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# The Cruciality of Environmental Degradation, Energy Use and Urbanization to Policy Framework for Sustainable Growth and Development: Evidence from Spain

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## Abstract

Attaining a sustainable environment has become an international commitment. Therefore, mitigating climate change concerns is pertinent for a sustainable ecosystem. This study focuses on the Spanish economy, which has enjoyed some positive growth trends over the years. However, there remains an unaddressed puzzle as to whether the experienced growth path is green or dirty given the wake of global connectedness. These concerns are related to the objective of the Sustainable Development Goals (SDGs) that comprises economic growth (SDGs-8), climate issues (SDGs 13) and responsible energy consumption and access to energy (SDGs 7, 12). Therefore, this research empirically explores the co-movement and coherence between CO<sub>2</sub> emissions and its driving factors—specifically renewable energy, fossil fuel consumption, urbanization, and economic growth using the wavelet tools. The result of the wavelet coherence shows that (i) renewable energy and CO<sub>2</sub> emissions are out-phase; (ii), economic growth and CO<sub>2</sub> are in-phase; urbanization and CO<sub>2</sub> are in-phase; and (iv) fossil fuel and CO<sub>2</sub> are in-phase. The result of the multiple wavelet coherence shows that CO<sub>2</sub> in Spain were strongly linked to urbanization, economic growth, and energy consumption. While coherence with renewable energy and urbanization weakened after 2000, fossil fuel reliance remained a key driver. These results are not desirable for the case study (Spain). Therefore, there is a necessity for a gradual and more aggressive shift in the Spanish energy mix to renewables. The shift to renewables is required for inclusive growth and a green growth path in Spain. More insights on environmental sustainability targets amidst growth paths are discussed in the concluding section.

**Keywords:** climate change mitigation; environmental sustainability; carbon reduction; Economic growth; wavelet coherence test; Spain

## 1. Introduction

For the last two decades, nations around the globe have been working to curb global warming in an attempt to avert the devastating effects of climate change. Although fossil-fuel burning is a key source of emissions, however, the major consideration is usually devoted to the greenhouse gas (GHG) emissions (mainly CO<sub>2</sub> emissions) arising from their combustion

(Balsalobre-Lorente *et al.*, 2018). Thus, a crucial task for policymakers and authorities is to boost the energy supply sector to generate cleaner and cheaper energy whilst at the same significantly minimizing GHGs emissions. As such, efforts must be made to ascertain alternative energy sources to fossil fuels. Both nuclear and green (solar, wind, geothermal, and hydro) energy sources could offer remedies to existing challenges of energy protection and global warming. In actuality, nuclear and green energy utilization may not directly affect GHG emissions. Even if the installation of a new nuclear or renewable power plant led to the closing of a coal-fired power station, it might also contribute to a cheaper price for coal, which, in essence, would allow more energy users to burn it instead of cleaner energy sources, thus raising overall CO<sub>2</sub> emissions (Sarkodie *et al.*, 2020). Hence, the degree to which expanded use of green energy reduces pollution over time is still an open issue. Another issue of particular interest is whether the implementation of "renewable" and energy-saving policies will allow economies to maintain sustainable economic development. Since economic growth usually requires an increase in the consumption of energy, and hence pollution, the goal of economic growth appears to contrast with emissions reduction goals (Ahmed *et al.*, 2020). Nevertheless, economic literature and concrete experiences from some nations suggest that a low-carbon policy can be reconciled with economic growth (Deutch, 2017; Pao and Chen, 2019).

Spain signed the Paris Agreement, which set the 2015 decarbonization campaign. In the contract, member governments promised to make many efforts have been made to ensure that the global average temperature increase remains below 2°C compared to pre-industrial levels. The Spanish electrical grid has reduced emissions by increasing green energy and reducing coal-fired output (EIA, 2020). As a result, in just five years, the tonnes of CO<sub>2</sub> equivalent recorded in 2019 has decreased by 30 million compared to those recorded in 2015 as seen in the data from the International Energy Agency (EIA, 2020). However, economic growth activities have been identified to be causing devastating effects of pollution in different economies using a variety of indicators in the empirical literature, and the quest to understand the true form of causality between growth and pollution is still high among many researchers (Udemba, 2020). Thus, having a clear understanding of this nexus is very important for an informed policy framework in the specific case of an individual country as the relationship between growth and pollution may notably vary from one economy to the other depending on the obtainable pattern of economic activities.

Economic activities like agriculture, petroleum, mineral exploration, and industry cause pollution (Udemba, 2020). Pollution from economic activity can harm public health by producing heart disease and cancer (Pope and Dockery, 2006). Experts agree that economic growth relies on the energy industry, which plays a crucial role in boosting income, employment, and productivity. Numerous energy economics studies confirm that economic growth and energy consumption significantly harm the environment. For instance, Olanrewaju *et al.* (2021) found that economic growth and energy consumption cause environmental degradation in several economies and regions. Alola *et al.* (2020), Dogan and Inglesi-Lotz (2020) found that nonrenewable energy use increases CO<sub>2</sub> emissions and environmental degradation. Research by Olanrewaju *et al.* (2021), Adebayo (2020) highlights the linkage between fossil fuel energy and economic growth, suggesting that higher GDP leads to higher energy usage and CO<sub>2</sub> emissions. Besides energy, agricultural activities like fertilizer application, herding, bush burning, land reclamation, and chemical use create greenhouse gasses. Furthermore, the interrelationship between economic growth and urbanization has been extensively studied, with conflicting results.

Research by Onjala and K'Akumu (2016), Sbia *et al.* (2017), Nguyen (2018), Faisal *et al.* (2018), Onifade *et al.* 2021b, and Long (2020) detected a positive correlation between

urbanization and economic growth. However, Kong et al. (2020) found an adverse correlation. More recently the study of Zafeiriou *et al.* (2023) also identified deforestation as key driver for environmental degradation for case of eastern European economies in a panel framework. The study leveraged on fully modified ordinary least squares alongside dynamic ordinary least squares (DOLS) and Pooled Mean Group autoregressive distributed lag methodology. The study failed to find empirical support for the EKC hypothesis but established an inverse N-shaped relationship between environmental degradation variable (deforestation) and economic growth European panel studies. Additionally Tampakis *et al.* (2017) explored the pivotal role of renewable energy sources to Greek island economic growth. The study submitted that economic growth is highly correlated to a country's availability, generation and distribution to its energy consumption. This position corroborated with the preposition of International Energy Agency (IEA, 2020; Kyriakopoulos *et al.* 2018). Furthermore, in the study of Zafeiriou *et al.* (2022) asserted also that efficient and sustainable exploitation of energy resources can guarantee a sustainable economic growth which may vary from bloc to blocs due to social, economic and political dynamics and management related issues. The study of Zafeiriou *et al.* (2022) for the Greek highlighted that economic growth generated by energy and minerals in an era of the country's efforts to shut down the lignite-run power production limited power over energy management. The study also leverages on the Bayesian vector auto-regressive model methodology and the results from the variance composition analysis confirms that his result implies that the growth generated by different energy and mineral resources are correlated.

Considering the mixed evidence regarding the nexus of urbanization and growth from many economies, this research is intended to inspect the intriguing nexus among these variables in Spain. The Spanish economy has enjoyed some positive growth trends over the years. However, there remains an unaddressed puzzle as to whether the experienced growth path is green or dirty given the wake of global connectedness. Aside from being a standing signatory to the Paris Agreement, which was the baseline for the decarbonization campaign in 2015, an analysis of the case of Spain is justifiable considering that the attainment of the global decarbonization quest requires the overall actions of all countries individually even though the challenge of climate change is a global phenomenon. Furthermore, the Sustainable Development Goals (SDGs 7, 8, 12, and 13) serve as inspiration for this research. It addresses precise energy utilization challenges (SDG-7) with prominence on clean and sustainable energy usage (SDGs 7 and 12) in order to accomplish the 2030 Agenda. This is done to prevent issues related to climate action (SDGs-13) and economic growth (SDG-8). As sustainable energy usage and environmental preservation are progressively being prioritized, studies on individual countries' environmental performances are steps in the right direction.

This current study is distinct for its growth-based methodology, which is predicated on the framework of EKC, in this scenario a linear form. This EKC is centered on the association between economic growth and environment. The majority of studies on Spain's emissions participation has taken into account an environmental perspective that frequently provides a distinct perspective of the country's emissions without any relevance to the growth of the economy. As such, the present study differs from previous studies in that it takes into consideration the determinants of economic growth such as energy consumption, urbanization, and CO<sub>2</sub> emissions while expanding and complementing the discussion on the growth-energy and emissions interconnection by Udemba et al. (2022). This research further adds to the growth-energy literature by using the innovative wavelet tools to examine these connections. The novelty of wavelet tools, particularly wavelet coherence (WC) and multiple wavelet coherence (MWC), lies in their ability to analyze the time-frequency dynamics of relationships between variables, offering deeper insights than traditional methods. Wavelet coherence uniquely captures the localized co-movement between two time series across different

frequencies, revealing whether their relationship is short-term, medium-term, or long-term. Multiple wavelet coherence extends this by analyzing the interaction among multiple variables simultaneously, addressing the limitations of pairwise analysis. This allows for a more comprehensive understanding of how complex systems evolve over time, making these tools particularly valuable for studying nonlinear, non-stationary relationships in environmental, economic, and energy-related datasets.

In the light of the foregoing and considering the high rate of population expansion, major measures must be taken to prevent the potential negative impacts of environmental degradation without affecting economic growth. As a result, we are motivated to scrutinize the determinants depicted in this current research, as we attempt to leverage this research findings to improve policy suggestions to policymakers and stakeholders. The importance of the ramifications of this research will also go beyond a localized relevance to the Spanish economy alone as there is relative applicability of some of the practical implications from the study to other similar European Union (EU) countries considering Spain's stance in the EU in terms of geography, economics, and politics.

The remainder of the study is presented as follows: Section 2 illustrates the methodology and data, Section 3 depicts analytical outcomes, and Section 4 concludes the research

## 2. DATA AND METHODS

### 2.1. Data

Table 1 provides key measurements and sources of data for various variables used in the analysis. CO<sub>2</sub> represents CO<sub>2</sub> emissions measured per capita, sourced from OWD (2024). FF denotes fossil fuel consumption per capita in kilowatt-hours (kWh), also sourced from OWD (2024). EG signifies economic growth, measured as GDP per capita in constant 2015 US dollars, obtained from WDI (2024). UB indicates urbanization, measured as the percentage of total population, sourced from WDI (2024). REC stands for renewable energy consumption per capita in kilowatt-hours (kWh), sourced from OWD (2024). The study time-frame span between 1969 to 2023. The unavailability of data for FF limits the dataset before 1969, and the absence of data after 2023 restricts the study to data up to 2023. To ensure the data align with a normal distribution, the study applied natural logarithm transformations to the variables used.

**Table 1:** Data Measurement and Information

Abbreviation	Full Name	Measurement	Sources
CO <sub>2</sub>	CO <sub>2</sub> Emissions	Per Capita	OWD (2024)
FF	Fossil Fuel Consumption	Per capita (kWh)	OWD (2024)
EG	Economic Growth	GDP Per Capita US\$ 2015 Constant	WDI (2024)
UB	Urbanization	Urban population (% of total population)	WDI (2024)
REC	Renewable Energy Consumption	Per capita (kWh)	OWD (2024)

### 2.2. Method

Through the use of wavelet coherence, it is possible to identify the time-frequency relationship between CO<sub>2</sub> emissions and energy consumption (both renewable energy and fossil fuels),

economic growth, and urbanization. The concept of time-frequency dependence captures changes that occur over time and how relationships evolve across different frequencies, making it increasingly important and strategic in policy formation. To balance both phase and amplitude considerations, the Morlet wavelet function was chosen, as it can be defined as:

$$\omega(n) = \pi^{-\frac{1}{4}} e^{-i\omega n} e^{-\frac{1}{2}n^2} \quad (1)$$

Using the non-dimensional frequency denoted as  $\omega$ ;  $\sqrt{-1}$   $p(n)$  represents  $i$ . Employing the space and time, with  $n = 0, 1, 2, 3, \dots, N-1$ . Meanwhile, the CWT (continuous wavelets transformation) is explained as:

$$\omega_{k,f}(n) = \frac{1}{\sqrt{h}} \omega\left(\frac{n-k}{f}\right), \quad k, f \in \mathbb{R}, f \neq 0 \quad (2)$$

where time and frequency are represented by  $k$  and  $f$ , respectively. CWT facilitates in the interrelationship of two parameters in cross wavelet analysis (Tiwari et al., 2020). The equation for the CWT is shown as:

$$\omega_p(k, f) = \int_{-\infty}^{\infty} p(n) \frac{1}{\sqrt{f}} \omega\left(\frac{n-k}{f}\right) dn, \quad (3)$$

The WPS (wavelet power spectrum) was employed to highlight the local variance. The WPS is defined by the following equation:

$$WPS_p(k, f) = |W_p(k, f)|^2 \quad (4)$$

The co-movement between two parameters is examined using the wavelet coherence approach (WTC), which is expressed in equation (11) below:

$$R^2(k, f) = \frac{|S(f^{-1}W_{pj}(k, f))|^2}{S(f^{-1}|W_p(k, f)|^2)S(f^{-1}|W_j(k, f)|^2)} \quad (5)$$

Where:  $S$  indicates the smoothing operator to scale and time with  $0 \leq R^2(k, f) \leq 1$ . The phase difference ( $\phi_{pq}$ ) for two parameters can be evaluated using WTC, which is expressed as follow:

$$\phi_{pq}(k, f) = \tan^{-1} \left( \frac{L\{S(f^{-1}W_{pj}(k, f))\}}{O\{S(f^{-1}W_{pj}(k, f))\}} \right) \quad (6)$$

where: the imaginary operator is indicated as  $L$  and the real part operator is denoted as  $O$ .

### 3. FINDINGS AND DISCUSSIONS

#### 3.1. Descriptive Statistics

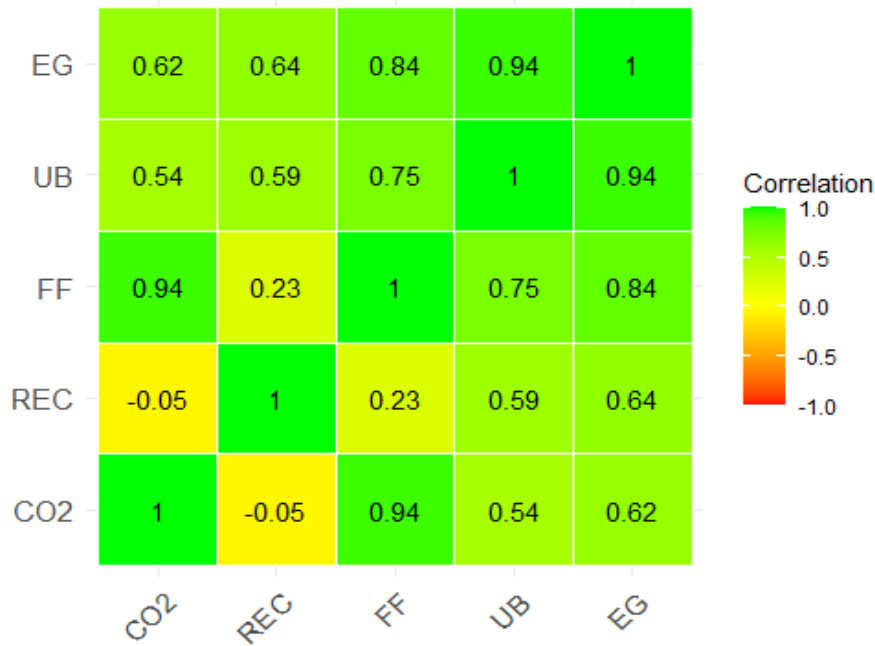
Table 2 presents the descriptive statistics for five variables: CO<sub>2</sub>, FF, EG, UB and REC. The minimum and maximum values indicate the range of observations for each variable, with CO<sub>2</sub> ranging from 1.061 to 2.126, and REC spanning from 7.301 to 9.018. The first and third quartiles (Q1 and Q3) suggest the spread of the middle 50% of the data, while the mean and median are close for most variables, indicating relatively symmetrical distributions. The mean values are 1.740 for CO<sub>2</sub>, 10.035 for FF, 9.885 for EG, 4.317 for UB, and 8.082 for REC. The standard error (SE) of the mean, which measures the precision of the sample mean, is smallest for UB (0.008) and largest for REC (0.064). Confidence intervals for the mean (LCL and UCL)

suggest that the true population mean is within a small range around the observed mean. The standard deviations (Stdev) show the extent of variability, with REC having the highest variability (0.478) and UB the lowest (0.058). The skewness values indicate that CO<sub>2</sub>, FF, EG, and UB distributions are left-skewed (negatively skewed), while REC is right-skewed (positively skewed). Lastly, the kurtosis values show that CO<sub>2</sub> and UB have slight positive kurtosis, suggesting that these distributions are somewhat peaked, whereas FF, EG, and REC have negative kurtosis, indicating flatter distributions compared to a normal distribution.

**Table 2:** Descriptive Statistics

	<b>CO<sub>2</sub></b>	<b>FF</b>	<b>EG</b>	<b>UB</b>	<b>REC</b>
<b>Minimum</b>	1.061	9.382	9.249	4.162	7.301
<b>Maximum</b>	2.126	10.439	10.250	4.398	9.018
<b>1. Quartile</b>	1.630	9.902	9.607	4.296	7.681
<b>3. Quartile</b>	1.847	10.179	10.152	4.358	8.547
<b>Mean</b>	1.740	10.035	9.885	4.317	8.082
<b>Median</b>	1.740	10.047	9.914	4.329	7.922
<b>SE Mean</b>	0.029	0.032	0.039	0.008	0.064
<b>LCL Mean</b>	1.682	9.971	9.807	4.301	7.953
<b>UCL Mean</b>	1.799	10.099	9.964	4.333	8.212
<b>Variance</b>	0.046	0.056	0.085	0.003	0.229
<b>Stdev</b>	0.215	0.238	0.291	0.058	0.478
<b>Skewness</b>	-0.470	-0.433	-0.407	-0.907	0.426
<b>Kurtosis</b>	0.750	0.069	-1.196	0.138	-1.101

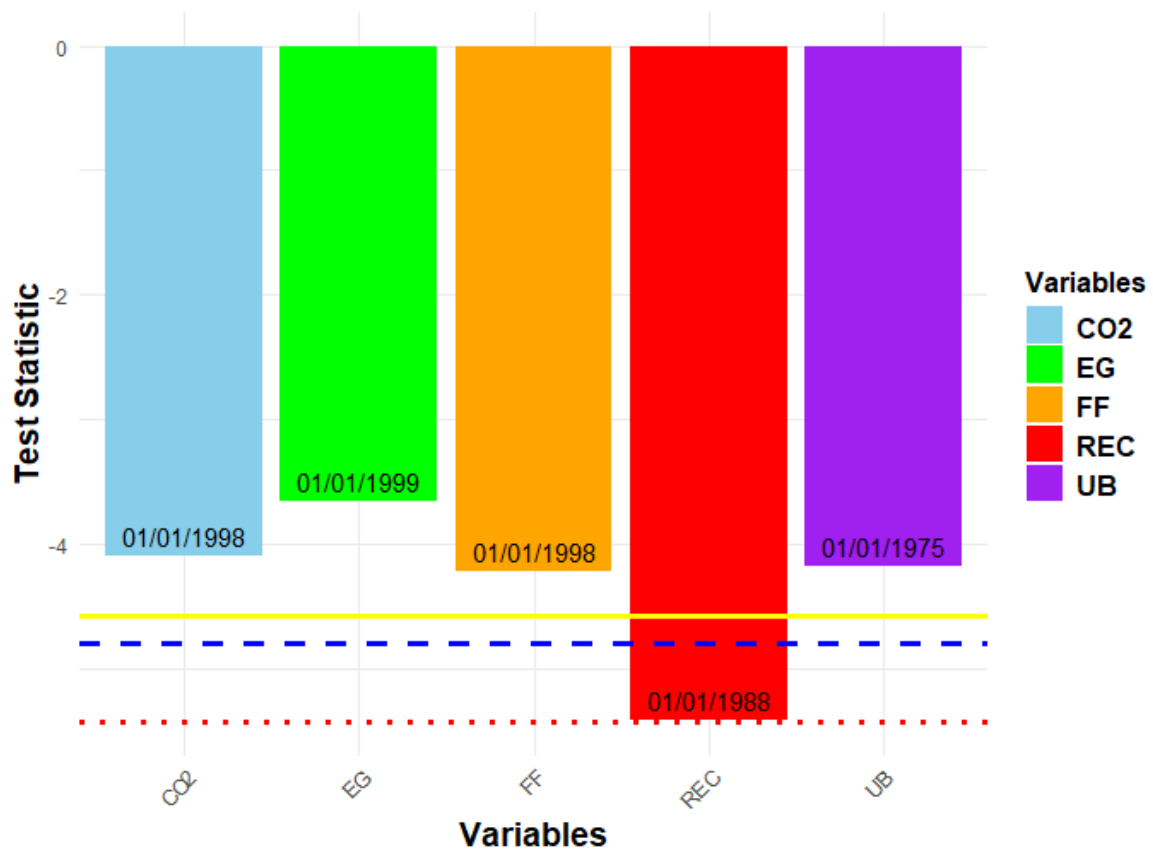
**Fig. 1** shows the correlation between CO<sub>2</sub> and its drivers. The correlation between FF and CO<sub>2</sub> is 0.94, indicating that increases in FF are highly associated with higher CO<sub>2</sub> emissions. CO<sub>2</sub> also shows a moderate positive correlation with EG at 0.62, suggesting that as economic growth rises, CO<sub>2</sub> emissions tend to increase as well. The correlation with UB is also moderate (0.54), implying that UB may contribute to CO<sub>2</sub>, although to a lesser extent. The negative correlation between CO<sub>2</sub> and REC (-0.05) suggests that renewable energy consumption has a very weak, almost negligible, relationship with CO<sub>2</sub> in this dataset.



**Fig. 1:** Correlation Result

### 3.2. Stationarity Test Result

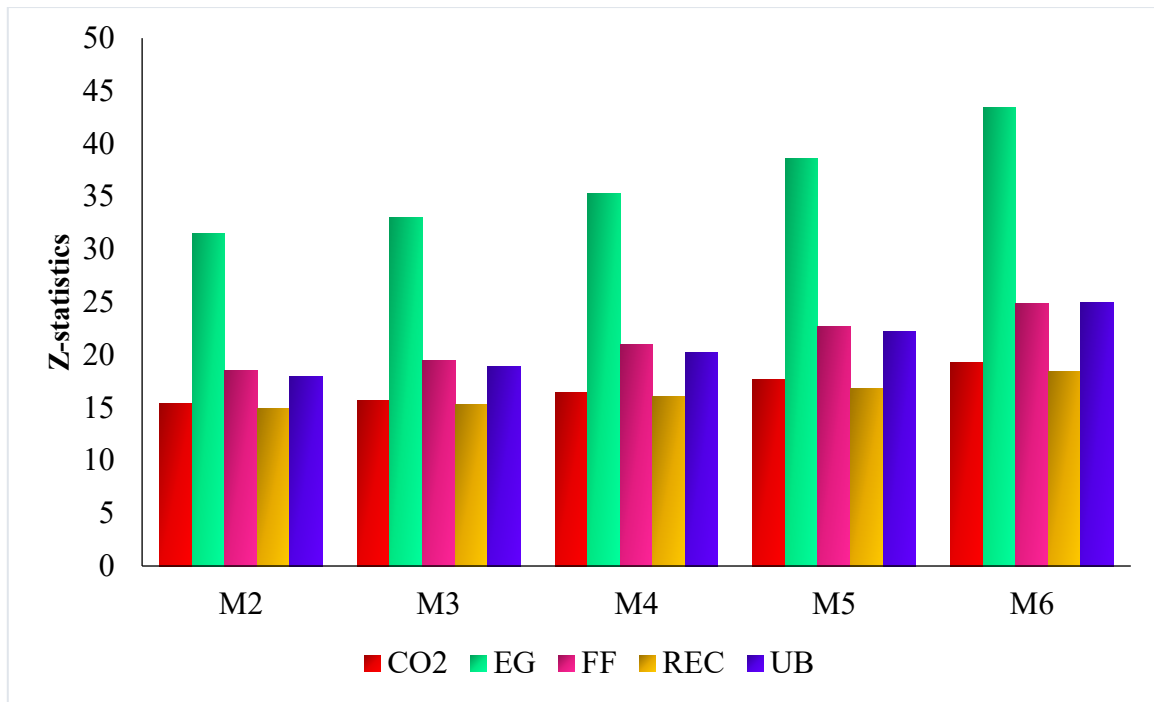
In the context of wavelet techniques, conducting a unit root test is not crucial for the analysis itself, as wavelet methods focus on analyzing the frequency components and local features of time series data across different scales rather than on stationarity. While traditional time series analysis often emphasizes the need for stationarity (through unit root tests) to ensure the validity of models, wavelet techniques are less sensitive to this requirement due to their ability to decompose non-stationary data into different frequency components (Percival & Walden, 2000). The primary purpose of conducting unit root tests in this context is to understand the properties of the variables and their underlying trends rather than to meet the assumptions of a specific model, as wavelet methods can accommodate non-stationary processes (Mutascu, 2018). In this study we used Zivot & Andrews (1992) test. While the Zivot & Andrews test (see **Fig. 2**) provides insights into the stationarity and structural breaks, it does not invalidate wavelet-based approaches, which are designed to handle time-varying and non-stationary data effectively. The result shows that only REC is stationary at level, with 1988 as the break date, while there is no evidence of stationarity for CO<sub>2</sub>, EG, FF, and UB.



**Fig. 2:** ZA Unit Root Test Results

### 3.4. Nonlinearity Test Result

Next the study examine the nonlinearity attribute of the series using the BDS test suggested by Broock et al., (1996). **Fig. 3** shows the BDS test result. The null hypothesis states that the time series data are independently and identically distributed (i.i.d.). The Z-statistics for each variable (CO<sub>2</sub>, EG, FF, REC, UB) across different time lags (M2 to M6) are compared to the critical values of 2.576 at the 1% level, 1.960 at the 5% level, and 1.645 at the 10% level. Since the Z-statistics for CO<sub>2</sub>, EG, FF, REC, and UB are greater than 2.576 at the 1% level for M2, M3, M4, M5, and M6, the null hypothesis of i.i.d. is rejected for all variables at the 1% significance level. This suggests the presence of nonlinearity or dependence in the time series data for these variables.



**Fig. 3: BDS Test Result**

**Note:** The critical values are approximately 2.576 at the 1% ( $\alpha = 0.01$ ), 1.960 at the 5% ( $\alpha = 0.05$ ), and 1.645 at the 10% ( $\alpha = 0.10$ ).

### 3.5. Wavelet Coherence Result

Next, the study utilized wavelet coherence to examine the co-movement between CO<sub>2</sub> and its drivers in Spain from 1969 to 2023. **Fig. 4(a-d)** illustrate the results of the wavelet coherence analysis.

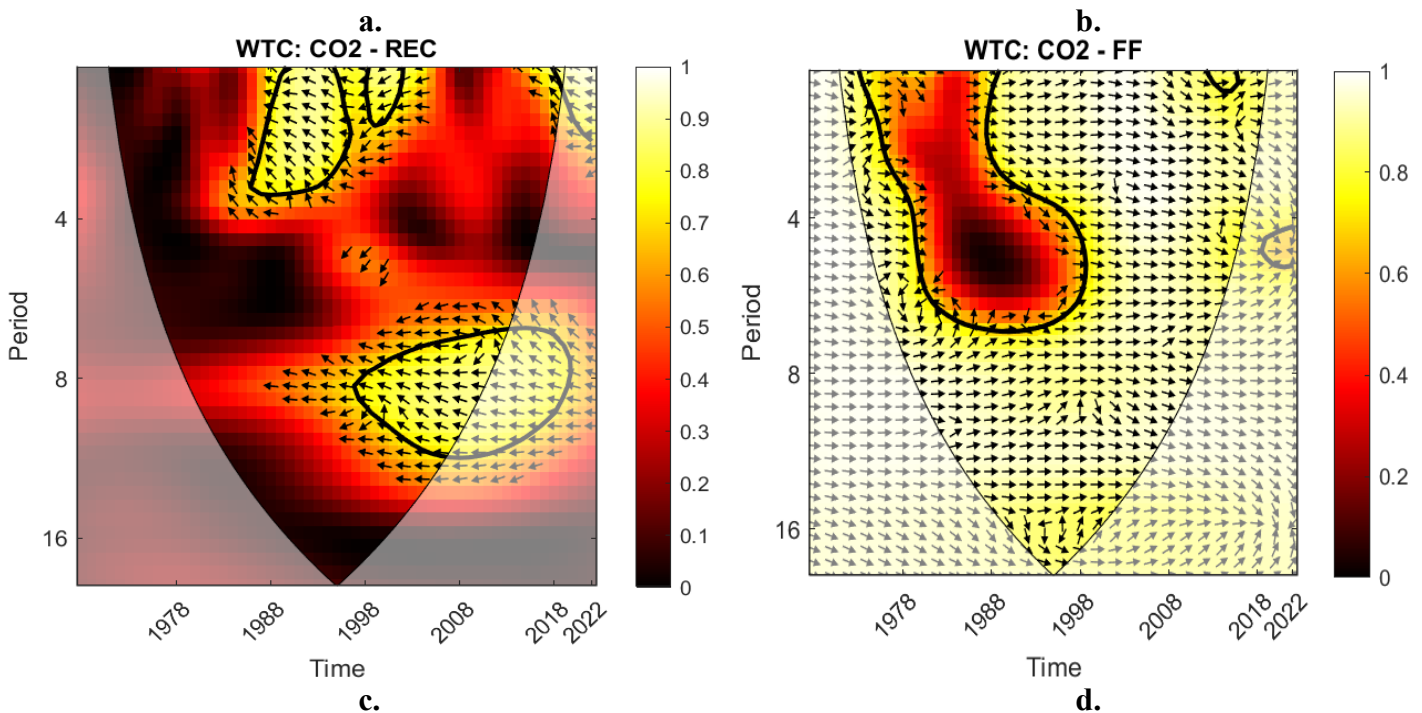
**Fig. 4a** showcase the coherence between CO<sub>2</sub> and REC in Spain. We observed that from 1985 to 1997, at high-frequency ranges (1-4 years), which correspond to the short-term, the relationship between CO<sub>2</sub> and REC is predominantly out-of-phase, as indicated by strong leftward arrows. This suggests that during this period, as renewable energy consumption increased, CO<sub>2</sub> decreased, or vice versa. This could reflect the initial stages of renewable energy adoption in Spain, where short-term industrial growth was associated with increasing CO<sub>2</sub>, while renewable energy sources had a limited immediate impact. The high-frequency range (1-4 years) reflects rapid, short-term fluctuations in the energy sector and energy policy impacts (Torrence & Compo, 1998). From 1998 to 2010, at frequencies of 8-16 years, which correspond to the long-term, the relationship between CO<sub>2</sub> and REC remains out-of-phase, as indicated by the continued leftward arrows. During this period, CO<sub>2</sub> and renewable energy consumption moved in opposite directions. This suggests that, while Spain continued to adopt renewable energy, it was insufficient to offset the rise in CO<sub>2</sub> driven by industrial and economic growth. The long-term frequency range (8-16 years) reflects more structural factors such as the gradual integration of renewable energy technologies and changes in energy consumption patterns, which did not immediately result in a significant reduction of CO<sub>2</sub>. From around 2010 onwards, the coherence weakens further, and the relationship becomes more complex, with both positive and negative co-movements at different frequencies. These findings highlight the need to consider both short-term and long-term factors when analyzing the evolving interaction between renewable energy consumption and CO<sub>2</sub> in Spain. These findings aligns with the findings of Abbasi et al., (2021), AlNemer et al., (2023) and Aslan et al., (2024).

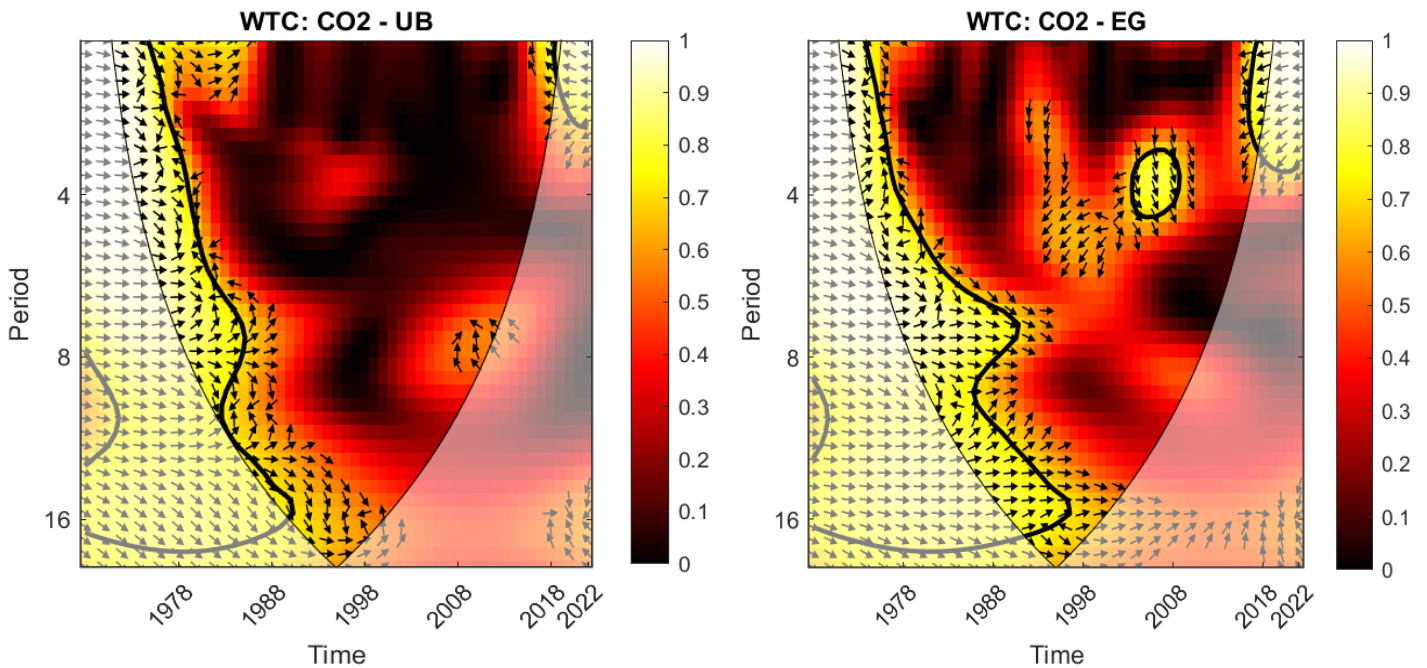
**Fig. 4b** display the connection between CO<sub>2</sub> and fossil fuel. The observed that between late 1980s and early 1990s, at short-term frequencies (1-4 years), the plot shows a strong in-phase co-movement between CO<sub>2</sub> and fossil fuel consumption, as indicated by the rightward arrows. This period corresponds to a time of rapid industrial growth and economic expansion in Spain, where increased energy demand led to higher fossil fuel consumption. Fossil fuels, particularly coal and oil, were the primary energy sources used to meet this demand, and as a result, CO<sub>2</sub> also rose. The rightward arrows in this short-term frequency range indicate that the relationship between fossil fuel consumption and CO<sub>2</sub> was tightly coupled, reflecting Spain's dependence on fossil fuels during this time, with little influence from renewable energy sources. In the 1990s and early 2000s, at medium-term frequencies (4-8 years), the positive co-movement between CO<sub>2</sub> and fossil fuel consumption continued, as shown by the rightward arrows. During this period, although renewable energy adoption was beginning, fossil fuel consumption remained the dominant factor driving CO<sub>2</sub> in Spain. While Spain started to integrate renewable energy sources like wind and solar into its energy mix, these sources were still not sufficient to replace the heavy reliance on fossil fuels. The rightward arrows at these frequencies indicate that, despite the increase in renewable energy, the relationship between fossil fuel consumption and CO<sub>2</sub> remained strong and in-phase due to the continued dominance of fossil fuels in the energy system. From around 2010 onwards, the coherence between CO<sub>2</sub> and fossil fuel consumption remains positive, with rightward arrows continuing across all frequencies. This period corresponds to a shift toward more significant renewable energy adoption, especially in electricity generation, with Spain investing heavily in solar and wind energy technologies. However, despite the growth of renewables, fossil fuels still played a major role in Spain's energy mix, and energy demand continued to rise in sectors like transportation and heating. The rightward arrows indicate that even though the renewable energy share was growing, the continued use of fossil fuels was still directly linked to CO<sub>2</sub>, preventing a complete decoupling. The findings affirmed the discoveries of Karakurt & Aydin (2023), Kartal et al., (2022) and Omri & Saadaoui (2023).

**Fig. 4c** display the connection between CO<sub>2</sub> and urbanisation. From the late 1980s to the early 2000s, at medium-term frequencies (4-8 years), the plot shows a strong in-phase co-movement between CO<sub>2</sub> and urbanization, as indicated by the rightward arrows. This suggests that as urbanization increased, CO<sub>2</sub> also rose, which can be attributed to the expansion of urban areas, industrial growth, and higher energy consumption typical of urban environments. As cities expand, infrastructure development, transportation needs, and higher energy demand typically increase, leading to more fossil fuel consumption and higher CO<sub>2</sub>. The rapid urbanization seen in Spain during this period was accompanied by an increase in economic activity, population density, and energy consumption, all of which contributed to the increase in CO<sub>2</sub>. This reflects the common phenomenon where urbanization, while often linked to economic development, also places significant pressure on the environment through higher resource consumption and emissions. As the analysis moves into the post-2010 period, we observed that the relationship between CO<sub>2</sub> and urbanization remains strong, with rightward arrows continuing to indicate in-phase co-movement at varying frequencies. However, the dynamics become more complex, with the role of renewable energy adoption and energy efficiency improvements starting to play a more significant role. Despite the increase in urbanization, the decoupling of CO<sub>2</sub> from economic growth became more apparent with the growth of renewable energy in the energy mix. The increasing reliance on renewable energy sources, along with improvements in energy efficiency, contributed to moderating the growth of CO<sub>2</sub> in urbanized areas. Nonetheless, urbanization continued to drive higher emissions, particularly in sectors such as transportation and residential energy consumption, emphasizing the ongoing challenge of achieving

sustainable urban growth without increasing environmental impacts. The findings correspond with the findings of Anwar et al., (2022), Bai et al., (2019), Lee & Zhao (2023).

**Fig. 4d** showcase the nexus between CO<sub>2</sub> and economic growth. The analysis shows strong coherence between CO<sub>2</sub> and economic growth, particularly from the late 1980s through the early 2000s, with consistent rightward arrows indicating that as economic growth increased, CO<sub>2</sub> also rose in tandem. This period corresponds to a time when Spain's industrial growth and economic expansion were driven by fossil fuel consumption, which directly contributed to the rise in CO<sub>2</sub>. From the late 1990s through the 2000s, the relationship between CO<sub>2</sub> and economic growth continues to show strong in-phase co-movement, as indicated by the persistent rightward arrows. This suggests that during this period, economic growth was closely linked to increased CO<sub>2</sub>, likely due to industrial activity, energy consumption, and transportation, all of which are major contributors to CO<sub>2</sub>. The persistent in-phase relationship at both short-term (1-4 years) and medium-term (4-8 years) frequencies reflects a strong economic-industrial connection, where the expansion of the economy led to greater energy demand, which in turn resulted in higher emissions. However, as we moves into the 2010s, while the coherence remains strong, the relationship becomes more complex. Factors such as increased renewable energy adoption, energy efficiency improvements, and changes in industrial activity started to influence the dynamic, though economic growth continued to exert pressure on emissions, particularly in sectors like transportation and residential energy use.





**Fig. 4:** Wavelet Coherence between CO<sub>2</sub> and RECFF, UB and EG

**Note:** The color intensity represents the strength of the coherence, with darker red areas indicating strong coherence and yellow areas showing weaker coherence. The arrows on the plot indicate the phase relationship between CO<sub>2</sub> and EG: rightward arrows represent a positive co-movement, or in-phase association

#### 4.4. Multiple Wavelet Coherence

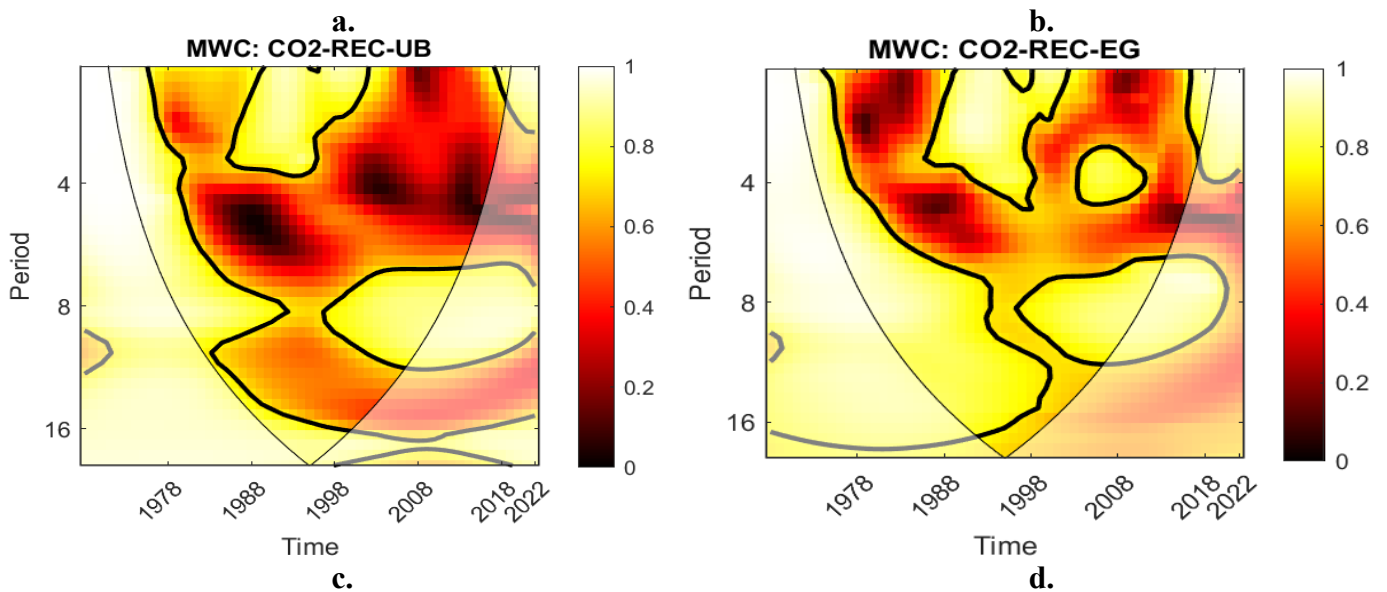
Multiple Wavelet Coherence (MWC) is an advanced time-frequency method that allows for the simultaneous examination of relationships between multiple time series variables across different time scales (frequencies). Unlike traditional wavelet coherence, which focuses on two time series at a time, MWC extends this approach by incorporating more than two variables, offering a more comprehensive understanding of their interdependencies.

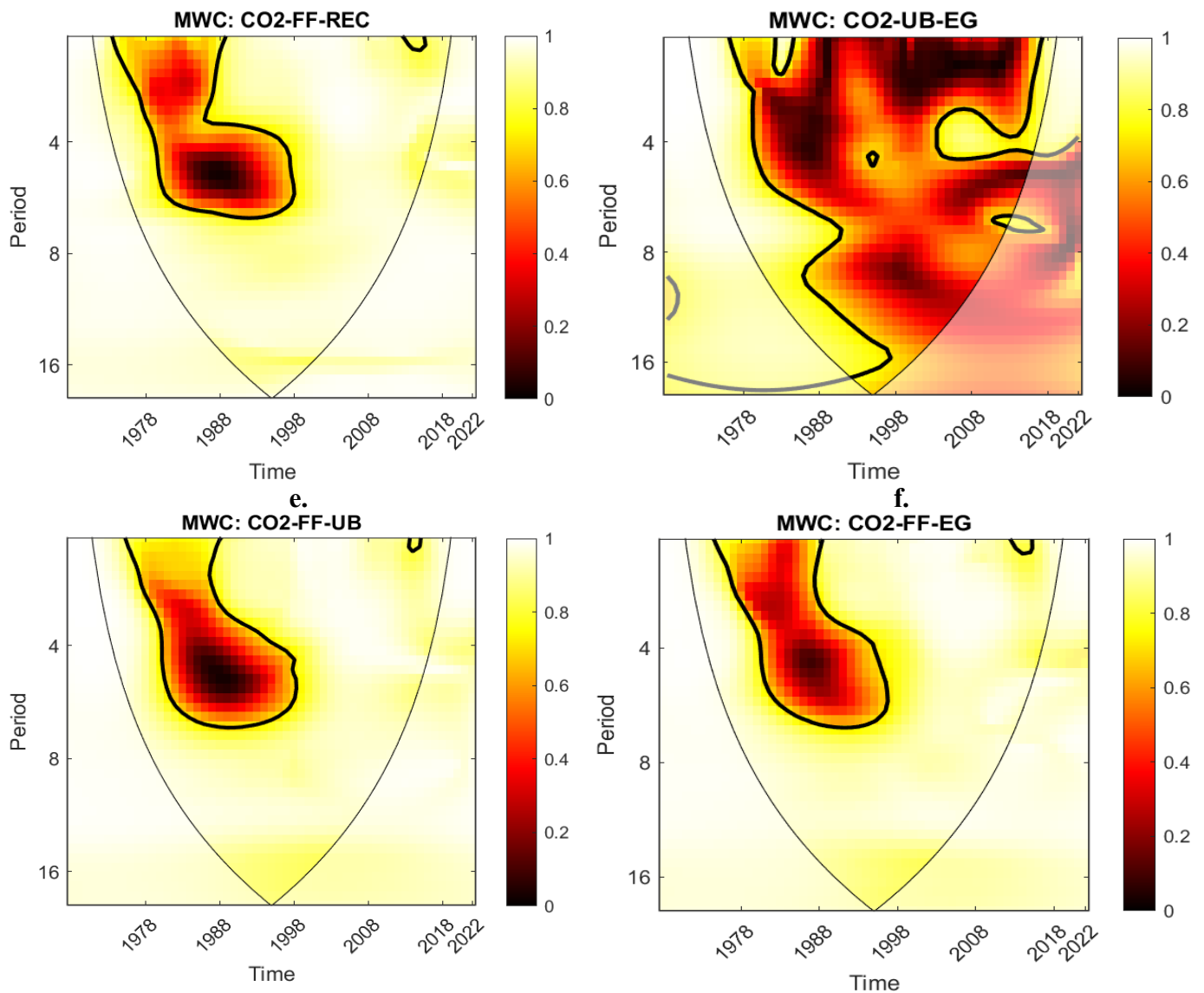
**Fig. 5a (MWC: CO<sub>2</sub>-REC-UB)** examines the coherence among CO<sub>2</sub> emissions, renewable energy consumption (REC), and urbanization (UB) over time. Significant coherence is observed in the medium-term (4–8 years) and long-term (8–16 years) periods, particularly between 1980 and 2000. This suggests that changes in urbanization and renewable energy adoption jointly influenced CO<sub>2</sub> emissions during these years. However, coherence weakens after 2000, possibly due to policy shifts or structural economic changes affecting energy and urban development. **Fig. 5b (MWC: CO<sub>2</sub>-REC-EG)** explores the relationship between CO<sub>2</sub> emissions, renewable energy consumption (REC), and economic growth (EG). Strong coherence is evident in both short-term (2–4 years) and medium-term (4–8 years) cycles, particularly from the late 1970s to the early 2000s. This implies that economic expansion and renewable energy uptake were significantly linked to CO<sub>2</sub> emissions over these periods. However, the coherence weakens in the later years, which could be attributed to the increasing diversification of energy sources and improved energy efficiency.

**Fig. 5c (MWC: CO<sub>2</sub>-FF-REC)** display the coherence between CO<sub>2</sub> emissions, fossil fuel consumption (FF), and renewable energy consumption (REC) is analyzed. The strongest coherence is observed in the 4–8-year period, particularly in the 1980s and 1990s. This suggests that fossil fuel reliance and renewable energy adoption jointly influenced emissions during these decades. The coherence diminishes in recent years, likely due to a gradual transition toward cleaner energy sources and technological advancements in energy production. **Fig. 5d**

**(MWC: CO<sub>2</sub>-UB-EG)** showcases the interaction between CO<sub>2</sub> emissions, urbanization (UB), and economic growth (EG). A strong coherence pattern emerges across multiple periods, particularly in the medium- to long-term cycles (4–16 years) from 1980 to 2010. This highlights the intertwined effects of urban expansion and economic development on CO<sub>2</sub> emissions. The persistence of high coherence indicates that urban and economic dynamics remained key drivers of emissions throughout the study period.

**Fig. 5e (MWC: CO<sub>2</sub>-FF-UB)** investigates the coherence among CO<sub>2</sub> emissions, fossil fuel consumption (FF), and urbanization (UB). High coherence is observed in the short- to medium-term cycles (2–8 years), particularly before the 2000s. This suggests that fossil fuel consumption and urbanization were strongly linked to CO<sub>2</sub> emissions, reflecting a period of rapid industrialization and urban expansion. The weakening coherence in later years indicates possible shifts toward cleaner energy sources and more sustainable urban planning. **Fig. 5f (MWC: CO<sub>2</sub>-FF-EG)** examines the coherence between CO<sub>2</sub> emissions, fossil fuel consumption (FF), and economic growth (EG). The strongest coherence is observed in the short- to medium-term periods (2–8 years), particularly from the 1970s to the early 2000s, indicating that economic expansion was heavily reliant on fossil fuel consumption, driving CO<sub>2</sub> emissions. The persistence of high coherence suggests that fluctuations in economic activity and fossil fuel usage were major contributors to emission trends. However, the reduction in coherence after 2000 may reflect efforts to diversify energy sources, improve efficiency, and implement environmental regulations aimed at decoupling economic growth from fossil fuel dependency.





**Fig. 5:** Multiple Wavelet Coherence

**Note:** The color intensity represents the strength of the coherence, with darker red areas indicating strong coherence and yellow areas showing weaker coherence.

## 4. CONCLUSION AND POLICY PATHWAYS

### 4.1. Conclusion

In this study, we examined the co-movement and coherence between CO<sub>2</sub> emissions and its driving factors—specifically renewable energy, fossil fuel consumption, urbanization, and economic growth—in Spain. The analysis utilized yearly data spanning from 1969 to 2023. Given the nonlinear and non-stationary nature of the series, the study applied wavelet tools, including wavelet coherence and multiple wavelet coherence. These approaches aid in detecting the association across different time-frequencies. The result of the wavelet coherence shows that (i) renewable energy and CO<sub>2</sub> emissions are out-phase; (ii), economic growth and CO<sub>2</sub> are in-phase; urbanization and CO<sub>2</sub> are in-phase; and (iv) fossil fuel and CO<sub>2</sub> are in-phase. The result of the multiple wavelet coherence shows that CO<sub>2</sub> in Spain were strongly linked to urbanization, economic growth, and energy consumption. While coherence with renewable energy and urbanization weakened after 2000, fossil fuel reliance remained a key driver.

## **4.2. Policy Formulation Based on Different Frequency Ranges**

### ***4.2.1. Short-Term (High-Frequency: 1–4 Years) Policies***

The high-frequency range represents short-term fluctuations driven by immediate policy interventions, energy price volatility, and economic cycles. The observed out-of-phase relationship between CO<sub>2</sub> emissions and renewable energy consumption (REC) in Spain from 1985 to 1997 suggests that while REC increased, CO<sub>2</sub> emissions fluctuated due to industrial reliance on fossil fuels. To enhance the effectiveness of renewable energy policies in the short term, Spain should implement dynamic carbon pricing mechanisms that adjust based on fossil fuel consumption trends. Additionally, short-term subsidies and tax incentives should be introduced to encourage industries and households to adopt renewable energy solutions. To address the strong in-phase relationship between CO<sub>2</sub> and fossil fuel consumption in the late 1980s and early 1990s, temporary restrictions on coal-fired power plants and fossil fuel subsidies should be enforced. Moreover, urban planning regulations should integrate short-term mitigation strategies such as green public transport expansion and incentives for electric vehicle adoption to counterbalance the emissions impact of urbanization.

### ***4.2.2. Medium-Term (4–8 Years) Policies***

The medium-term period reflects structural transitions in energy consumption patterns and the gradual impact of policy measures. From the 1990s to the early 2000s, Spain's economic growth was closely linked to rising CO<sub>2</sub> emissions due to continued dependence on fossil fuels. To break this link, the government should implement medium-term investment policies, including mandatory renewable energy procurement targets for industries and public-private partnerships (PPPs) for green infrastructure. The strong coherence between CO<sub>2</sub> and urbanization at this frequency suggests the need for integrated smart city policies that promote energy efficiency, sustainable building codes, and district heating systems powered by renewables. Additionally, Spain should establish energy efficiency mandates for commercial and residential buildings to mitigate urbanization-driven CO<sub>2</sub>. To counteract the persistent link between CO<sub>2</sub> and fossil fuel consumption in this period, sectoral decarbonization strategies should be introduced, focusing on retrofitting industries with clean technologies and expanding carbon capture and storage (CCS) projects.

### ***4.2.3. Long-Term (8–16 Years) Policies***

The long-term frequency range reflects deep structural changes in the economy, energy infrastructure, and industrial transformation. The observed out-of-phase relationship between CO<sub>2</sub> and REC from 1998 to 2010 suggests that renewable energy adoption was not yet sufficient to offset industrial emissions. To address this, Spain should implement long-term renewable energy transition strategies, such as phasing out fossil fuels through binding decarbonization roadmaps and large-scale investment in grid modernization to support higher renewable energy penetration. Since CO<sub>2</sub> and urbanization continue to co-move at long-term frequencies, urban sustainability measures must include mandatory net-zero emissions targets for major cities and the expansion of high-speed rail and low-carbon transportation networks. Additionally, to decouple CO<sub>2</sub> from economic growth in the long run, Spain should prioritize research and development (R&D) investments in green innovation and circular economy models that reduce carbon-intensive production processes. These structural policies will ensure that Spain transitions toward a low-carbon economy while maintaining economic growth and sustainable urban development.

### 4.3. Limitation and Future Directions

Though this study employs a powerful technique that captures relationships at different time frequencies, it has certain limitations. First, it considers only REC, FF, EG, and UB as the core drivers of CO<sub>2</sub> emissions, neglecting other important factors such as financial development, climate policy uncertainty, and globalization. Future studies should address these gaps. Second, the generalization of the findings is limited to Spain; therefore, future research should extend the analysis to other developed and developing nations. Third, the study does not account for relationships across different distributions, so future studies could benefit from using techniques such as wavelet quantile regression.

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