

# Impact of innovation and economic structure on CO<sub>2</sub> emissions in Poland and Spain: Evidence from Bayesian Fourier autoregressive distributed lag modelling

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## ABSTRACT

**Objective:** The article aims to determine the impact of innovation, the level of economic activity (measured as GDP per capita), and the added value of key economic sectors (agriculture, industry, and services) on CO<sub>2</sub> emissions in Poland and Spain, and to assess whether innovations could significantly reduce emissions considering economic structural differences and dynamics.

**Research Design & Methods:** The study employed a quantitative research design. It used Fourier autoregressive distributed lag (FARDL) and Bayesian Fourier autoregressive distributed lag (Bayesian FARDL) econometric models to analyse data from 1995 to 2022. The sample encompassed macroeconomic data for Poland and Spain.

**Findings:** The study revealed significant differences between Poland and Spain. In Poland, despite a higher number of patent applications, technological innovations did not significantly affect CO<sub>2</sub> emissions, indicating limited application in high-emission sectors. Conversely, in Spain, innovations positively impacted CO<sub>2</sub> emissions, particularly in energy-intensive sectors. Energy consumption strongly influenced emissions in both countries, with Spain showing a more pronounced long-term effect. GDP negatively affected CO<sub>2</sub> emissions in Poland over the long run, whereas the study did not identify such relationship for Spain. The industrial and service sectors significantly impacted emissions and innovation in Poland, while in Spain, the industrial sector and patent activity were crucial determinants.

**Implications & Recommendations:** The findings highlight the need for tailored economic and energy policy adjustments in both countries, especially focused on innovation, to enhance the effectiveness of their green transitions.

**Contribution & Value Added:** This article contributes by providing a comparative analysis of Poland and Spain using advanced econometric methods, identifying country-specific dynamics between innovation, sectoral structure, the level of economic activity, and CO<sub>2</sub> emissions, thus providing novel insights for policymaking in the context of sustainability. Moreover, the study applied a relatively new and advanced Bayesian Fourier ARDL modelling, enhancing the analysis' methodological rigour.

**Article type:** research article

**Keywords:** CO<sub>2</sub> emissions; innovation; economic development; sectoral analysis; Bayesian ARDL

**JEL codes:** Q54, O44, C11

Received: 16 April 2025

Revised: 20 January 2026

Accepted: 30 January 2026

## Suggested citation:

Suproń, B., Łącka, I., Brelik, A., & Minguez Vera, A. (2026). Impact of innovation and economic structure on CO<sub>2</sub> emissions in Poland and Spain: Evidence from Bayesian Fourier autoregressive distributed lag modelling. *Entrepreneurial Business and Economics Review*, 14(2), 199-223. <https://doi.org/10.15678/EBER.2026.140211>

## INTRODUCTION

Contemporary global economic challenges related to global warming, but also other economic, environmental, social, political and military problems, are forcing European Union (EU) countries and their economic entities to seek innovative solutions in many areas. These innovations will allow for taking the necessary measures against the negative consequences of global warming and reducing greenhouse gas emissions (as envisioned in the European Green Deal and other international agreements

(Kabeyi *et al.*, 2021). These challenges require implementing green technologies in all areas of the economy (Olaleru *et al.*, 2021). According to Yusuf *et al.* (2018), technological environmental innovations are the way forward for Malaysia's sustainable development that will help reduce global risks. They will enable EU member states to make the energy transition by reducing fossil fuel reliance (oil, gas, coal, and lignite), lowering the carbon intensity of their economies, and implementing circular economy principles, all while striving to remain competitive within the EU and globally.

As Oyebanji *et al.* (2022) note, such technological innovation may result from in-country research and development, as well as the transfer of technology from abroad. However, this requires the intensification of sustainable and integrated non-market activities. The strengthening of patent protection and developing public-private partnerships are important for the development of environmental technologies that aim to solve global climate problems and reduce national or local energy and environmental risks (Oyebanji *et al.*, 2022). Recurring environmental disruptions, including climate-related hazards and ecosystem degradation, create substantial obstacles for countries striving to advance sustainable development. Therefore, ensuring economic growth while safeguarding ecological stability has become a shared priority for governments worldwide (Shin *et al.*, 2022).

There have been protracted discussions in the EU on the necessary basis for implementing the European Green Deal, and some member countries exhibit social and political resistance to the pace and scope of the green transition on account of its effects on the competitiveness of economies and the social costs of these processes (Stockmann, 2024). Additional influences are the recent changes in US policy on sustainable development and the geopolitical and military situation in the world, which represent strong threats to security in general. Altogether, these factors create a less favourable environment for a broad transformation within the EU and its member states. Sgaravatti *et al.* (2024) indicate that, to achieve a zero-carbon economy, the EU should revise its current approach.

This requires forming strategic partnerships to advance global decarbonisation, while simultaneously addressing competitiveness and strategic autonomy. The development level, economic structure, dependence on fossil fuels, carbon intensity, and innovation capacity all influence the differing positions of member states on the green and energy transition (implementation of environmentally friendly technologies and renewable energy sources to ensure sustainable development, and the development and application of strategies and practices aimed at protecting natural resources) (Tomaszewski, 2020). Characteristics of individual countries are shaped, among other things, by how long they have been members of the EU. There are development and technological gaps between Central European countries and the older EU member states. A recent International Energy Agency (IEA) report indicates that global CO<sub>2</sub> emissions climbed to 37.4 billion tonnes in 2023, with the majority originating from fossil-fuel combustion. To curb emissions and reduce dependence on conventional fossil energy sources, both the United States and the European Union have introduced a Government Green Fund (GGF) designed to support the expansion of emerging renewable energy sectors, including wind and solar power (Ibikunle *et al.*, 2017; Silva *et al.*, 2016).

The above issues inspired a study on the relationship between innovation, GDP, economic structure and value added of the dominant sectors in the economy and the size of CO<sub>2</sub> emissions in two selected countries belonging to the so-called new and old European Union. One of them was Poland, which joined the EU in 2004. The other country studied was Spain, which has been a member of the EU since 1986. These countries differ in many respects, such as their economic structure, the innovation level, but also the rate of CO<sub>2</sub> emissions. Spain belongs to the group of moderate innovators, while Poland has been included for years first in the group of catching up and then emerging innovators (European Commission, 2024a). The emissions of the Spanish economy are lower than those of other member countries and has been declining over the years. On the other hand, Poland is one of the leaders in CO<sub>2</sub> emissions in the EU, and although it has significantly reduced the carbon intensity of its economy in recent years, it is still among the highest in Europe (Łacka *et al.*, 2024). Climate mitigation efforts encompass not only lowering consumption levels but also achieving net negative emissions. Under a business-as-usual (BAU) trajectory, estimates suggest that between 640 and 950 Gt of CO<sub>2</sub> would need to be extracted from the atmosphere to keep global warming within the 1.5°C threshold by the end of the century (Luderer *et al.*, 2018). By 2024, five years after the launch of the European Green Deal, EU countries (including Poland) had

significantly reduced their reliance on coal and gas in favour of renewable energy sources, enabling progress in decarbonising the Polish economy (Rosslowe *et al.*, 2025).

The research aimed to understand and determine the impact of innovation, the level of economic activity (measured as GDP per capita), and the value added of key economic sectors (agriculture, industry and services) on CO<sub>2</sub> emissions in Poland and Spain. Furthermore, the study sought to assess whether innovation can significantly contribute to reducing CO<sub>2</sub> emissions, considering the differences in economic structure and development trajectories between the two countries. While working on the research problem, we formulated the following research questions:

- RQ1:** What are the differences in the innovation level between Poland and Spain and what factors account for them?
- RQ2:** Does innovation contribute to reducing CO<sub>2</sub> emissions in Poland and Spain?
- RQ3:** Do specific sectors of the economy influence the development of innovation in Poland and Spain?
- RQ4:** Do CO<sub>2</sub> emissions depend on the value added generated by each economic sector in Poland and Spain?
- RQ5:** Do the level of economic activity (measured as GDP per capita) and energy consumption significantly impact CO<sub>2</sub> emissions in Poland and Spain?

A literature review indicates that this issue has not yet been explored to much depth, despite its importance in the context of current economic development conditions. The findings may provide valuable insights for shaping economic policies that support innovation in EU countries facing significant challenges in the green transition with Poland being a notable example. The long-term scope of the study (1995-2022) made it possible to capture changes in the analysed variables influenced by events such as Poland's EU accession, the 2008-2013 global financial crisis, the COVID-19 pandemic, and Russia's invasion of Ukraine, along with the resulting energy crisis.

To address the research questions and objectives, we employed a range of methods, including literature review, critical source analysis, inductive and econometric techniques, including the Fourier autoregressive distributed lag (ARDL) model and the Bayesian autoregressive distributed lag model. The analysis used data on GDP per capita, CO<sub>2</sub> emissions per capita, energy consumption, and patent applications from the World Development Indicators (WDI) for Poland and Spain. We used patent applications as an indicator of innovation activity. We also assessed the level of innovation in both countries using the European Innovation Scoreboard and the Global Innovation Index (WIPO). To examine the impact of economic structure and transformation on CO<sub>2</sub> emissions, we analysed the value added by agriculture, industry, and services (as shares of GDP), enabling evaluation of the relative sectoral contributions to emissions. We sourced all structural data from the WDI database. The novelty and originality of this study lie in its comparative perspective, specifically analysing Poland and Spain, and applying advanced econometric methods (Fourier ARDL and Bayesian ARDL), which previous studies on this subject have rarely combined.

The article is structured as follows. The first section provides an introduction, and the second section presents a literature review. The third section discusses the research methods and data sources used. The fourth section presents the study results, and the fifth section includes a discussion of the results. The final, sixth section concludes the research and gives recommendations for policymakers.

## LITERATURE REVIEW

### **Innovation, Technological Capabilities, and the European Union's Response to Global Challenges**

At the beginning of the 2020s, European Union member states were facing global challenges that determined their environmental, energy, economic, social, health (*e.g.*, pandemics), digital, and geopolitical security (Balfour *et al.*, 2024). Countering these threats and turning them into development opportunities and gaining resilience to these and new unpredictable challenges are the basis for achieving prosperity, long-term sustainability and competitiveness of the community's economy

and its members (Calliari *et al.*, 2022). Achieving these ambitious goals requires the use of innovation and research and development (R&D) focused on green and digital technologies. The Oslo Manual describes innovation as encompassing both the actions undertaken to develop something new and the outcomes of these efforts. It refers to a product or process, or a combination of the two, that is substantially different from what an organisation previously used or offered, and which has been either introduced to users or implemented within the organisation (OECD, 2018). European Commission experts state that any innovation that reduces negative impacts on the environment, promotes increased resilience of that environment or increases efficiency in the use of natural resources can be called an eco-innovation. Such innovative products, services, and technological solutions are expected to help achieve the goals of the European Green Deal, *i.e.*, climate neutrality and the circular economy (European Commission, 2024a). The implementation of eco-innovation in the economy requires support from the state and its policies. Grasping the nature of these interdependencies is essential for formulating sound policies that support environmental protection and advance sustainable agricultural development (Iyke-Ofoedu *et al.*, 2024).

One widely used measure of innovative performance is the count of patent applications submitted by non-residents through the Patent Cooperation Treaty (PCT) system to national patent offices. Under this agreement, a PCT application indicates the applicant's intention to seek protection for an invention in at least three countries, and potentially in all treaty signatories. In 2025, 142 countries were members of this agreement. This is not the only measure of a country's innovation, but due to the long period of WIPO's collection of information and the large number of countries covered by the PCT, it can be used in long-term comparative analyses of countries' innovation performance and technological capabilities. The data collected by WIPO also allowed us to compare other metrics and indicators on intellectual property protection, such as trademark and design applications, geographical indications and plant varieties. Mendonça *et al.* (2004) and Flikkema *et al.* (2019) argue that trademarks constitute an important indicator of innovation and industrial dynamism.

Technological progress involves the introduction of new and improved machinery, equipment, tools and new technologies that enable more efficient use of existing and new resources. In the growth-accounting perspective, technological progress refers specifically to the discovery and adoption of more efficient production methods that increase total factor productivity. Both processes form part of broader innovation dynamics, although innovation activity and technological progress remain analytically distinct concepts. They affect economic growth and the competitiveness of the economy and its entities. The level of economic development is strongly correlated with the level of intellectual property protection and invention protection rights, as shown by Greenhalgh and Rogers (2010) and Sherwood (2019). Studies by Lundvall (2010) and Cooke *et al.* (1997) show that national and regional intellectual property protection systems and ecosystems are important factors in countries' innovation and economic success. As Squicciarini *et al.* (2013) note, these areas also improve economic productivity and growth.

A study by Su and Moaniba (2017) shows that in each country, patents for new technologies to combat climate change are determined by the amount of greenhouse gas emissions (including CO<sub>2</sub>). A country's emissions affect inventive activity and the number of patent applications. Simultaneously, the implementation of new solutions, which are costly and resource-intensive for economic players, need protection from copying and imitation by competitors. The lack of or inadequate protection of intellectual property means that companies cannot recoup the high costs of environmental technologies, which may discourage the development and diffusion of such innovation. On the other hand, copying someone else's technology, imitating a product or process innovation by a given enterprise, may enable it to allocate its R&D resources to create other green innovations (Oyebanji *et al.*, 2022).

In contrast, a study by Musah *et al.* (2021) shows that as the economy grows, the demand for energy increases, which becomes a heavy financial and social burden in less developed and emerging economies that mainly use fossil fuels as an energy source. As countries become wealthier, societies tend to show greater support for environmental protection and for pursuing sustainable development. The existence of an inverted U-shaped relationship between environmental deterioration and economic growth is indicated by the environmental Kuznets curve (EKC) developed by Grossman and Krueger (1995). Scholars have repeatedly empirically verified this relationship over the past three decades. We may find an exten-

sive list of such analyses in the works of Genstwa (2020), Lau *et al.* (2023), Gültekin *et al.* (2023), and Suproń (2025). These studies have provided ample evidence to support the course of EKC. Wang *et al.* (2024) conclude that due to contemporary global challenges, especially climate challenges, further research on the shape of the global EKC and understanding the determinants of its course are necessary. The results of their analysis indicate that there is an environmental Kuznets curve in the form of the letter N. Its course is determined by as many as 12 additional factors from four areas: institutions and risks, digital technologies, resource and energy use, and other social factors (omitted from EKC analysis in the past). The study by Wang *et al.* (2024) revealed six distinct groups of countries, each adopting different strategies for reducing greenhouse gas emissions among the 214 nations analysed.

According to the European Commission report assessing innovation performance in the European Union and several non-EU countries, innovation is viewed as a fundamental driver of long-term competitiveness (Koç *et al.*, 2025). It supports productivity improvements and is crucial for environmentally sustainable development, macroeconomic resilience and social fairness (European Commission, 2024b). Innovation constitutes an important factor in promoting development and convergence in the countries and regions of the European Union. Technological innovations are essential to realise the full potential of new energy.

Many researchers also focus on their impact on energy poverty alleviation from the perspective of technological innovation and its impact on the development of green technologies (Albino *et al.*, 2014; Dong *et al.*, 2022; Meka'a *et al.*, 2024). Despite significant improvements in the level of innovation in the member countries over the past thirty years, there is still a strong variation in this regard between countries and regions in Europe. For certain underdeveloped and peripheral regions of Europe, there is even talk of the existence of an innovation gap (European Commission, 2024b). This is revealed by the results of reports published by the European Commission dedicated to assessing the innovativeness of EU regions and countries, *i.e.*, the Regional Innovation Scoreboard and the European Innovation Scoreboard studies.

### **Innovativeness Comparison Based on Innovation Rankings**

The most recent report of the European Commission (European Commission, 2024b) evaluates innovation performance across EU countries as well as a group of non-EU economies. This provides a basis for comparing Poland and Spain with respect to their innovation profiles and recent trends. WIPO's Global Innovation Index 2024 provides additional insights.

The European Commission's 2024 study shows that Poland belongs to the group of emerging innovators and ranks 23rd in the innovation ranking of the 27 member countries. For years, despite improvement in the results of the Summary Innovation Index (SII), the country has been among those countries with the lowest innovation indicators (Romania, Bulgaria, Latvia, Slovakia, Croatia). Poland's position is evidenced by its distance in terms of innovation not only from the innovation leaders in the European Union (Denmark, Sweden, Finland, the Netherlands), but also from some of the other post-communist countries that joined the EU in 2004, such as Estonia (*strong innovators*), Slovenia, the Czech Republic, Lithuania and Hungary (*moderate innovators*). In 2024, the synthetic innovation index for Poland accounted for 65.9% of the EU SII average. Analysing the components of the SII in the EU ranking, one can note that in some areas of this indicator, Poland performs better than e, and in others its achievements are much lower. Such SII components include human resources (72.2% of the EU average), digitalisation (80.1% of the EU average), use of information technologies (99.1% of the average), linkages (73.3% of the average), intellectual assets (85.9% of the EU average). Poland performs much worse in such areas of innovation as attractive research systems (37.5% of the EU average), innovators (45.5%), employment impacts (59.3%) and environmental sustainability (60.3% of the average), sales impacts (60.4%), finance and support (61.7%), and firm investments (62.2%). Examining the detailed components of the various areas that make up the synthetic innovation index, one can determine the relative strengths and weaknesses of Poland's innovation.

These analyses indicate that Poland has significant limitations in important areas that determine the innovation improvement. They account for its weaknesses in this regard. These weaknesses in-

clude: a small share of foreign doctoral students as a proportion of all doctoral students, a small number of doctoral graduates and a small number of patent applications, a small amount of spending on innovation (both public and private), a small number of SMEs introducing product and process innovations, a small amount of spending by venture capital funds, a small amount of investment in innovation per employee, a small number of SMEs entering into partnerships with other entities, low resource productivity, insufficient development and use of environmental technologies, and a small share of enterprises that earn revenues from exporting products that are new to the market or new to companies, and exporting knowledge-intensive services. Poland's relative strengths include design applications, a population with tertiary education, and enterprises providing ICT training

Spain is in a completely different position in the European Innovation Scoreboard 2024. It is ranked as a *moderate innovator* (*moderate innovators*). In the innovation ranking of the EU member countries, it ranks 14th with a score of 89.9% of the EU SII average. Spain performs well above the EU average in such innovation areas as human resources (124.3% of the average), digitalisation (144.9%), and finance and support (103.9%). By contrast, in areas such as attractive research systems (90.2% of the EU average), firm investments (61.8%), innovators (61.8%), use of information technologies (89.3%), intellectual assets (81.3%), employment impacts (61.3%), sales impacts (79.0%), linkages (92.8%) and environmental sustainability (96.8%), Spain performs worse than the EU average.

Spain's relative innovation weaknesses include knowledge-intensive services exports (33.5% of average), employment in innovative enterprises (44.6%) and SMEs introducing business process innovations (49.9%), innovation expenditures per person employed (52% of average), but also patent applications (68.7%). In contrast, Spain's innovation strengths include sales of new-to-market and new-to-firm innovations (170.5% of the EU average), individuals with above basic overall digital skills (148.7%), population with tertiary education (148.4%), resource productivity (136.9%), direct and indirect government support of business R&D (116.4%), and venture capital expenditures (114.9%)

A comparison of Poland and Spain in terms of the synthetic innovation index and its components reveals that there are both similarities and differences in strengths and weaknesses in this regard. In the context of the research problem undertaken, we may note that both countries studied are characterised by the occurrence of a lower number of patent applications than the EU average, and a small number of innovative SMEs. An analysis of the results of the Global Innovation Index 2024 (World Intellectual Property Organization) leads to similar conclusions about the positions of Poland and Spain in the innovation rankings. In this study, Poland is ranked 40th, while Spain is ranked 28th.

## RESEARCH METHODOLOGY

### Variables and Data Sources

In this study, we used data from the World Development Indicators (WDI) database for Poland and Spain. The maximum period for which complete data was available for both countries was 1995-2022. The dependent variable (Y) was CO<sub>2</sub> emissions per capita, expressed in metric tons. Among the independent variables were energy consumption (in kilograms of oil equivalent per capita), EC, GDP per capita (in constant 2015 prices, expressed in USD), GDP, and innovation activity, represented by the number of patent applications (IP). We used the number of patent applications as an indicator of innovation output rather than technological progress in the growth-accounting sense. This choice followed previous empirical studies that use patent counts as a proxy for innovative activity (Adedoyin *et al.*, 2022; Kirikkaleli & Sofuoğlu *et al.*, 2023; Kortum & Lerner, 1998; Kumaresan & Miyazaki, 1999; Samargandi, 2017; Serener *et al.*, 2023; Sohag *et al.*, 2015).

Furthermore, we considered several sectoral variables to capture the effect of economic structure on CO<sub>2</sub> emissions: agricultural value added, industrial value added, and services value added, each expressed as a share of GDP. However, because these variables were components of GDP, they exhibited strong collinearity and move in the same direction as GDP itself, which made their joint inclusion in the ARDL specification inappropriate. For this reason, they were not included in the ARDL estimations but served *ex post* in the causality analysis to explore sector-specific dynamics.

### Methods and Model

The purpose of the analysis was to examine the impact of innovation, the level of economic activity (measured as GDP per capita), and the value added of key economic sectors (agriculture, industry, and services) on CO<sub>2</sub> emissions (the so-called ecological footprint) in Poland and Spain between 1995 and 2022. Moreover, the analysis assessed whether innovation could significantly contribute to reducing CO<sub>2</sub> emissions, considering differences in economic structure and development trajectories between the two countries. The model intentionally combined variables expressed in levels (CO<sub>2</sub> emissions, GDP per capita, energy consumption) with a flow-type variable (annual patent applications). This specification was consistent with the ARDL framework, which allows for mixed integration orders, and reflects the aim to analyse how long-run equilibrium levels of CO<sub>2</sub> respond to dynamic innovation activity.

We used a Fourier ARDL model for the analysis, considering GDP and energy consumption as control variables. Equation (1) represents the empirical analysis model, which was based on the extended environmental concept of the Kuznets curve, presented in logarithmic long-term form.

$$\ln CO_{2t} = \beta_0 + \beta_1 \ln GDP_t + \beta_2 \ln EC_t + \beta_3 \ln IP_t + \varepsilon_t \quad (1)$$

in which:

$\ln CO_2$  - the natural logarithm of carbon emissions per capita;

$\ln GDP$  - the natural logarithm of GDP per capita (real based on 2015 data);

$\ln EC$  - the natural logarithm of energy consumption per capita;

$\ln IP$  - the natural logarithm of the number of patent applications;

$\varepsilon_t$  - the error term.

Before estimating the ARDL models, we verified the order of integration of all variables. We examined the series stationarity using the Fourier ADF and Fourier KPSS tests, which are specifically designed to account for smooth structural breaks and low-frequency nonlinearities that may bias classical unit-root procedures (Enders & Lee, 2012). We selected frequency parameter  $k$  in the Fourier approximation using the Bayesian information criterion (BIC). One should interpret it solely as a flexible representation of smooth structural breaks rather than as an indicator of economic cycles. From a theoretical perspective, we expected CO<sub>2</sub> emissions, GDP per capita, and energy consumption to be I(1), while annual patent applications, being a flow variable – I(0). To assess practical sources of low power in unit-root/stationarity testing, we screened the innovations from the estimated UECM models for serial correlation (Ljung-Box), ARCH-type heteroskedasticity (ARCH-LM), and non-normality/outliers (Jarque-Bera; standardised residuals).

Standard cointegration tests are not applicable when variables exhibit different integration orders. To overcome this problem, Pesaran *et al.* (2001) proposed a cointegration test approach within the ARDL model. This method makes it possible to account for independent variables with different degrees of integration, provided that the dependent variable is an I(1) process. In addition, Narayan (2005) extended the use of ARDL tests in the study of cointegration by developing arrays of critical F-test values specific to small samples. The relationship of cointegration between variables is examined by comparing test statistics with lower and upper bounds labelled I(0) and I(1). The basic hypothesis that there is no cointegration is rejected if the test statistic is higher than the key upper bound values. The ARDL model automatically decomposes the relationship into long-run coefficients and short-run adjustments. Re-parameterising the ARDL into an error-correction model (ECM) made this structure explicit: the differenced variables describe short-run effects, while the error-correction term (ECT), derived from the estimated long-run equation, measures the speed at which the system corrects deviations from long-run equilibrium. A negative and significant ECT confirms cointegration. Equation (2) represents the ARDL model used in this study. We modelled all variables (CO<sub>2</sub>, GDP, EC, IP) in natural logarithms.

$$\Delta \ln CO_{2,t} = \beta_0 + \beta_1 (\ln CO_2)_{t-1} + \beta_2 (\ln GDP)_{t-1} + \beta_3 (\ln EC)_{t-1} + \beta_4 (\ln IP)_{t-1} + \sum_{i=0}^{\rho} \gamma_i' (\Delta \ln CO_2)_{t-i} + \sum_{i=0}^{\rho} \vartheta_i' (\Delta \ln GDP)_{t-i} + \sum_{i=0}^{\rho} \sigma_i' (\Delta \ln EC)_{t-i} + \sum_{i=0}^{\rho} \phi_i' (\Delta \ln IP)_{t-i} + \varepsilon_t \quad (2)$$

in which:

$\Delta$  - represents the first difference;

$t$  - represents the lag length;

$\varepsilon_t$  - is the error term.

We chose the optimal lag length for small samples based on Schwarz's information criterion (SC). Following the methodology of Pesaran *et al.* (2001), we determined the cointegration relationship using both the F-test and the t-test described in equations (3) and (4). Moreover, we adopted a test proposed by McNown *et al.* (2018), which was developed to evaluate the null hypothesis, as shown in equation (5).

$$H0A: \beta_1 = \beta_2 = \beta_3 = \beta_4 = 0 \quad (3)$$

$$H0B: \beta_1 = 0 \quad (4)$$

$$H0C: \beta_2 = \beta_3 = \beta_4 = 0 \quad (5)$$

The time series under study reflected numerous structural changes resulting from Poland's economic transition, the 2008 and 2013 crises, and the COVID-19 pandemic (2020-2022). To address this, we adopted an innovative approach by extending the ARDL model with Fourier functions (Eq. 7). This method captures fluctuations and breaks in the data without the need for dummy variables (Adebayo, 2020; Olayeni *et al.*, 2021). Moreover, the Fourier terms allow for capturing nonlinear patterns in the data, eliminating the need for additional tests of structural changes or modifications to the estimated model to account for these changes (Serener *et al.*, 2023; Yilanci & Pata, 2020). Equation (6) shows the full FARDL model used in the study. We selected the optimal lag length using AIC/BIC, and for both countries the preferred specification was ARDL (1,1,1,1), which corresponds to  $\rho = 2$  in the parameterisation used in Equation (6).

$$\Delta \ln CO_{2,t} = \beta_0 + d(t) + \beta_1 (\ln CO_2)_{t-1} + \beta_2 (\ln GDP)_{t-1} + \beta_3 (\ln EC)_{t-1} + \beta_4 (\ln IP)_{t-1} + \sum_{i=0}^{\rho} \gamma_i' (\Delta \ln CO_2)_{t-i} + \sum_{i=0}^{\rho} \vartheta_i' (\Delta \ln GDP)_{t-i} + \sum_{i=0}^{\rho} \sigma_i' (\Delta \ln EC)_{t-i} + \sum_{i=0}^{\rho} \phi_i' (\Delta \ln IP)_{t-i} + \varepsilon_t \quad (6)$$

$$d(t) = \alpha_1 \sin\left(\frac{2\pi kt}{T}\right) + \alpha_2 \cos\left(\frac{2\pi kt}{T}\right) \quad (7)$$

in which:

$K$  - is the number of specific frequencies selected using the Bayesian Information Criterion (BIC);

$t$  - is the time index, and 'T' is the sample size;

$T$  - is the sample size.

To test causality, we used the cumulative Fourier-frequency Granger causality test proposed by Enders and Jones (2016). Fourier-frequency Granger causality is a temporal causality analysis method that uses the Fourier transform to capture complex relationships between variables in the frequency domain. The technique assesses how causal relationships change over different frequency ranges and then combines the results to provide an overall picture of causality (Nazlioglu *et al.*, 2019). This approach allows for more precise modelling of nonlinear relationships and the identification of dependencies across different frequencies. Such patterns are difficult to detect using classical methods, particularly in the presence of structural breaks (Zheng *et al.*, 2023). To increase the power of test statistics in a small sample, we used bootstrapping to estimate probability values.

To confirm the results' robustness and to better capture nonlinearity and uncertainty, the study also employed a Bayesian ARDL model. In the Bayesian version of the model, we included the same Fourier (harmonic) terms as in the classical Fourier ARDL specification. Thus, the Bayesian ARDL model shares the same likelihood function and deterministic Fourier structure as the classical specification; the difference lies solely in the estimation approach, which relies on Bayesian inference using HMC/NUTS rather than classical (frequentist) estimation.

We estimated the model using the Hamiltonian Monte Carlo (HMC) algorithm, a type of Markov Chain Monte Carlo (MCMC) method. The Bayesian model, unlike frequency inference, assumes that the observed data are constant and the estimation parameters are random (Bernardo & Smith, 2009). The Bayesian model assumes that  $\epsilon_t \sim N(0, \sigma^2)$  are error residuals.

We used the No-U-Turn Sampler (NUTS) algorithm to estimate the posteriori parameters. We conducted the estimation using the BRMS package in R. The number of iterations was set to 4 000 (including 1 000 warm-up iterations, the so-called burn-in), and the number of chains was set to 4. The following prior distributions were assumed for the model parameters: one for the coefficients (Equation 8) and another for the error variance (Equation 9). In the Bayesian ARDL estimation, all regression coefficients (including lagged terms) and the intercept were assigned independent Normal (0, 1) priors, while the residual standard deviation  $\sigma$  followed a  $\theta \sim t_3(0, 2.5)$  prior, consistent with the default specification in the brms package.

$$\beta_0, \beta_1, \beta_2, \beta_3, \beta_4, \gamma_i', \vartheta_i', \sigma_i', \phi_i' \sim N(0, 1) \quad (8)$$

$$\sigma \sim Student - t(3, 0, 2.5) \quad (9)$$

We configured the MCMC algorithm with the following control settings: *adapt\_delta* = 0.8 and *max\_treedepth* = 12. We assessed model fit using diagnostics including convergence statistics, trace plot analysis, and evaluation of posterior parameter distributions.

## RESULTS AND DISCUSSION

### Exploratory Data Analysis

Table 1 presents descriptive statistics for the time series studied for Poland and Spain from 1995 to 2022. Poland had higher average CO<sub>2</sub> emissions (8.48 t per capita) than Spain (6.62 t per capita) during the period studied, with a lower standard deviation (0.42 vs. 1.12). Emissions varied from 7.82 t per capita to 9.59 t per capita in Poland and from 4.58 t per capita to 8.47 t per capita in Spain, suggesting greater variability in Spain. The average GDP per capita in Spain (USD 25 110.23) was higher than in Poland (USD 10 409.08), but Poland showed greater variability in these values (standard deviation of 3 263.43 in Poland vs. 2 156.49 in Spain), indicating faster economic change in Poland during the studied period. Energy consumption in Poland (average: 1 672.97 kg oe/capita) was lower than in Spain (1 879.38 kg oe/capita), with less scatter in the data for Poland. This suggests greater stability in the country's energy consumption.

Agriculture's contribution to GDP averaged 3.11% in Poland and 3.01% in Spain. This indicates the similar importance of this sector in both countries, with greater variability in Poland. Spain had a higher share of the service sector in GDP (63.97%) than Poland (55.59%), which may indicate a more advanced service-based economy. In contrast, Poland had a higher share of industry in GDP (29.45%) than Spain (24.21%). The average level of patent applications was higher in Poland (3 102.89) than in Spain (2 580.46), but Poland was also characterised by greater variability in this indicator. The results suggest that Poland underwent a more rapid economic transition between 1995 and 2022, with a strong industrial sector, while Spain showed greater development in the service sector and more stable trends in some indicators. The high volatility of the series in Poland was due to the faster pace of economic development and economic transition during the studied period.

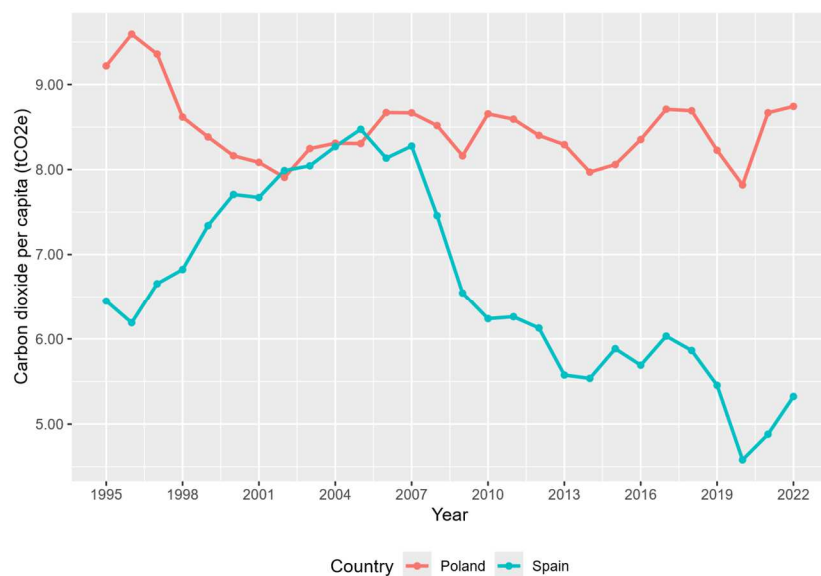
Figures 1-3 shows trends of selected variables for the studied countries over time. Notably, CO<sub>2</sub> emissions per capita remained relatively stable in Poland from 1995 to 2004, and then began to decline slightly after 2007, reaching their lowest level around 2013. In Spain, during the analysed period, emissions were higher than in Poland until 2010, reaching a value close to 10 tCO<sub>2</sub>e per capita in the 1990s, and then decreased successively (especially after 2008), which we may link to the economic crisis and changes in the energy structure.

Figure 2 shows the per capita energy consumption of the two countries from 1995 to 2022. In Spain, energy consumption grew rapidly in the 1990s and peaked in 2004-2007 (over 2 200 kg of oil equivalent per capita). After 2008, a marked reduction in energy consumption was observed, related to the recession and a change in the approach to energy management. In Poland, energy consumption was lower than in Spain throughout the period. However, since 2004, there has been a gradual increase. This phenomenon reflects the economic development and improvement in the quality of life in Poland, especially after joining the EU. At the same time, it indicates the dominance of fossil energy sources in the country's energy mix, which influenced high CO<sub>2</sub> emission rates.

**Table 1. Descriptive statistics for Poland**

Variable	Mean		Standard deviation		Min		Max	
	Poland	Spain	Poland	Spain	Poland	Spain	Poland	Spain
CO <sub>2</sub>	8.48	6.62	0.42	1.12	7.82	4.58	9.59	8.47
GDP	10 409.08	25 110.23	3 263.43	2 156.49	5 628.45	20 001.79	17 178.67	28 087.90
EC	1 672.97	1879.38	166.14	194.75	1 435.93	1 557.19	1 991.24	2 247.66
AGDP	3.11	3.01	0.79	0.66	2.24	2.27	5.58	4.39
SGDP	55.59	63.97	2.14	4.02	49.15	59.17	58.86	68.53
IGDP	29.45	24.21	1.52	3.54	26.64	19.87	33.48	28.33
IP	3 102.89	2 580.46	861.80	730.85	2 028.00	1 150.00	4 676.00	3 632.00

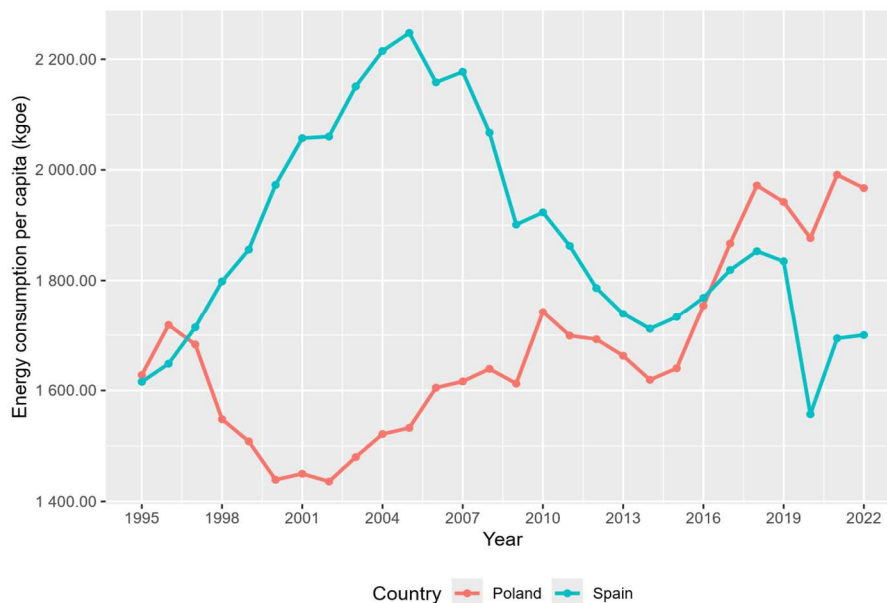
Source: own study in Stata.



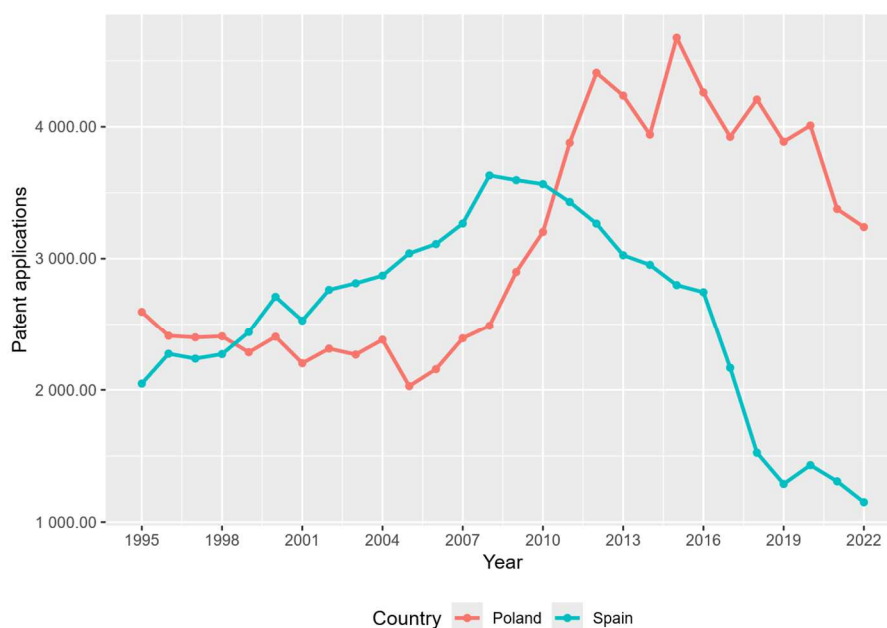
**Figure 1. Carbon dioxide (CO<sub>2</sub>) per capita (tCO<sub>2</sub>e) in Poland and Spain**

Source: own elaboration based on investment results.

Figure 3 illustrates trends in patent applications as an indicator of innovation activity in both countries. In Spain, the number of filings increased steadily from the 1990s, peaking between 2010 and 2013 (over 4 500 applications), before declining sharply due to financial constraints following the economic crisis. In Poland, the trend was different: the number of filings gradually increased until around 2010, reaching just over 3 000 filings, but from then on, it began a steady decline, albeit a slower one than in Spain. This indicates differences in innovation potential and economic structures between the countries.



**Figure 2. Energy consumption per capita (kg of oil equivalent) in Poland and Spain**  
 Source: own elaboration based on investment results.



**Figure 3. Number of patent applications in Poland and Spain**  
 Source: own elaboration based on investment results.

**Model Results and Causality Analysis**

The conventional ADF/KPSS procedures are known to exhibit low power in finite samples and to be sensitive to departures from their maintained assumptions. Notably, ADF inference depends on an appropriate specification of deterministic components (intercept and/or trend) and on sufficient lag augmentation so that innovations are approximately white noise. Meanwhile, KPSS inference depends on the correct specification of the deterministic component (level- versus trend-stationarity) and on long-run variance estimation. Given the annual sample (1995-2022), potential power losses may arise from small-sample size, MA-type dependence, heteroskedasticity, and outliers. Fourier-augmented

ADF/KPSS tests primarily mitigate deterministic misspecification by flexibly capturing smooth/low-frequency shifts without dating breaks. However, they do not fully remove potential distortions due to finite-sample size, heteroskedasticity, or non-Gaussian errors.

Given that the data exhibit numerous structural breaks, we applied the Fourier ADF unit root test (Enders & Lee, 2012) and the Fourier KPSS test (Becker *et al.*, 2006). We selected the delays and number of frequencies ( $k$ ) based on Schwarz's information criterion. Tables 2 and 3 shows the tests' results. In the case of Poland, most of the variables were stationary at the level, but a few variables achieved stationarity when differentiated. In the case of Spain, most of the variables were non-stationary at the level but became stationary after the first differentiation. Thus, the data were suitable for applying the ARDL model to both countries, since the variables were both  $I(0)$  and  $I(1)$ .

Table A1-A2 (Appendix A) reports the conventional ADF/KPSS results under standard deterministic specifications. The overall integration assessment was consistent with the Fourier-based evidence; whenever interpretation differed, we relied on the Fourier tests because smooth deterministic shifts were plausible for the analysed macro series.

**Table 2. Fourier unit root test for Poland**

Variables	k	ADF (level)	ADF ( $\Delta$ , first difference)	KPSS (level)	KPSS ( $\Delta$ , first difference)
CO <sub>2</sub>	2	-4.154*	-4.992*	0.377	0.083
GDP	1	-5.060*	-4.391**	0.241*	0.095
IP	2	-2.266	-5.133*	1.053*	0.045
EC	5	-4.839*	-3.176	0.130*	0.065
AGDP	5	-4.324*	-3.389	0.067**	0.020
SGDP	5	-3.627**	-5.260*	0.125*	0.032
IGDP	5	-3.425	-4.270**	0.078*	0.033

Note: \*, \*\*, and \*\*\* denote 10%, 5%, and 1% significance levels, respectively.

Source: own study in Aptech Gauss/tsplib library.

**Table 3. Fourier unit root test for Spain**

Variables	k	ADF (level)	ADF ( $\Delta$ , first difference)	KPSS (level)	KPSS ( $\Delta$ , first difference)
CO <sub>2</sub>	1	-2.944	-4.342**	0.113	0.040
GDP	3	-3.283**	-3.864**	1.332*	0.184
IP	4	-1.418	-4.590*	0.795*	0.111
EC	5	-1.529	-5.752*	0.357*	0.068
AGDP	4	-2.867***	-5.588*	0.732*	0.191
SGDP	2	-0.979	-3.870**	0.619*	0.081
IGDP	1	-2.743	-3.702**	0.808*	0.040

Note: \*, \*\*, and \*\*\* denote 10%, 5%, and 1% significance levels, respectively.

Source: own study in Aptech Gauss/tsplib library.

Table 4 shows the results of tests in the cointegration area conducted using the Fourier ARDL model. We selected the optimal Fourier frequency (harmonic variable  $k$ ) based on Schwarz's information criterion and was set at 2.429 for Poland and 0.870 for Spain. In both Poland and Spain, there was strong evidence of cointegration between variables, which means that the Fourier ARDL model could be used to analyse the long-run and short-run relationships between variables. In addition, the results of the degeneration test (F-test) ruled out problems with the identifiability of cointegration in the model.

In the next stage of the analysis, we applied the ARDL model to examine both short-term dynamics and long-term relationships. Table 5 presents the results of the estimated Fourier ARDL model for Poland and Spain, including both short- and long-term effects, along with diagnostic test outcomes. In the final ARDL-ECM representation, we retained only statistically significant dynamic terms. We found short-run IP terms ( $\Delta IP$ ) and some auxiliary lagged coefficients (including  $\psi$  and selected  $\gamma$ -parameters) to be insignificant and thus we omitted them from the reported tables in line with standard ARDL

reduction practice. Moreover, the Fourier coefficients ( $\alpha_{1j}$ ,  $\alpha_{2j}$ ) were part of the deterministic component of the model, but we did not include them in Tables 5 and 6 because they did not affect the interpretation of the long- and short-run elasticities of CO<sub>2</sub> emissions.

**Table 4. Bound test for Fourier ARDL**

Country	Bounds F-test	Bounds t-test	Degenerate cointegration F-test
Poland	6.80*	-6.42*	8.56*
Spain	5.56*	-5.17*	12.20*

Note: \*, \*\*, and \*\*\* denote 10%, 5%, and 1% significance levels, respectively.

Source: own study in R-studio/ARDL library.

The results of the study indicate that in both countries, energy consumption is the main determinant of CO<sub>2</sub> emissions in both the short and long term, with its impact being stronger in Spain in the long term. In Poland, GDP had a small but significant impact on CO<sub>2</sub> emissions in the long term, while in Spain there was no significance in the long term. In the short term, in both countries, GDP had a positive effect on CO<sub>2</sub> emissions. In Spain, the number of patent applications had a significant positive impact on CO<sub>2</sub> emissions in the long term, which may be related to innovation in high-carbon sectors. In Poland, this impact was not significant. ECT denotes the error correction term from the ARDL error-correction representation and captures the speed at which deviations from the long-run equilibrium are corrected. In addition, Spain had a faster rate of recovery (ECT=-0.92) than Poland (ECT=-0.74).

**Table 5. Fourier ARDL-ECM model**

Variable	Poland	Spain
Intercept	0.25 (0.22)	-7.62 *** (1.56)
lnCO <sub>2t-1</sub>	-0.74 *** (0.08)	-0.92 *** (0.15)
lnEC <sub>t-1</sub>	0.30 *** (0.04)	1.33 *** (0.24)
lnGDP <sub>t-1</sub>	-0.09 ** (0.03)	-0.20 (0.18)
lnIP	-0.01 (0.03)	0.17 *** (0.04)
ECT <sub>t-1</sub>	-0.74 *** (0.08)	-0.92 *** (0.15)
ΔlnEC	0.73 *** (0.07)	0.68 * (0.29)
ΔlnGDP	0.56 *** (0.11)	0.78 * (0.30)
<b>Error Metrics and Diagnostic Tests</b>		
R <sup>2</sup> / R <sup>2</sup> adjusted	0.939 / 0.913	0.863 / 0.812
AIC	-153.704	-106.429
Log-likelihood	86.852	62.215
X <sup>2</sup> BG	7.48	10.9
X <sup>2</sup> LM	2.07	5.25
X <sup>2</sup> Ramsey RESET	0.212	0.984
W <sub>LR</sub>	11.7***	6.73***

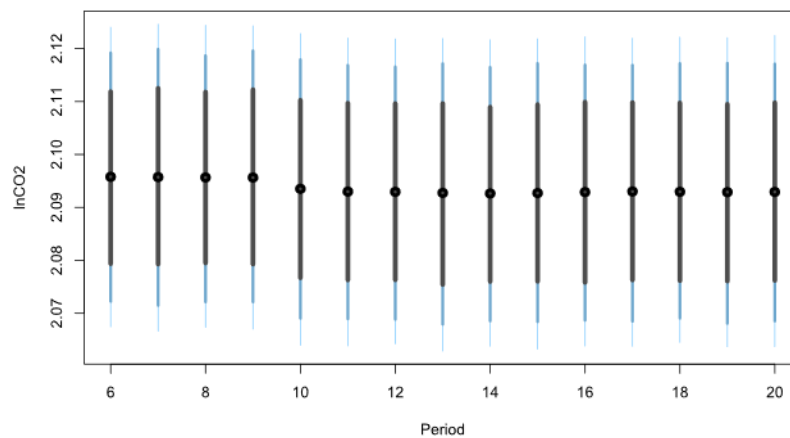
Note: \*, \*\*, and \*\*\* denote 10%, 5%, and 1% significance levels, respectively. The column 'Variable' corresponds to the parameters defined in Equation (6):  $\beta$  for long-run coefficients,  $\gamma$  and  $\phi$  for short-run dynamics.

Source: own study in R-studio/ARDL library.

Diagnostics confirmed that Fourier ARDL models were well fitted and stable. The absence of autocorrelation, heteroskedasticity, and specification problems indicates that the results of the models were reliable and could be used to analyse relationships between variables. In addition,

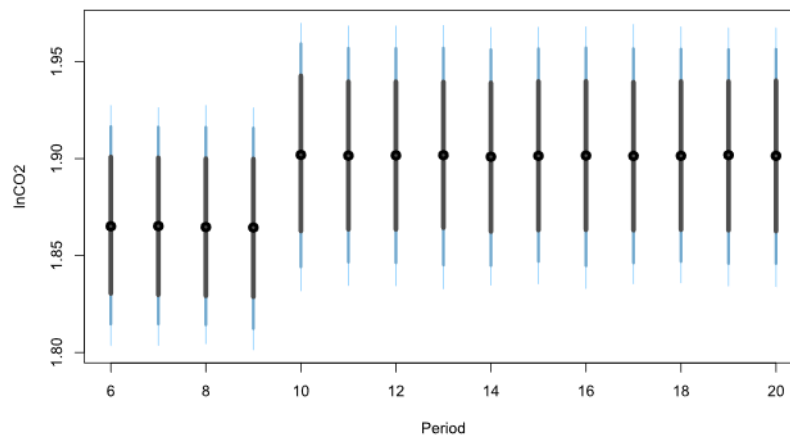
Figure A1 (Appendix A) shows CUSUM plots, which confirm the stability of the tested models over time. The UECM residual screening did not indicate strong serial correlation, ARCH effects, non-normality, or outliers (Table A3, Appendix A).

We used the estimated ARDL model to estimate the impact of innovation, measured by the number of patent applications, using the *dynardl* package. For this scenario analysis, we assumed a 15% long-term increase in patent applications for both countries. Figure 4 presents the predicted average CO<sub>2</sub> emission values, with error bars indicating uncertainty ranges based on confidence intervals. The estimated long-run response indicates that a change in the number of patent applications in Poland ( $\Delta IP$ ) induced a small decrease in CO<sub>2</sub> emissions in the long term (Figure 4). Figure 5 presents the estimated effect of changes in the number of patent applications ( $\Delta IP$ ) on the logarithm of CO<sub>2</sub> emissions ( $\ln CO_2$ ) in Spain. Patent applications expressing innovation in Spain had a small but positive effect on CO<sub>2</sub> emissions in the long run.



**Figure 4. Impact of a 15% increase in patent applications in Poland: Scenario analysis**

Source: own elaboration based on investment results.



**Figure 5. Impact of a 15% increase in patent applications in Spain: Scenario analysis**

Source: own elaboration based on investment results.

In the next stage of the study, we used a Bayesian approach to confirm the robustness of the results obtained, to capture nonlinear patterns, and to more fully account for uncertainty in the model parameters and results. Furthermore, the Fourier Bayesian ARDL model enabled a better capture of potential asymmetric responses of CO<sub>2</sub> emissions to changes in energy consumption, GDP or the number of patent applications, which could be more difficult with traditional ARDL models. As with the traditional ARDL model, the Bayesian model indicated that the key driver of CO<sub>2</sub> emissions in both countries is energy consumption, with the effect stronger in Spain. In Poland, the level of

GDP per capita also played an important role in emissions, which may suggest the more carbon-intensive nature of the current stage of economic development (Table 6).

**Table 6. Fourier Bayesian ARDL model**

Predictors	Estimates	CI (95%)	Estimates	CI (95%)
	Poland		Spain	
Intercept	0.25 (0.26)	-0.27 to 0.78	-8.34 (3.09)	-14.34 to -1.82
lnCO <sub>2</sub> <sub>t-1</sub>	-0.72 (0.12)	-0.95 to -0.24	-0.61 (0.19)	-0.95 to -0.50
lnEC <sub>t-1</sub>	0.30 (0.08)	0.15 to 0.46	1.39 (0.47)	0.39 to 2.27
lnGDP <sub>t-1</sub>	-0.09 (0.04)	-0.17 to -0.01	-0.20 (0.30)	-0.79 to 0.43
lnIP	-0.01 (0.04)	-0.09 to 0.06	0.21 (0.10)	-0.01 to 0.40
ΔlnEC	0.72 (0.08)	0.55 to 0.89	0.75 (0.31)	0.11 to 1.36
ΔlnGDP	0.55 (0.14)	0.26 to 0.84	0.72 (0.37)	-0.01 to 1.46
Observations	27		27	
R <sup>2</sup> Bayes	0.936		0.973	
MCMC iterations	4000		4000	
MCMC sample size	12000		12000	
Log (ML)	40.69		27.09	
Acceptance rate	0.85		0.83	

Note: \*, \*\*, and \*\*\* denote 10%, 5%, and 1% significance levels, respectively. The short-run IP term ( $\Delta IP$ ) was excluded from the final specification because it was statistically insignificant.

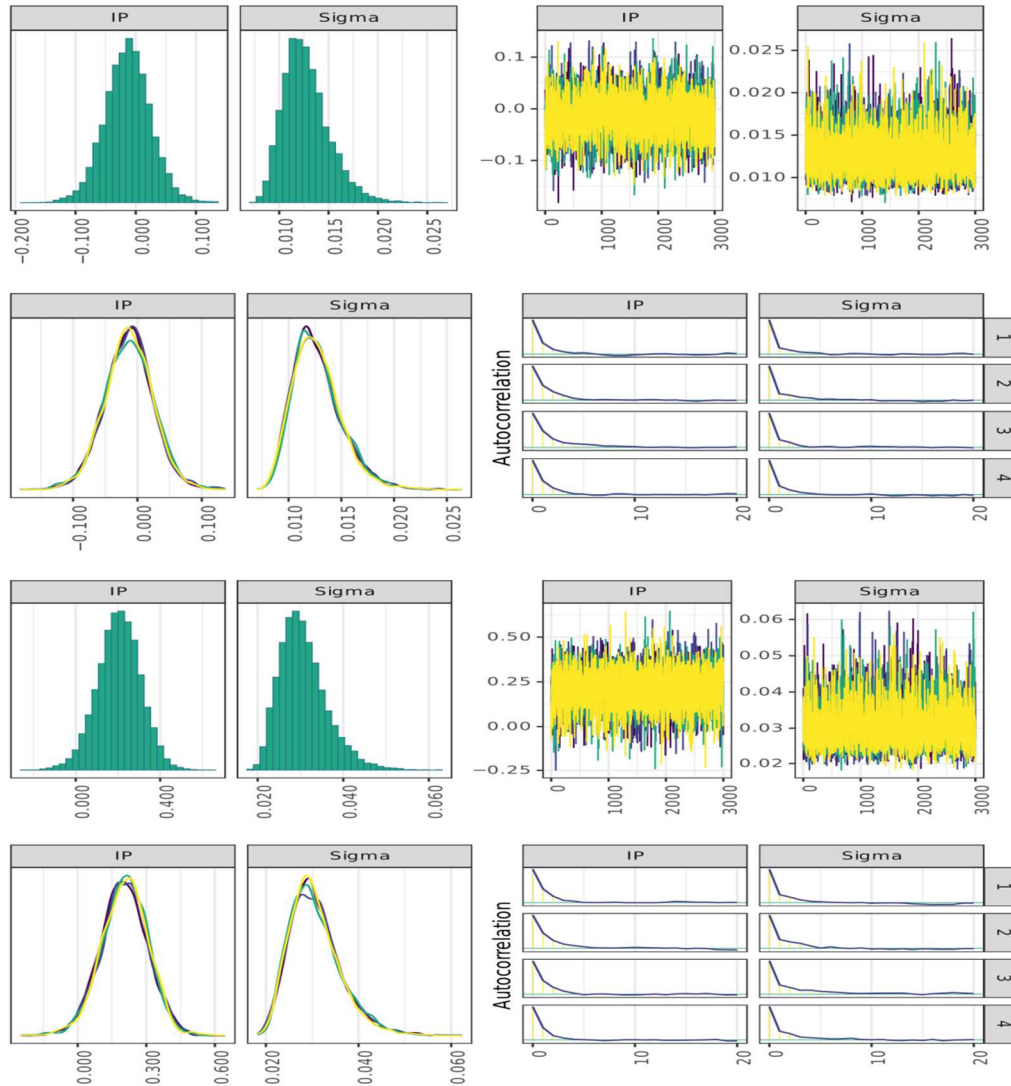
Source: own study in R-studio/Rstan library.

The analysis of credibility intervals for the number of patent applications in the case of Poland, presented in Figure 6, indicates that there was no significant effect of the number of patents on CO<sub>2</sub> emissions in Poland. The wide credibility interval confirms this. It includes both positive and negative values. The high uncertainty of the estimate indicates that there was no clear relationship between innovation activity and CO<sub>2</sub> emissions in Poland. The point estimate for Spain suggests that a higher number of patent applications may be associated with increased CO<sub>2</sub> emissions, but the credibility interval included zero, indicating that the effect was not statistically significant. The width of the CI interval indicates uncertainty in estimating the impact of the number of patent applications on CO<sub>2</sub> emissions. However, the concentration of the middle of the interval within positive values indicates that their impact was in a small but positive way on CO<sub>2</sub> emissions.

Figure 7 shows the causal relationships (Fourier Granger causality) between innovation, basic economic sectors, and CO<sub>2</sub> emissions in Spain and Poland. Table A4 (Appendix A) presents full data for the causality tests conducted. Before interpreting the causality results, it is important to clarify the nature of the previously mentioned collinearity. The sectoral variables (agriculture, industry, and services value added), expressed as shares of GDP, were mechanically correlated with each other because they constitute the components of GDP. However, we did not analyse them jointly nor entered them simultaneously with GDP per capita in any causality equation. Instead, we examined each sectoral variable separately, which prevented multicollinearity from influencing the direction or significance of the causality results. Therefore, the observed collinearity did not affect the validity of the Granger causality findings.

In Poland, the service sector showed causality toward technological innovation (IP) and CO<sub>2</sub> emissions. At the same time, like services, industry displayed bidirectional causality with innovation activity. In turn, CO<sub>2</sub> emissions exhibited causality toward the agricultural sector. Causality was shaped

differently for Spain. Changes in the industrial sector (IGDP) showed causality toward the number of patent applications (IP). In contrast, the number of patent applications, the industrial sector, and the service sector were significant causal factors for changes in CO<sub>2</sub> emissions. Moreover, in the case of Spain, in line with previously established model results, the assumption of a direct effect of innovation on CO<sub>2</sub> emissions showed uncertainty.

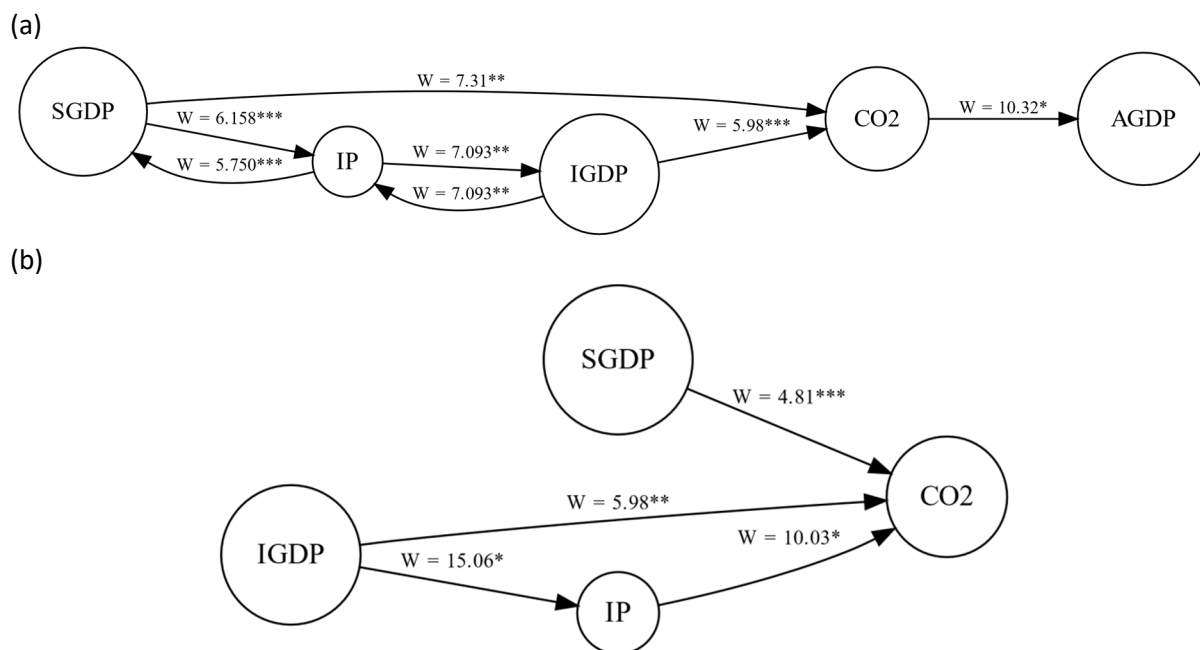


**Figure 6. Fourier Bayesian ARDL for Poland and Spain: IP impact for CO<sub>2</sub> emission, histogram, trace, density, and ACF**

Source: own elaboration based on investment results.

### Discussion

The findings show that technological innovations in Poland have had a limited impact on CO<sub>2</sub> reduction, which may be due to the low intensity of these innovations in high-carbon sectors. In contrast, in Spain, despite there being fewer patent applications, innovations have shown a positive impact on CO<sub>2</sub> emissions, especially in energy-intensive industries. The study confirmed the dominant role of energy consumption as a key determinant of CO<sub>2</sub> emissions in both Poland and Spain, although its long-term impact was more pronounced in Spain. The results also indicate differences in the way that the level of economic activity (measured as GDP per capita) affects CO<sub>2</sub> emissions. Namely, in Poland, higher GDP per capita was associated with a significant, long-term reduction in emissions. Meanwhile, we did not observe any such effect in Spain.



**Figure 7. Fourier Granger causality test result**

Source: own elaboration based on investment results.

Comparing these results with the results of previous studies is challenging for several reasons. Firstly, there is a limited number of studies that cover the effects of innovation, economic structure, and the level of economic activity on CO<sub>2</sub> emissions simultaneously. In addition, few of those studies were conducted in the context of the EU, which makes it impossible to directly relate to the results of other authors. Secondly, the use of Fourier ARDL methodology and Bayesian ARDL model distinguishes this study from most analyses limited to standard Granger causality tests, based on simple regression. Thirdly, the selection of Poland and Spain as countries representing different levels of innovation development and economic structure makes comparison with analyses using different criteria for classifying countries difficult.

Nevertheless, when we compare these results with other studies analysing the impact of innovation and economic structure on CO<sub>2</sub> emissions, we find some parallels. Ghorbal *et al.* (2024) analysed data for South Korea and indicated that a higher number of domestic patent applications contributes to environmental degradation. In contrast, in a similar study for Saudi Arabia, Samargandi (2017) indicated that technological innovation was insignificant in contributing to CO<sub>2</sub>. Similarly, Genstwa's (2020) results provide evidence of a stable long-term association between the level of economic activity (measured as GDP per capita) and emissions, following the Environmental Kuznets Curve (EKC) theory – a pattern reflected in the results obtained for Poland. The direction of the effect of GDP per capita on the reduction of CO<sub>2</sub> emissions from the economy is also in line with the results obtained by Myszczyzyn and Suproń (2021) for the countries of the Visegrad Group, which includes Poland.

Other studies have arrived at divergent conclusions. Georgescu and Kinnunen (2024) analysed CO<sub>2</sub> emissions in Finland using the FARDL model and indicated that innovation had a significant negative impact on CO<sub>2</sub> emissions, but only in the long term. Kirikkaleli, Abbasi *et al.* (2023) obtained similar results for Denmark. Referring only to eco-innovations, Sadiq *et al.* (2024) indicated their positive impact on reducing CO<sub>2</sub> emissions in BRICS countries. Sun *et al.* (2022) confirmed similar results for China. In contrast, the FARDL model for Poland proposed by Addai and Kirikkaleli (2023) indicates that higher GDP per capita contributed to CO<sub>2</sub> emissions in Poland.

In attempting to reconcile the findings of this study with those of earlier studies, the conclusions of Albino *et al.* (2014) are significant. They noted that the influence of technological innovation on emissions varies according to a country's economic structure and development profile, which aligns

with the findings obtained for Poland and Spain. Gültekin *et al.* (2023) showed a significant role for the structure of the economy in determining CO<sub>2</sub> emissions, especially the industrial sector, which is in line with the results for both Poland and Spain. Some differences in the results may also result from different methodologies, periods of analysis, and the specifics of the studied economies.

In conclusion, the results presented suggest that the effectiveness of innovation policies and their impact on CO<sub>2</sub> emissions strongly depend on the economic and structural peculiarities of individual countries. The diversity of the results obtained indicates the need for further research, especially in identifying the determinants of the effectiveness of innovation in reducing CO<sub>2</sub> emissions under different economic conditions.

## CONCLUSIONS

We aimed to assess the dynamic impact of the level of economic activity (measured as GDP per capita), economic structure, and the level of innovation on CO<sub>2</sub> emissions in Poland and Spain. For this purpose, we analysed time series data from 1995-2022 using advanced econometric methods, including the Fourier ARDL model and the Bayesian ARDL model.

The analysis shows that in Poland, increases in GDP per capita are linked with lower CO<sub>2</sub> emissions in the long run, offering partial support for the environmental Kuznets curve (EKC) hypothesis. However, for Spain, we did not identify any statistically meaningful long-term association between economic performance and CO<sub>2</sub> emissions. These differences result from the specific structural conditions of the economies in both countries. Analysing the role of technological innovation, we observed that in Poland, their impact on CO<sub>2</sub> emissions is limited, mainly due to their low intensity in carbon-intensive sectors (*e.g.*, cement production, metal production, production of chemicals and chemical products, and production and processing of coke and refined petroleum products). On the other hand, in Spain, technological innovation contributes to an increase in emissions, which may be due to the concentration of these innovations in energy-intensive industries.

Poland is a country belonging to the group of emerging innovators in the European Union's innovation ranking, and has a lower SII than Spain, which is ranked among moderate innovators. Weaknesses of Polish innovation include unattractiveness and insufficient efficiency of innovation systems, insufficient financing of innovation from private and public funds, insufficient development of innovation support from venture capital funds, too few innovative small and medium-sized enterprises, too few patent applications, and unwillingness of business entities to cooperate in innovation processes. As previously stated, Poland's inherent weaknesses constrain its capacity to address the demands of the contemporary economic landscape effectively. Moreover, these limitations hinder Poland's potential for leveraging innovation to enhance economic sustainability and reduce carbon dioxide emissions. Spain's greater innovativeness is due to the presence of such strengths as the ability to generate revenues from the sale of innovations, *i.e.*, new products, services or technological solutions for the market or new to companies, a large share of people with digital skills, the percentage of people educated to the third level of studies, direct and indirect government support for private investment in R&D, and the use of venture capital funds to finance innovative activities. These factors positively determine the development of eco-innovation and energy transition processes. The structure of the economy has also emerged as a key determinant of CO<sub>2</sub> emissions. Poland, with a dominant industrial sector, faces greater challenges in reducing emissions. Spain, with a developed service sector, shows different mechanisms for affecting emissions and has a higher potential for adaptation in terms of innovation.

In conclusion, the findings of the current study suggest the need to intensify policies that support the development of environmental technologies and increase energy efficiency as key elements in the effective reduction of CO<sub>2</sub> emissions. Evidently, these recommendations are important for Poland, where the innovation potential is underutilised, and the process of transitioning to a low-carbon energy source is progressing at a more gradual pace. Future development strategies should account for local economic peculiarities and promote activities that support green economic transformation, emphasising innovation and sustainable sectoral practices.

The findings imply that the effectiveness of CO<sub>2</sub> emission reductions requires adapting public policies to the specifics of the national economic structure and innovation potential. Poland should particularly focus on increasing energy efficiency and supporting the innovation sector to accelerate the green transition and reduce emissions more effectively. In Spain, policies should incorporate the specificity of innovation, focusing on eco-innovation in high-carbon sectors, while promoting diversification and supporting innovation in low-carbon sectors. This study constitutes an element of the ongoing discourse about the need to adapt economic strategies to national particularities, with a view to the effective mitigation of greenhouse gas emissions.

Limitations of the study include the use of data relating to only two countries and a specific period of analysis. The results may not be directly transferable to other countries with different economic structures or technological conditions. In the future, we recommend expanding the analysis to include more countries and employing more complex models that capture the interactions between various structural and innovation factors. An additional direction for future research would be to use panel data and apply a panel ARDL framework, allowing for joint estimation across countries while accounting for heterogeneity.

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## Appendix A:

**Table A1. ADF/KPSS tests for Poland data**

Variable	Test	ADF (c)	ADF (c+t)	KPSS ( $\mu$ )	KPSS ( $\tau$ )
AGDP	Level	-1.907	-2.774	0.665**	0.158**
AGDP	$\Delta$ (diff)	-2.842*	-2.488	0.379*	0.114
CO <sub>2</sub>	Level	-4.086***	-3.467*	0.218	0.108
CO <sub>2</sub>	$\Delta$ (diff)	-3.618***	-3.399*	0.150	0.052
EC	Level	-0.933	-2.410	0.719**	0.156**
EC	$\Delta$ (diff)	-2.900*	-2.797	0.190	0.058
GDP	Level	-1.174	-3.690**	1.036***	0.116
GDP	$\Delta$ (diff)	-2.931**	-3.035	0.101	0.091
GDP	Level	-2.896*	-1.578	0.178	0.131*
GDP	$\Delta$ (diff)	-4.470***	-4.502***	0.226	0.114
IP	Level	-1.419*	-0.358	0.749***	0.128*
IP	$\Delta$ (diff)	-2.038	-2.378	0.181	0.180**
SGDP	Level	-2.139	-1.461	0.299	0.138*
SGDP	$\Delta$ (diff)	-5.173***	-6.312***	0.298	0.159**

Notes: \*ADF: H<sub>0</sub> = unit root; \*, \*\*, \*\*\* denote rejection at the 10%, 5%, and 1% levels (evidence of stationarity). KPSS: H<sub>0</sub> = stationarity; \*, \*\*, \*\*\* denote rejection at the 10%, 5%, and 1% levels (evidence of non-stationarity).

Source: own elaboration in Apteck Gauss/tspdlb library.

**Table A3. Screening of model innovations: Serial correlation, ARCH effects, normality and outliers**

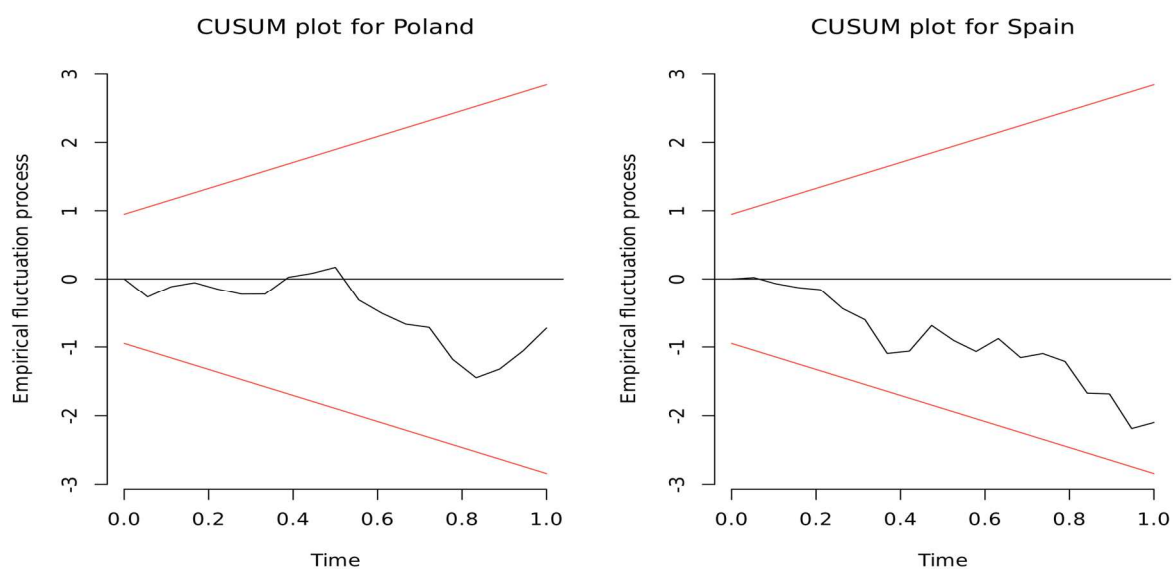
Country	N	LB (p)	ARCH-LM (p)	JB (p)	Outliers >3 $\sigma$	Outliers >2.5 $\sigma$
Poland	27	0.130	0.303	0.795	0	0
Spain	27	0.183	0.490	0.610	0	0

Notes: The table reports p-values from Ljung-Box tests of residual serial correlation (LB(p), lag = 4), ARCH-LM tests of conditional heteroskedasticity (ARCH(p), lags = 4), and Jarque-Bera tests of normality (JB(p)). outliers >3 $\sigma$  and outliers >2.5 $\sigma$  count standardised-residual outliers exceeding  $|z| > 3$  and  $|z| > 2.5$ , respectively. n denotes the number of residuals used in the tests. Source: own elaboration in Aptech Gauss/tspdlb library.

**Table A4. Cumulative Fourier-frequency Granger causality**

Direction	Wald	Bootstrap p-value	Frequency	Wald	Bootstrap p-value	Frequency
	Poland			Spain		
SGDP → CO <sub>2</sub>	8.813	0.029	2	3.015	0.102	2
CO <sub>2</sub> → SGDP	0.219	0.901	2	4.265	0.051	2
IGDP → CO <sub>2</sub>	5.701	0.08	2	0.097	0.759	1
CO <sub>2</sub> → IGDP	1.277	0.541	2	2.919	0.098	1
AGDP → CO <sub>2</sub>	0.721	0.706	2	1.671	0.211	1
CO <sub>2</sub> → AGDP	4.313	0.155	2	1.557	0.227	1
AGDP → IP	2.246	0.16	3	2.5	0.323	3
IP → AGDP	0.01	0.918	3	1.688	0.453	3
SGDP → IP	6.158	0.069	3	2.951	0.257	3
IP → SGDP	5.75	0.086	3	0.594	0.751	3
IGDP → IP	5.899	0.08	3	15.064	0.006	3
IP → IGDP	7.093	0.053	3	1.936	0.405	3

Source: own elaboration in Aptech Gauss/tspdlb library.

**Figure A1. Fourier Bayesian ARDL for Poland and Spain CUSUM**

Source: own elaboration based on investment results.


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The contribution share of authors is 35% to the corresponding author (BS), 35% to Irena Łącka (IL), and 30% distributed equally to the rest of the authors. Conceptualisation BS, IL; methodology BS; data collection BS; writing – original draft preparation BS, IL; writing – review and editing BS, IL, AB, AMV; funding acquisition IL.

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### Acknowledgements and Financial Disclosure

The article presents the effect of a foreign research internship at the Universidad de Murcia in Spain under the supervision of Professor Antonio Minguez Vera from Catedrático de Universidad en Economía Financiera. This research was funded by the project within the framework of the Faculty of Economics, West Pomeranian University of Technology in Szczecin, Poland under the name 'Green Lab. Research and Innovations.'

### Use of Artificial Intelligence

The authors confirm that the manuscript is free of AI/GAI-generated content. DeepL and Grammarly were used solely for language proofreading and minor linguistic adjustments. No generative AI tools were used for creating, rewriting, or analysing the scientific content.

### Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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