49  | 0.07    | 1.00  | 0.86        | 0.92  |
| Netherlands                     | −0.62  | −0.14   | 0.86  | 1.00        | 0.83  |
| Spain                           | −0.36  | 0.16    | 0.92  | 0.83        | 1.00  |
| Average of crossed correlations |        | 0.18    |       |             |       |
| PROCESSES                       |        |         |       |             |       |
|                                 | France | Germany | Italy | Netherlands | Spain |
| France                          | 1.00   | 0.87    | 0.80  | −0.58       | −0.02 |
| Germany                         | 0.87   | 1.00    | 0.61  | −0.78       | −0.16 |
| Italy                           | 0.80   | 0.61    | 1.00  | −0.26       | 0.41  |
| Netherlands                     | −0.58  | −0.78   | −0.26 | 1.00        | 0.51  |
| Spain                           | −0.02  | −0.16   | 0.41  | 0.51        | 1.00  |
| Average of crossed correlations |        | 0.14    |       |             |       |
| TRANSPORT                       |        |         |       |             |       |
|                                 | France | Germany | Italy | Netherlands | Spain |
| France                          | 1.00   | 0.93    | 0.97  | 0.93        | 0.93  |
| Germany                         | 0.93   | 1.00    | 0.91  | 0.84        | 0.78  |
| Italy                           | 0.97   | 0.91    | 1.00  | 0.95        | 0.93  |
| Netherlands                     | 0.93   | 0.84    | 0.95  | 1.00        | 0.93  |
| Spain                           | 0.93   | 0.78    | 0.93  | 0.93        | 1.00  |
| Average of crossed correlations |        | 0.91    |       |             |       |
| WASTE                           |        |         |       |             |       |
|                                 | France | Germany | Italy | Netherlands | Spain |
| France                          | 1.00   | −0.39   | 0.13  | −0.13       | 0.82  |
| Germany                         | −0.39  | 1.00    | 0.52  | 0.89        | −0.50 |
| Italy                           | 0.13   | 0.52    | 1.00  | 0.41        | 0.00  |
| Netherlands                     | −0.13  | 0.89    | 0.41  | 1.00        | −0.32 |
| Spain                           | 0.82   | −0.50   | 0.00  | −0.32       | 1.00  |
| Average of crossed correlations |        | 0.14    |       |             |       |

Note. In bold, average of crossed correlations of 75 % or higher.

**Table 8B**

Country cointegration tests per specific sector.

| AGRICULTURE        |               |                    |                |                    |
|--------------------|---------------|--------------------|----------------|--------------------|
| Dependent          | tau-statistic | Prob. <sup>a</sup> | z-statistic    | Prob. <sup>a</sup> |
| France             | −3.577        | 0.334              | −20.949        | 0.314              |
| Germany            | −2.641        | 0.769              | −12.628        | 0.769              |
| <b>Italy</b>       | <b>−4.817</b> | <b>0.039</b>       | <b>−47.013</b> | <b>0.000</b>       |
| Netherlands        | −1.242        | 0.993              | −6.852         | 0.969              |
| Spain              | −2.475        | 0.830              | −8.537         | 0.933              |
| BUILDINGS          |               |                    |                |                    |
| Dependent          | tau-statistic | Prob. <sup>a</sup> | z-statistic    | Prob. <sup>a</sup> |
| France             | −3.303        | 0.459              | −18.526        | 0.439              |
| Germany            | −3.660        | 0.299              | −20.002        | 0.362              |
| Italy              | −3.999        | 0.180              | −27.150        | 0.109              |
| Netherlands        | −4.132        | 0.144              | −25.981        | 0.136              |
| Spain              | −4.130        | 0.145              | −26.189        | 0.131              |
| FUEL               |               |                    |                |                    |
| Dependent          | tau-statistic | Prob. <sup>a</sup> | z-statistic    | Prob. <sup>a</sup> |
| France             | −3.406        | 0.410              | −19.311        | 0.397              |
| Germany            | −3.185        | 0.517              | −16.618        | 0.546              |
| Italy              | −3.304        | 0.459              | −15.544        | 0.608              |
| Netherlands        | −3.956        | 0.193              | −24.106        | 0.191              |
| Spain              | −3.782        | 0.252              | −23.840        | 0.200              |
| INDUSTRIAL         |               |                    |                |                    |
| Dependent          | tau-statistic | Prob. <sup>a</sup> | z-statistic    | Prob. <sup>a</sup> |
| <b>France</b>      | <b>−4.607</b> | <b>0.059</b>       | <b>−18.991</b> | <b>0.414</b>       |
| Germany            | −3.362        | 0.431              | −15.986        | 0.583              |
| Italy              | −3.240        | 0.490              | −16.590        | 0.548              |
| <b>Netherlands</b> | <b>−4.648</b> | <b>0.054</b>       | <b>−32.158</b> | <b>0.037</b>       |
| Spain              | −3.212        | 0.504              | −19.738        | 0.375              |
| POWER              |               |                    |                |                    |
| Dependent          | tau-statistic | Prob. <sup>a</sup> | z-statistic    | Prob. <sup>a</sup> |
| France             | −2.404        | 0.853              | −10.927        | 0.850              |
| Germany            | −0.696        | 0.999              | −2.667         | 0.998              |
| Italy              | −3.412        | 0.407              | −19.169        | 0.404              |
| Netherlands        | −2.440        | 0.841              | −13.843        | 0.705              |
| <b>Spain</b>       | <b>−4.802</b> | <b>0.039</b>       | <b>−32.473</b> | <b>0.034</b>       |
| PROCESSES          |               |                    |                |                    |
| Dependent          | tau-statistic | Prob. <sup>a</sup> | z-statistic    | Prob. <sup>a</sup> |
| France             | −3.205        | 0.507              | −17.234        | 0.511              |
| Germany            | −3.844        | 0.230              | −23.658        | 0.206              |
| Italy              | −3.284        | 0.468              | −16.748        | 0.539              |
| Netherlands        | −3.997        | 0.181              | −25.585        | 0.147              |
| Spain              | −3.611        | 0.319              | −19.155        | 0.405              |
| TRANSPORT          |               |                    |                |                    |
| Dependent          | tau-statistic | Prob. <sup>a</sup> | z-statistic    | Prob. <sup>a</sup> |
| France             | −2.884        | 0.664              | −13.892        | 0.703              |
| Germany            | −2.607        | 0.782              | −13.612        | 0.718              |
| Italy              | −2.421        | 0.847              | −11.257        | 0.836              |
| Netherlands        | −1.638        | 0.979              | −8.285         | 0.940              |
| Spain              | −3.384        | 0.421              | −22.350        | 0.253              |
| WASTE              |               |                    |                |                    |
| Dependent          | tau-statistic | Prob. <sup>a</sup> | z-statistic    | Prob. <sup>a</sup> |
| <b>France</b>      | <b>−6.706</b> | <b>0.000</b>       | <b>−49.160</b> | <b>0.000</b>       |
| <b>Germany</b>     | <b>−4.620</b> | <b>0.057</b>       | <b>−31.379</b> | <b>0.044</b>       |
| <b>Italy</b>       | <b>−5.121</b> | <b>0.019</b>       | <b>−35.797</b> | <b>0.015</b>       |
| Netherlands        | −4.173        | 0.134              | −25.943        | 0.137              |
| <b>Spain</b>       | <b>−7.847</b> | <b>0.000</b>       | <b>−57.206</b> | <b>0.000</b>       |

Note. Engel & Granger (1987) cointegration results. The null hypothesis is that series are not cointegrated. In bold, confidence level of 90 % or higher.

<sup>a</sup> MacKinnon [87] p-values.

approach can be based on Chebyshev polynomials over time [101], which could evaluate the impact of these non-linearities.

Finally, to address the second research question, we have examined relationships within a single sector across different countries. We have found evidence of a strong correlation in the transport sector (0.91) and a noticeable value in the industrial sector (0.77), but with no evidence of

general cointegration relationships in these sectors. Conversely, we observed a long-term cointegration relationship in the waste sector (0.14), although there was no short-term correlation. These findings suggest a potential absence of a general coordinated framework, with the exception of the previously mentioned ones. Consequently, our study may offer empirical evidence to support the findings of several papers ([25,33,34,96], etc.) that call for more coordinated policies across countries to achieve more effective emission reduction in the EU.

This paper has some limitations that could guide future research. In particular, we have limited the crossed coordination relationships by groups and studied these relationships in isolation for each group to make the paper easier to understand. Further research could examine Stechemesser et al.'s (2024) study, which found that most structural breaks were aligned with two or more policies. In this line, we could extend the traditional long-term cointegration tests [86] to an FCVAR environment [102,103]. Classical cointegration relationships ( $d = b = 1$ ) can be extended to cointegration orders ( $d, b$ ) with fractional values. This allows us to determine whether shocks are short- or long-lived. Moreover, we can use the fully modified ordinary least squares (FMOLS) method or quantile regressions to determine the cointegration equation and the value of the coefficients. This would provide a better understanding of the long-term relationship between these series.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## References

- [1] M.S. Nakhli, M. Shahbaz, M.B. Jebli, S. Wang, Nexus between economic policy uncertainty, renewable & non-renewable energy and carbon emissions: contextual evidence in carbon neutrality dream of USA, *Renew. Energy* 185 (2022) 75–85, <https://doi.org/10.1016/j.renene.2021.12.046>.
- [2] European Union Directive 2003/87/EC, Establishing a system for greenhouse gas emission allowance trading within the European Union. <https://eur-lex.europa.eu/legal-content/ES/LSU/?uri=celex:32003L0087>, 2003. (Accessed 18 March 2023).
- [3] European Commission (EC), COM(2008) 30 final. 20 20 by 2020. Europe's climate change opportunity. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, 2008. <https://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0030:FIN:en:PDF.Lastview>. (Accessed 5 June 2023).
- [4] I. Tiseo, *Emissions in the EU - Statistics & Facts*, Statista, 2023.
- [5] European Commission, Stepping up Europe's 2030 climate ambition, SWD (2020) 2020) 177 final. Retrieved from, <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020SC0177>. viewed June 06, 2023.
- [6] S. Solarin, L.A. Gil-Alana, M. Goenechea, M.A. Martín-Valmayor, Black carbon emissions persistence: evidence from 27 European Union countries using fractional integration, *Renew. Sustain. Energy Rev.* 212 (2025) 115327.
- [7] M. Christidou, T. Panagiotidis, A. Sharma, On the stationarity of per capita carbon dioxide emissions over a century, *Econ. Modell.* 33 (2013) 918–925.
- [8] N. Apergis, J.E. Payne, Per capita carbon dioxide emissions across U.S. states by sector and fossil fuel source: evidence from club convergence tests, *Energy Econ.* 63 (2017) 365–372, <https://doi.org/10.1016/j.eneco.2016.11.027>.
- [9] L.A. Gil-Alana, J. Cunado, R. Gupta, Persistence, mean-reversion and non-linearities in CO<sub>2</sub> emissions: evidence from the BRICs and G7 countries, *Environ. Resour. Econ.* 67 (4) (2017) 869–883, <https://doi.org/10.1007/s10640-016-0009-3>.
- [10] L.A. Gil-Alana, T. Trani, Time trends and persistence in the global CO<sub>2</sub> emissions across Europe, *Environ. Resour. Econ.* 73 (2019) 213–228, <https://doi.org/10.1007/s10640-018-0257-5>.
- [11] K. Tiwari, M.A. Nasir, M. Shahbaz, D. Ibrahim, I.D. Raheem, Convergence and club convergence of CO<sub>2</sub> emissions at state levels: a nonlinear analysis of the USA, *J. Clean. Prod.* 288 (2021) 125093, <https://doi.org/10.1016/j.jclepro.2020.125093>.
- [12] S. Erdogan, U.K. Pata, S.A. Solarin, et al., On the persistence of shocks to global CO<sub>2</sub> emissions: a historical data perspective (0 to 2014), *Environ. Sci. Pollut.*

- Control Ser. 29 (2022) 77311–77320, <https://doi.org/10.1007/s11356-022-21278-8>.
- [13] U.K. Pata, M. Aydin, Persistence of CO<sub>2</sub> emissions in G7 countries: a different outlook from wavelet-based linear and nonlinear unit root tests, *Environ. Sci. Pollut. Control Ser.* 30 (2023) 15267–15281, <https://doi.org/10.1007/s11356-022-23284-2>.
  - [14] J. Infante, L.A. Gil-Alana, M.A. Martin-Valmayor, GHG in EUROPE. Evidence of persistence across markets using fractional integration, *Ecol. Indic.* 160 (2024), <https://doi.org/10.1016/j.ecolind.2024.111730>.
  - [15] S.C. Bhattacharyya, W. Matsumura, Changes in the GHG emission intensity in EU-15: lessons from a decomposition analysis, *Energy* 35 (8) (2010) 3315–3322.
  - [16] J. Jia, M. Khalid Anser, M. Yao-Ping Peng, S.U. Yousaf, S. Hyder, K. Zaman, M. S. Bin Nordin, Economic determinants of national carbon emissions: perspectives from 119 countries, *Economic research-Ekonomska istraživanja* 36 (1) (2023) 1099–1119.
  - [17] G. Tariq, H. Sun, I. Ali, A.A. Pasha, M.S. Khan, M.M. Rahman, Q. Shah, Influence of green technology, green energy consumption, energy efficiency, trade, economic development and FDI on climate change in South Asia, *Sci. Rep.* 12 (1) (2022) 16376.
  - [18] G. Lapinskienė, K. Peleckis, M. Radavičius, Economic development and greenhouse gas emissions in the European Union countries, *J. Bus. Econ. Manag.* 16 (6) (2015) 1109–1123.
  - [19] J.M. Belbute, A.M. Pereira, ARFIMA reference forecasts for worldwide CO<sub>2</sub> emissions and the national dimension of the Policy efforts to meet IPCC targets, *J. Econ. Dev.* 47 (1) (2022) 1–27.
  - [20] L. Andrés, E. Padilla, Driving factors of GHG emissions in the EU transport activity, *Transp. Policy* 61 (2018) 60–74.
  - [21] W.F. Lamb, T. Wiedmann, J. Pongratz, R. Andrew, M. Crippa, J.G. Olivier, J. Minx, A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018, *Environ. Res. Lett.* 16 (7) (2021) 073005.
  - [22] M. Robaina-Alves, V. Moutinho, Decomposition of energy-related GHG emissions in agriculture over 1995–2008 for European countries, *Appl. Energy* 114 (2014) 949–957.
  - [23] M. Simionescu, Y. Bilan, P. Zawadzki, A. Wojciechowski, M. Rabe, GHG emissions mitigation in the European Union based on labor market changes, *Energies* 14 (2) (2021) 465.
  - [24] P. Mielcarek-Bocheńska, W. Rzeźnik, Greenhouse gas emissions from agriculture in EU countries—state and perspectives, *Atmosphere* 12 (11) (2021) 1396.
  - [25] V. Parravicini, P.H. Nielsen, D. Thornberg, A. Pistocchi, Evaluation of greenhouse gas emissions from the European urban wastewater sector, and options for their reduction, *Sci. Total Environ.* 838 (2022) 156322.
  - [26] J.L. Martín-Ortega, M. González-Sánchez, Sectoral composition of GDP and greenhouse gas emissions: an empirical analysis in EU27, *Environ. Dev. Sustain.* (2023) 1–28.
  - [27] P. D'Orazio, Mapping the emergence and diffusion of climate-related financial policies: evidence from a cluster analysis on G20 countries, *Int. Econ.* 169 (2022) 135–147.
  - [28] P.M. Clarkson, Y. Li, M. Pinnuck, G.D. Richardson, The valuation relevance of greenhouse gas emissions under the European Union carbon emissions trading scheme, *Eur. Account. Rev.* 24 (3) (2015) 551–580.
  - [29] A.F. Hof, M.G.J. Den Elzen, A. Mendoza Beltran, The EU 40% greenhouse gas emission reduction target by 2030 in perspective, *Int. Environ. Agreements Polit. Law Econ.* 16 (2016) 375–392, [https://doi.org/10.1016/0304-4076\(92\)90104-Y](https://doi.org/10.1016/0304-4076(92)90104-Y).
  - [30] A. Moro, L. Lanza, Electricity carbon intensity in European Member States: impacts on GHG emissions of electric vehicles, *Transport. Res. Transport Environ.* 64 (2018) 5–14.
  - [31] S. Akdag, H. Yıldırım, Toward a sustainable mitigation approach of energy efficiency to greenhouse gas emissions in the European countries, *Heliyon* 6 (3) (2020) e03396.
  - [32] A. Jäger-Waldau, I. Kougias, N. Taylor, C. Thiel, How photovoltaics can contribute to GHG emission reductions of 55% in the EU by 2030, *Renew. Sustain. Energy Rev.* 126 (2020) 109836.
  - [33] F. Cucchiella, L. D'Adamo, M. Gastaldi, S.C. Koh, E.D. Santibanez-Gonzalez, Assessment of GHG emissions in Europe: future estimates and policy implications, *Environmental Engineering & Management Journal (EEMJ)* 19 (1) (2020).
  - [34] B. Gavurova, M. Rigelsky, V. Ivankova, Greenhouse gas emissions and health in the countries of the European Union, *Front. Public Health* 9 (2021) 756652.
  - [35] S. Fawzy, A.I. Osman, N. Mehta, D. Moran, A.A.H. Al-Muhtaseb, D.W. Rooney, Atmospheric carbon removal via industrial biochar systems: a techno-economic-environmental study, *J. Clean. Prod.* 371 (2022) 133660.
  - [36] B. Doda, S.F. Verde, S. Borghesi, ETS Alignment: a Price Collar Proposal for Carbon Market Integration, *European University Institute*, 2022.
  - [37] R.R. Bhandary, K.S. Gallagher, A.M. Jaffe, Z. Myslikova, F. Zhang, M. Petrova, A. Yimere, Demanding development: the political economy of climate finance and overseas investments from China, *Energy Res. Social Sci.* 93 (2022) 102816.
  - [38] R.M. Roman-Cuesta, M. den Elzen, Z. Araujo-Gutierrez, N. Forsell, W.F. Lamb, E. McGlynn, G. Grassi, Land remains a blind spot in tracking progress under the Paris agreement due to lack of data comparability, *Commun. Earth Environ.* 6 (1) (2025) 598.
  - [39] A. Al-lami, Á. Török, Regional forecasting of driving forces of CO<sub>2</sub> emissions of transportation in central Europe: an ARIMA-based approach, *Energy Rep.* 13 (2025) 1215–1224.
  - [40] R. Inglesi-Lotz, B. Kuziboev, E. Ibadullaev, O. Saidmammatov, A.N. Çatık, Energy uncertainty and geopolitical tensions: impacts on european CO<sub>2</sub> emissions, *Energy* (2025) 138592.
  - [41] J. Chovancová, I. Petruška, U.K. Pata, P. Adamišin, Diverse pathways to decarbonization: cluster-specific impacts of energy sources on CO<sub>2</sub> emissions in the European Union, *Energy Nexus* 17 (2025) 100367.
  - [42] N.M. Doran, R.M. Bădîrcea, E. Jianu, M.E. Antoniu, R.M. Ciobanu, Ș.C. F. Ciobanu, Unveiling CO<sub>2</sub> emission dynamics under innovation drivers in the European Union, *Sustainability* 17 (8) (2025) 3463.
  - [43] S. Adebola-Solarin, L.A. Gil-Alana, M. Goenechea, M. Martin-Valmayor, Black Carbon Emissions Persistence: Evidence from 27 European Union Countries Using Fractional Integration, 2025.
  - [44] A.K.M.A. Rahman, J.C. Galiana, M. Murshed, et al., Reinvigorating the environmental Kuznets curve hypothesis in the context of highly polluted nations: evidence using advanced panel estimation techniques, *Environ. Sci. Pollut. Res.* 30 (2023) 103212–103224, <https://doi.org/10.1007/s11356-023-29237-7>.
  - [45] H. Mahmood, N. Saqib, Trade globalization, remittance inflows, and environment nexus in the Middle East and North Africa: cross-sectional dependence analysis, *Int. J. Energy Econ. Pol.* 15 (2) (2025) 657–665, <https://doi.org/10.32479/ijeeep.18961>.
  - [46] M.S. Alsubaie, H. Mahmood, Women labor participation, urbanization, and energy intensity in Saudi Arabia: asymmetrical analysis, *Int. J. Sustain. Dev. Plann.* 20 (5) (2025) 2147–2155, <https://doi.org/10.18280/ijssdp.200530>.
  - [47] M. Abbas, H. Mahmood, T.J. Qaralleh, Financial sector performance and environmental sustainability: assessing the moderating effect of social responsibility, *Int. J. Sustain. Dev. Plann.* 20 (3) (2025) 1005–1013, <https://doi.org/10.18280/ijssdp.200308>.
  - [48] V.C. Jauunky, The CO<sub>2</sub> emissions-income nexus: evidence from rich countries, *Energy Policy* 39 (3) (2011) 1228–1240, <https://doi.org/10.1016/j.enpol.2010.11.050>.
  - [49] D.A. Dickey, W.A. Fuller, Distribution of the estimators for autoregressive time-series with a unit root, *J. Am. Stat. Assoc.* 74 (1979) 427–431, 1979.
  - [50] D.A. Dickey, W.A. Fuller, Likelihood ratio statistics for autoregressive time series with a unit root, *Econometrica* 49 (1981) 1057–1072, 1981.
  - [51] X.-L. Li, D.P. Tang, T. Chang, CO<sub>2</sub> emissions converge in the 50 U.S. states — sequential panel selection method, *Econ. Modell.* 40 (2014) 320–333, <https://doi.org/10.1016/j.econmod.2014.04.003>.
  - [52] P.C.B. Phillips, P. Perron, Testing for a unit root in time series regression, *Biometrika* 75 (1988) 335–346.
  - [53] D. Kwiatkowski, P.C.B. Phillips, P. Schmidt, Y. Shin, Testing the null hypothesis of stationarity against the alternative of a unit root, *J. Econom.* 54 (1992) 159–178.
  - [54] A.K. Tiwari, P. Kyophilavong, C.T. Albulescu, Testing the stationarity of CO<sub>2</sub> emissions series in sub-saharan African countries by incorporating nonlinearity and smooth breaks, *Res. Int. Bus. Finance* 37 (2016) 527–540, <https://doi.org/10.1016/j.ribaf.2016.01.005>.
  - [55] V. Yilanci, U.K. Pata, Are shocks to ecological balance permanent or temporary? Evidence from LM unit root tests, *J. Clean. Prod.* 276 (2020), <https://doi.org/10.1016/j.jclepro.2020.124294>.
  - [56] U.K. Pata, V. Yilanci, Investigating the persistence of shocks on the ecological balance: evidence from G10 and N11 countries, *Sustain. Prod. Consum.* 28 (2021) 624–636, <https://doi.org/10.1016/j.spc.2021.06.027>.
  - [57] S.A. Solarin, U.K. Pata, S. Erdogan, I. Okumus, Persistence of shocks on sectoral non-methane volatile organic compound from 1820 to 2019: insights from a Fourier quantile unit root test, *J. Environ. Manag.* 325 (2023), <https://doi.org/10.1016/j.jenvman.2022.116436>.
  - [58] F.X. Diebold, G.D. Rudebusch, On the power of dickey- fuller tests against fractional alternatives, *Econ. Lett.* 35 (1991) 155–160.
  - [59] U. Hassler, J. Wolters, On the power of unit root tests against fractional alternatives, *Econ. Lett.* 45 (1) (1994) 1–5.
  - [60] G.M. Caporale, L.A. Gil-Alana, Fractional cointegration and tests of present value models, *Rev. Financ. Econ.* 13 (3) (2004) 245–258.
  - [61] G.M. Caporale, L.A. Gil-Alana, Fractional integration and cointegration in US financial time series data, *Empir. Econ.* 47 (2014) 1389–1410, <https://doi.org/10.1007/s00181-013-0780-8>.
  - [62] L.A. Gil-Alana, M. Monge, Global CO<sub>2</sub> emissions and global temperatures: are they related, *Int. J. Climatol.* 40 (15) (2020) 6603–6611, <https://doi.org/10.1002/joc.6601>.
  - [63] G. Claudio-Quiroga, L.A. Gil-Alana, CO<sub>2</sub> emissions persistence: evidence using fractional integration, *Energy Strategy Rev.* 43 (2022).
  - [64] L.R. Asturias-Schaub, L.A. Gil-Alana, CO<sub>2</sub> emissions in Latin America: a time series perspective based on fractional integration, *Environ. Sci. Pollut. Control Ser.* 30 (50) (2023) 109585–109605.
  - [65] F. Taghizadeh-Hesary, A. Zakari, N. Yoshino, I. Khan, Leveraging on energy security to alleviate poverty in Asian economies, *Singapore Econ. Rev.* 68 (4) (2023) 1063–1090.
  - [66] C. Brooks, *Introductory Econometrics for Finance*, fourth ed., Cambridge University Press, 2019.
  - [67] G.M. Caporale, L.A. Gil-Alana, C. Poza, The COVID-19 pandemic and the degree of persistence of US stock prices and bond yields, *Q. Rev. Econ. Finance* 86 (2022) 118–123, <https://doi.org/10.1016/j.qref.2022.06.007>.
  - [68] G.M. Caporale, L.A. Gil-Alana, A. Imeri, Exogenous shocks and time-varying price persistence in the EU27, *J. Appl. Econ.* 27 (1) (2024), <https://doi.org/10.1080/15140326.2024.2329857>.
  - [69] E.J.A. Abakah, G.M. Caporale, L.A. Gil-Alana, Economic policy uncertainty: persistence and cross-country linkages, *Res. Int. Bus. Finance* 58 (2021) 101442, <https://doi.org/10.1016/j.ribaf.2021.101442>.
  - [70] C.W. Granger, Testing for causality: a personal viewpoint, *J. Econ. Dynam. Control* 2 (1980) 329–352.

- [71] C.W. Granger, Some properties of time series data and their use in econometric model specification, *J. Econom.* 16 (1) (1981) 121–130.
- [72] C.W. Granger, R. Joyeux, An introduction to long-memory time series models and fractional differencing, *J. Time Anal.* 1 (1) (1980) 15–29.
- [73] J.R.M. Hosking, Lagrange-multiplier tests of multivariate time-series models, *J. Roy. Stat. Soc. B* 43 (2) (1981) 219–230.
- [74] R.T. Baillie, Long memory processes and fractional integration in econometrics, *J. Econom.* 73 (1) (1996) 5–59.
- [75] L.A. Gil-Alana, P.M. Robinson, Testing of unit root and other nonstationary hypotheses in macroeconomic time series, *J. Econom.* 80 (2) (1997) 241–268.
- [76] L. Mayoral, Further evidence on the statistical properties of real GNP, *Oxf. Bull. Econ. Stat.* 68 (2006) 901–920.
- [77] F. Sowell, Maximum likelihood estimation of stationary univariate fractionally integrated time series models, *J. Econom.* 53 (1–3) (1992) 165–188.
- [78] J.A. Doornik, M. Ooms, Computational aspects of maximum likelihood estimation of autoregressive fractionally integrated moving average models, *Comput. Stat. Data Anal.* 42 (3) (2003) 333–348.
- [79] M. Crippa, D. Guizzardi, F. Pagani, M. Banja, M. Muntean, E. Schaaf, W. Becker, F. Monforti-Ferrario, R. Quadrelli, A. Risquez Martin, P. Taghavi-Moharamli, G. Grassi, S. Rossi, J. Melo, D. Oom, A. Branco, J. San-Miguel, G. Manca, E. Pisoni, E. Vignati, F. Pekar, GHG emissions of all world countries – JRC/IEA 2024 report, Luxembourg, <https://data.europa.eu/doi/10.2760/4002897,JRC138862>, 2024.
- [80] J. Bai, P. Perron, Computation and analysis of multiple structural change models, *J. Appl. Econom.* 18 (1) (2003) 1–22.
- [81] A. Stechemesser, N. Koch, E. Mark, E. Dilger, P. Klösel, L. Menicacci, D. Nachtigall, F. Pretis, N. Ritter, M. Schwarz, H. Vossen, A. Wenzel, Climate policies that achieved major emission reductions: global evidence from two decades, *Science* 385 (6711) (2024) 884–892, <https://doi.org/10.1126/science.adl6547>.
- [82] T. Haas, H. Sander, Decarbonizing transport in the European Union: emission performance standards and the perspectives for a European green deal, *Sustainability* 12 (20) (2020) 8381, <https://doi.org/10.3390/su12208381>.
- [83] L.A. Gil-Alana, S. Chang, M. Balcilar, G.C. Aye, R. Gupta, Persistence of precious metal prices: a fractional integration approach with structural breaks, *Resour. Policy* 44 (2015) 57–64, <https://doi.org/10.1016/j.resourpol.2014.12.004>.
- [84] O.S. Yaya, L.A. Gil-Alana, A.A. Adepoju, Fractional integration and structural breaks in bank share prices in Nigeria, *Review of Development Finance* 5 (1) (2015) 13–23, <https://doi.org/10.1016/j.rdf.2014.07.004>.
- [85] G.M. Caporale, L.A. Gil-Alana, C. Poza, Persistence, non-linearities and structural breaks in European stock market indices, *Q. Rev. Econ. Finance* 77 (2020) 50–61, <https://doi.org/10.1016/j.qref.2020.01.007>.
- [86] Robert F. Engle, C.W.J. Granger, Co-integration and error correction: representation, estimation, and testing, *Econometrica* 55 (1987) 251–276.
- [87] J.G. MacKinnon, Numerical distribution functions for unit root and cointegration tests, *J. Appl. Econom.* 11 (6) (1996) 601–618. <http://www.jstor.org/stable/2285154>.
- [88] ICAP, International carbon action partnership. <https://icapcarbonaction.com/en/ets/german-national-emissions-trading-system> Lastview, 2025. (Accessed 24 March 2025).
- [89] K. Lindloff, Beyond ‘Trading Up’: Environmental Federalism in the European Union: the Case of Vehicle Emission Legislation, Nomos, Baden-Baden, Germany, 2016. ISBN 3848730510.
- [90] R. Danielis, M. Scorrano, M. Giansoldati, Decarbonising transport in Europe: trends, goals, policies and passenger car scenarios, *Res. Transport. Econ.* 91 (2022), <https://doi.org/10.1016/j.retrec.2021.101068>.
- [91] J. Sporkmann, Y. Liu, S. Spinler, Carbon emissions from European land transportation: a comprehensive analysis, *Transp. Res. Part D* 121 (2023), <https://doi.org/10.1016/j.trd.2023.103851>.
- [92] C. Panoutsou, S. Germer, P. Karka, S. Papadokostantakis, Y. Kroyan, M. Wojcieszky, K. Maniatis, P. Marchand, I. Landalv, Advanced biofuels to decarbonise European transport by 2030: markets, challenges, and policies that impact their successful market uptake, *Energy Strategy Rev.* 34 (2021) 100633, <https://doi.org/10.1016/j.esr.2021.100633>.
- [93] IEA, Global EV Outlook 2024, IEA, Paris, 2024. <https://www.iea.org/reports/global-ev-outlook-2024>. Licence: CC BY 4.0.
- [94] K. Dolge, A. Barisa, V. Kirsanovs, D. Blumberga, The status quo of the EU transport sector: cross-Country indicator-based comparison and policy evaluation, *Appl. Energy* 334 (2023), <https://doi.org/10.1016/j.apenergy.2023.120700>.
- [95] E. Marišová, M. Valenčíková, EU legislative support in the waste sector, *E. U. Agrar. Law* 10 (2) (2021) 21–27, <https://doi.org/10.2478/eual-2021-0009>.
- [96] K. Tsimnadis, G.L. Kyriakopoulos, Investigating the role of municipal waste treatment within the European Union through a novel created common sustainability point system, *Recycling* 9 (3) (2024) 42, <https://doi.org/10.3390/recycling9030042>.
- [97] A.A. Kalveram, S.R. Pătarlăgeanu, A.F. Gheorghe, Disparities in the EU-27 regarding pollution and generated waste, *Proceedings of the International Conference on Business Excellence* 18 (1) (2024) 1542–1551, <https://doi.org/10.2478/picbe-2024-0127>.
- [98] J. Brodny, M. Tutak, Analysis of the diversity in emissions of selected gaseous and particulate pollutants in the European Union countries, *J. Environ. Manag.* 231 (2019) 582–595.
- [99] I. Martínez-Zarzoso, M. Vidovic, A.M. Voicu, Are the central east European countries pollution havens? *J. Environ. Dev.* 26 (1) (2017) 25–50.
- [100] M. Dueñas, A. Mandel, Regional Emission Dynamics Across Phases of the EU ETS, 2024, <https://doi.org/10.48550/arXiv.2408.15438>.
- [101] J.C. Cuestas, L.A. Gil-Alana, Testing for long memory in the presence of non-linear Chebyshev polynomials in time, *Stud. Nonlinear Dynam. Econom.* 20 (1) (2016) 57–74.
- [102] S. Johansen, M. Nielsen, Likelihood inference for a nonstationary fractional autoregressive model, *J. Econom.* 158 (1) (2010) 51–66, <https://doi.org/10.1016/j.jeconom.2010.03.006>.
- [103] S. Johansen, M.Ø. Nielsen, Likelihood inference for a fractionally cointegrated vector autoregressive model, *Econometrica* 80 (2012) 2667–2732.