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Decoupling economic growth and carbon emissions: a time-varying analysis of the environmental kuznets curve hypothesis in France (1890–2019)

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Abstract

Global concerns regarding climate change and the necessity for sustainable economic pathways have sharpened the focus on the Environmental Kuznets Curve (EKC) hypothesis. For France, grasping the long-term dynamics between economic expansion, energy usage, and technological advancement is vital for creating effective low-carbon strategies. To explore this, we utilize an extensive dataset spanning 1890–2019 and employ sophisticated econometric methods. These include unit root tests incorporating Fourier functions, a cointegration test adept at handling both smooth and abrupt structural breaks, the Fourier Toda-Yamamoto causality procedure, and partial wavelet coherency analysis. Our goal is to rigorously probe the enduring connections among carbon dioxide (CO_2) emissions, energy consumption, economic freedom, and total factor productivity. The empirical analysis confirms a stable cointegrating link between these variables. Notably, both energy consumption and economic freedom show a significant positive correlation with CO_2 emissions. Evidence supporting the EKC hypothesis—specifically, an inverted U-shaped relationship between economic growth and emissions—appears only during distinct historical periods. Furthermore, time-varying coefficient estimates and causality tests reveal evolving dynamics influenced by structural transformations, economic occurrences, and technological progress. These outcomes suggest that decoupling economic growth from environmental harm in France hinges on policies that bolster energy efficiency, carefully integrate economic freedom with strong environmental rules, and actively promote green technological innovation.

Highlights

- Energy consumption, economic freedom, GDP growth positively linked to emissions long-term.
- Partial support for Environmental Kuznets Curve hypothesis.
- Time-varying dynamics influenced by structural changes and events.
- Co-movement between emissions and explanatory variables across time scales.

Major findings: The study finds a long-run equilibrium relationship between CO2 emissions and key economic factors like energy consumption, economic freedom, and economic growth in France from 1890-2019. While energy use and economic freedom historically increased emissions, their impact has declined recently, potentially due to transitions towards cleaner energy sources and environmental regulations. Economic growth exhibits an inverted U-shaped relationship with emissions in some periods, providing partial support for the Environmental Kuznets Curve hypothesis. The analysis reveals complex, time-varying linkages between these variables shaped by economic events and policy shifts over the past 130 years.

Extended author information available on the last page of the article

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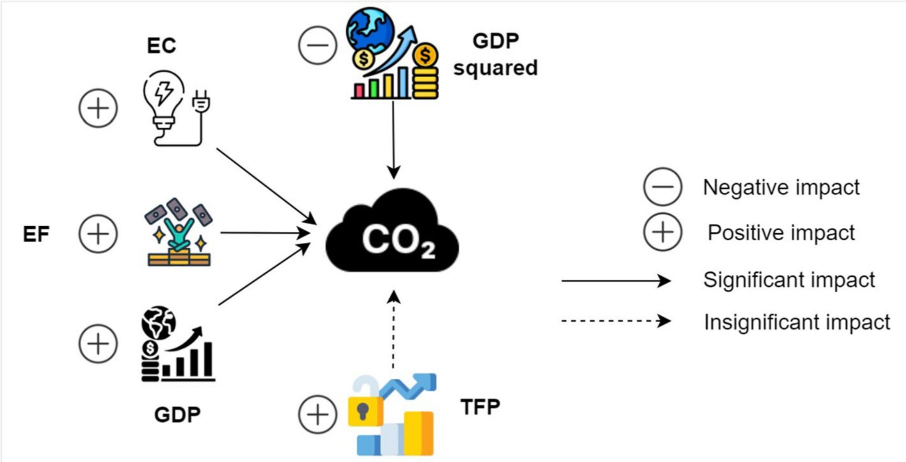
Graphical Abstract



Keywords Environmental Kuznets Curve · Fourier Function · Wavelet Coherence · Time Varying Estimation

1 Introduction

As the drive to harmonize economic development with environmental integrity intensifies, research examining this connection gains prominence, especially studies integrating variables reflecting both economic progress and environmental conditions. The existing literature features numerous analyses evaluating how factors like economic freedom, gross domestic product (GDP), overall economic growth, energy consumption (EC), and renewable energy (REN) usage affect environmental indicators such as the carbon and fishing footprints. Comprehending these relationships is critical to the global pursuit of development and prosperity while simultaneously tackling environmental threats and climate change.

Among theories investigating the complex link between economic expansion and environmental effects, the Environmental Kuznets Curve (EKC) is particularly prominent and is the central focus of this research. The EKC proposes a non-linear connection between economic progress and environmental quality. It posits that environmental pollution tends to worsen during the initial phases of economic growth, eventually peaking, and then diminishing as income levels rise further. This pattern is commonly visualized as an inverted U-shaped curve. Kuznets (1955) first introduced this concept regarding income inequality, suggesting that economic growth initially widens income gaps in early development stages but later narrows them as economies advance. Subsequently, Grossman and Krueger (1991) applied this hypothesis to environmental concerns, notably pollution and carbon emissions (CE). Empirical investigations into the EKC hypothesis have produced varied outcomes, primarily due to differences in economic structures and policy measures across nations and regions (Stern, 2004). Research examining various pollutants, model setups, and econometric methods has revealed diverse patterns, such as N-shaped or monotonic relationships, or even no clear connection between the variables studied (Ozturk et al., 2024; Liu et al., 2024; Mu, 2024; Aydin & Degirmenci, 2024; Makarov & Alataş, 2024; Yılancı et al., 2023; Fang & Gao, 2023). Additionally, many studies targeting specific geographic areas have tried to refine the EKC interpretation by including extra variables in their models (Ercan et al., 2024; Moalla, 2024; Saud et al., 2024; Uzar & Eyuboglu, 2024). As detailed later in the literature review, some studies affirm the inverted U-shaped link between per capita income and environmental degradation while incorporating variables that strengthen the EKC framework within their models (Selden & Song, 1994; Tsurumi & Managi, 2010; Wang et al., 2022). Consequently, studies focusing on the EKC emphasize the necessity of nuanced analysis and context-specific considerations to fully understand the intricate dynamics of economic development and environmental sustainability.

Despite extensive research on the EKC hypothesis, particularly concerning France, several critical gaps persist, motivating the present study. Firstly, many existing analyses are constrained by relatively short timeframes, potentially obscuring the long-term evolutionary dynamics crucial for evaluating the EKC phenomenon and decoupling trends over distinct historical epochs. Secondly, the prevalent use of standard econometric techniques often fails to adequately address the structural breaks (both sharp and smooth) inherent in long historical data, casting doubt on the robustness of previous findings regarding the growth-environment nexus. Thirdly, the specific long-term impact of technological progress, particularly as captured by Total Factor Productivity (TFP), alongside drivers like economic freedom, has not been sufficiently integrated and rigorously examined within the French EKC context using advanced time-series methods capable of handling these complexities. This study aims to directly address these gaps.

The mixed results from EKC studies and their potential policy implications demand a critical look at current methodologies and a search for more dependable analytical tools. In this light, the current research aims to enhance the existing literature by using extensive datasets and applying a strict analytical framework crucial for assessing the EKC as a long-duration phenomenon. To manage the influence of structural shifts on unit root test results, we adopt the novel unit root test from Enders and Lee (2012). Furthermore, we tackle the potential impact of structural breaks on causality by using a modern causality test from Nazlioglu et al. (2016). This test offers a unique benefit by incorporating a Fourier function, which helps identify and adjust for multiple gradual structural changes during causality analysis. Crucially, this research employs the recently introduced cointegration test by Yılancı et al. (2023), specifically crafted to identify both gradual and abrupt structural changes in cointegration relationships. This methodological innovation builds on the framework by Gregory and Hansen (1996), which used a dummy variable for a single structural break. Yılancı et al. (2023) enhance this by adding a Fourier function to handle multiple gradual changes. The adaptability of this cointegration test allows for a thorough investigation of the link between independent and dependent variables, deepening the analytical insight and making a unique contribution. This study's novel approach, using the Yılancı et al. (2023) cointegration test, overcomes limitations of older tests like Gregory and Hansen (1996), which could only detect single sharp breaks. By integrating a Fourier function and a dummy variable, the Yılancı et al. (2023) test identifies and accounts for both smooth and sharp structural shifts in long-term relationships. This data-driven method, avoiding the need to pre-define break points, boosts the analysis's robustness and objectivity, yielding more precise and trustworthy evaluations of long-run connections. Thus, this study provides greater certainty regarding the EKC hypothesis validity and the influence of economic factors on CO_2 emissions in France. Additionally, alongside Fourier-based methods, this research uses partial wavelet coherency (PWC) analysis to examine variable synchronicity across various time scales (short-, medium-, long-term) and frequencies. PWC facilitates simultaneous insight into both time and frequency characteristics, adeptly identifying and separating cyclical patterns while balancing temporal and spectral accuracy. It also offers improved capability in spotting evolving trends and key discontinuities within the dataset. A detailed explanation of the employed methodologies follows in the econometric methodology section.

The intrinsic long-term aspect of the EKC hypothesis requires a broad temporal view for valid analysis. Therefore, the extensive timeframe of our study, 1890 to 2019, is a key strength, contrasting with the shorter durations often seen in related literature. This wide period, marked by continuous data availability, covers diverse economic development stages in France—pre-industrial, industrial, and post-industrial—offering a richer backdrop for understanding the EKC's evolution. While Yılancı et al. (2023) also analyzed the UK over a similarly long period, many other studies on France use considerably shorter timeframes compared to our research's extensive duration (Azam et al., 2023; Ciarlantini et al., 2023). Moreover, our study adds to the literature by integrating the relatively new variable of total factor productivity (TFP) into the EKC model. First employed by Chimeli and Braden (2005) in their EKC work, TFP is recognized by Amri (2018) as a vital economic activity indicator for multiple reasons. Unlike GDP, TFP offers a more refined measure of growth, highlighting the role of technological innovation in national development. It represents the core engine of growth beyond simple factor inputs, encompassing both technological progress and overall economic efficiency. The inclusion of economic freedom and EC variables is also consistent with their common use in EKC studies (Akadiri et al., 2021; Ozcan & Ulucak, 2021). A primary limitation of this study should be noted: due to data constraints reaching back to the 1890 s, the model could not include certain important control variables like trade openness and foreign direct investment (FDI).

This research contributes to the EKC field by analyzing the long-run connection between CO_2 emissions and crucial economic indicators in France over a vast historical timeline (1890–2019). Moving beyond standard EKC analyses, this study uniquely incorporates total factor productivity (TFP)—a key driver of technological advancement, resource efficiency, and sustainable growth—alongside economic freedom. Additionally, the study utilizes robust, previously underused econometric methods to rigorously evaluate long-term relationships, presenting a fresh and thorough analysis of the EKC hypothesis within the French context. Our results confirm a cointegrating link among CO_2 emissions and the selected variables. EC, economic freedom, and economic growth show a positive correlation with carbon emissions. While the EKC hypothesis finds partial validation through an inverted U-shaped pattern in specific periods, wavelet coherence analysis indicates significant time-varying correlations at various time scales.

2 Literature review

Grossman and Krueger (1991) pioneered the investigation into the non-linear link between per capita income and environmental degradation, proposing an inverted U-shaped pattern later known as the EKC. Since its introduction, the EKC hypothesis has attracted significant interest in both academic and practical circles, leading to a substantial body of empirical research. This section aims to provide a thorough overview of key studies focused on

France, primarily evaluating the methodological strategies used and identifying the main strengths and weaknesses within this research stream.

Ang (2007) explored the dynamic causal links among pollutant emissions, EC, and output in France using cointegration and vector error-correction models. The study suggested strong interconnections, finding a durable long-term relationship over the 1960–2000 period. Causality tests supported the idea that economic expansion significantly drives both EC and pollution growth long-term, thus backing the EKC hypothesis for that timeframe. The article's main argument is that energy use, efficiency, and development are sustainably linked; specifically, higher EC leads to efficiency improvements, ultimately fostering development. While an early study on France, its variables lacked the robustness needed for a thorough EKC evaluation, and crucial control variables reinforcing the EKC interpretation were missing.

Building on this, Iwata et al. (2010) extended the analysis to evaluate the EKC in France by incorporating the contribution of nuclear energy (NE) to electricity generation, using data from 1960 to 2003. Utilizing the ARDL cointegration approach for estimation, they also examined model stability and Granger causality. Their findings supported the EKC hypothesis and indicated a significant causal link from NE to CO_2 emissions, highlighting NE's importance in reducing CO_2. Although NE is frequently mentioned as a way to cut carbon emissions, its inclusion in long-term policies for achieving Sustainable Development Goals remains a complex and debated issue.

Shahbaz et al. (2018) widened the scope by examining factors affecting carbon emissions in France from 1955 to 2016, incorporating FDI, financial development, economic growth, EC, and energy research innovations. Their results showed FDI positively impacting carbon emissions, while energy research innovations had a negative effect. Financial development correlated with lower carbon emissions, supporting better environmental quality. Furthermore, FDI aligned with the pollution-haven hypothesis in France, whereas financial development and energy innovations contributed to environmental improvement. Conversely, EC displayed a positive link with carbon emissions. The connection between economic growth and CO_2 emissions followed an inverted-U shape, confirming the EKC. This study stands out for its frequent inclusion of financial variables, less common in related literature. The investment and finance variables used have significant implications for crafting economic and environmental policies aimed at sustainable growth and emission targets.

Neagu (2019) examined the EKC framework in a wider European context, investigating the link between the economic complexity index and CO_2 emissions across 25 EU nations, including France, from 1995 to 2017. Using cointegrating polynomial regression in both panel data and individual country time-series settings, the study also included'energy intensity'as a key determinant of carbon emissions. Results pointed to a non-linear, inverted U-shaped relationship between CO_2 emissions and economic complexity. This research, notable for integrating economic complexity, is significant for the French literature due to its use of both time-series and panel data analyses and its focus on sustainable development requirements. However, its limited time span might restrict its relevance for long-term EKC analysis.

Işik et al. (2020) tested the EKC hypothesis validity for the Group of Seven (G7) nations, France included, covering 1995 to 2015. Beyond the EKC evaluation, the study aimed to clarify the effects of increased REN consumption and international tourism revenue on CO_2 emissions. Employing a panel bootstrap cointegration test and an augmented mean group (AMG) estimator, they found the tourism-induced EKC hypothesis applied solely to

France. They also discovered that higher REN consumption correlated with reduced CO_2 emissions in France. The identification of the tourism-induced EKC as relevant only to France is a valuable addition to the literature, though the study's timeframe is somewhat restricted. Based on their findings, the study suggests French policymakers reassess current tourism policies and move towards a framework integrating sustainable practices and renewable energy. Bella (2018) also investigated the EKC hypothesis using tourism data for France over a similar period, finding a negative long-term link between tourism growth and pollutant emissions, implying tourism could have a sustainable impact on destination resources. Ciarlantini et al. (2023) looked into the tourism-induced EKC over a decade (2009–2018), studying the connection between tourism expansion and air pollution in five major European tourist destinations, including France. Their findings showed varied correlations between economic development and environmental degradation within France and highlighted the need for tourism policies to balance promotion with environmental mitigation by integrating sustainability principles.

Ma et al. (2021) quantified links between real GDP, CO_2 emissions, renewable and nonrenewable energy use, tourism, and labor force in France and Germany, considering their leadership in advancing the Paris Agreement. Using 1995–2015 data, they confirmed a long-term inverted U-shaped relationship between CO_2 emissions and real GDP, validating the EKC hypothesis. The tourism sector was also shown to aid carbon reduction. Pata and Samour (2022) explored the EKC hypothesis for France (1977–2017) using Fourier co-integration and causality tests. They assessed the impacts of nuclear and renewable energy on ecological footprint, CO_2 emissions, and load capacity factor, pioneering the examination of NE's effect on the latter. Findings showed no inverted U-shape for CO_2 and income but supported the EKC for the load capacity factor. NE was found to reduce CO_2 emissions and enhance load capacity, improving environmental quality. Renewable energy, however, showed no long-term environmental effect, stressing NE's role in green sustainability. Prioritizing NE and energy efficiency investments could help France accelerate sustainable economic growth. Building on this, Pata and Naimoglu (2024) studied the influence of energy prices and technological advances in renewables and NE on CO_2 emissions in France (1990–2020). Their unique work explores energy-tech developments'impact on French ecological quality, addressing a research gap. They recognize environmental quality's importance for sustainability and stress the growing significance of R&D in clean energy as a viable path, while also noting the negative ecological impacts of continued fossil fuel reliance.

Azam et al. (2023) analyzed the effects of alternative energy, resource use, and government spending on France's environmental sustainability (1990–2018) within the EKC framework. Long-term analysis showed an inverse link between CO_2 emissions and alternative/NE, natural resources, and government expenditures. Economic expansion, however, correlated positively with CO_2 emissions. Furthermore, CO_2 emissions negatively correlated with squared economic growth, supporting the EKC hypothesis. Reviewing related literature reveals most studies cover the 1990 s-2010 s. Balado-Naves et al. (2018), also covering this era, stand out due to sample size, assessing influences of REN use, service sector GDP contribution, energy intensity, and real per capita income on per capita CO_2 emissions. Using panel data for 173 countries (including France, 1990–2014), they estimated an augmented EKC model incorporating neighbor effects. Forecasts for 2015–2100 assessed global sustainability, adding originality. Findings suggest widespread EKC adherence, with higher energy intensity in neighboring nations correlating with increased national per capita emissions.

Using the EKC framework, Ridwan et al. (2023) assessed the impacts of alternative energy, natural resources, and government spending on France's ecological sustainability (1990–2021). FMOLS was used for long-run estimates, with DOLS checking robustness. Results showed an inverse long-term relationship between CO_2 emissions and renewable/nuclear energy, natural resources, and government spending. A positive correlation existed between CO_2 emissions and economic development. Crucially, CO_2 emissions negatively associated with squared economic progress, backing the EKC hypothesis. Frodyma et al. (2022) examined EKC validity across EU countries (1970–2017), testing three specifications, comparing production-based (PBA) and consumption-based (CBA) emissions, and including energy transformation impacts. Using ARDL bounds testing due to heterogeneity, findings suggested EKC models inadequately explain the income-PBA relationship for most countries. Across most cases, no long-term relationship was found for any EKC specification. CBA results also rejected the EKC hypothesis. Mutascu (2018), using wavelet analysis, investigated the trade openness-CO_2 emissions link in France (1960–2013). Strengths include the methodology and relatively broad timeframe. Findings indicated no short-term co-movement ('neutral hypothesis'). However, CO_2 emissions positively influenced trade openness at medium frequencies (suggesting weaker environmental rules boost trade, especially pollutant-linked exports). Interestingly, trade openness positively affected CO_2 at low frequencies, indicating a long-term interaction via the business cycle.

Omri et al. (2024) analyzed effects of green tech, trade, income, and oil prices on French CO_2 emissions and ecological footprint (1980–2022). They found a positive long-run GDP-environment link, but negative short-term GDP shock impact on CO_2. They suggest more research on the French EKC considering green tech and trade for a fuller understanding. Uzar (2024), studying G7 countries (including France, 2006–2022), found economic growth and EC raised CO_2 emissions, while trade and economic freedom had insignificant effects. While not directly testing EKC, findings hint at a potential positive growth-CO_2 link during the period.

Economic freedom has been identified as a potential driver, direct or indirect, of CO_2 emissions. Carlsson and Lundström (2001, 2003) examined its impact across income levels, finding contrasting effects: mostly positive direct effects in high-income countries, mostly negative in low-income. Indirect effects were largely positive across levels, suggesting freedom indirectly raises emissions. Wood and Herzog (2014) studied causality between economic freedom (EFW Index) and air pollution. While finding a negative freedom-CO_2 link, it wasn't robust. They confirmed an inverted U-shaped income-CO_2 relationship peaking at high income. Joshi and Beck (2018) explored links between novel economic freedom measures and carbon emissions across OECD/non-OECD groups using GMM estimation, finding no CO_2 EKC evidence in either region. Freedom's impact varied regionally. Shahnazi and Shabani (2021) used a spatial dynamic panel model for EU countries (2000–2017), finding REN consumption negatively impacted CO_2, while observing a non-linear, U-shaped freedom-CO_2 link. They confirmed the EU EKC hypothesis, implying a U-shaped effect of freedom on CO_2. Mamkhezri et al. (2022) studied the EF-environmental pollution link in 17 Asia–Pacific nations (2000–2017) using a spatial Durbin model. They assessed impacts of EF, urbanization, resources, EC, and economic growth (EG) on ecological footprint (ECOF). Energy intensity significantly impacted ECOF, and an EKC was confirmed. Economic freedom showed positive spillover and total effects on environmental quality. Bjørnskov (2024), significantly contributing by incorporating economic freedom, investigated its influence on greenhouse gas emissions using a standard EKC model for 155 countries (1975–2015). Findings suggest freedom aids emission reduction while lowering the Kuznets Curve peak income level. This novel work examines freedom's link to environmental transition speed/characteristics. EKC literature with economic freedom has also used fishing footprint. Karimi et al. (2022) examined economic factors' impact on Asia–Pacific fishing footprint (2000–2017). Using 17 datasets, they analyzed nine freedom indicators' influence on fishery status under environmental pressure, confirming the EKC for fishing grounds footprint (positive GDP-footprint link).

Overall, the French EKC literature generally supports its existence, showing CO_2 initially rising with growth then falling. This pattern appears in studies focusing on EC, tourism, and nuclear/renewable energy influences. However, REN's impact remains debated, needing more research. Economic freedom's effects are mixed, with studies showing both positive and negative CO_2 links. While most research uses data from the 1990 s-2010 s, future work, like ours, should cover longer periods for better long-term trend understanding. Expanding scope beyond CO_2 to other indicators (water pollution, biodiversity) would also improve comprehensiveness.

In conclusion, our research distinguishes itself by adding TFP as a new variable for France, using robust, previously unused methodologies, and covering an extensive historical period. These elements boost the analytical strength and relevance of our findings compared to prior literature.

3 Methods

This section details the methodological framework employed in the study. It begins by presenting the data sources, variable definitions, and the specific functional form of the model used to test the EKC hypothesis in the French context. Following the data description, the section outlines the sequence of advanced econometric procedures applied to rigorously analyze the long-run relationships and dynamic interactions among the variables.

3.1 Data and model

This research assesses the EKC hypothesis for France with a comprehensive dataset from 1890 to 2019, examining the effects of EC, economic freedom, and total factor productivity. Data availability primarily determined this period selection. The EKC hypothesis is tested using the functional form:

$$CO_2 = f(GDP, GDP^2, EC, EF, TFP) \tag{1}$$

Here, CO_2 signifies per capita carbon emissions (tonnes/person), EC is per capita energy consumption (gigajoules/person), GDP represents per capita gross domestic product (constant 2010 US$), and GDP^2 is its square, capturing the potential non-linearity between growth and environmental degradation central to the EKC. EF stands for the economic freedom index (0–10 scale). Following Prados de la Escosura (2023), economic freedom means the lack of external coercion or undue interference in individual/organizational economic decisions, allowing autonomous operation. High EF values (near 10) indicate greater freedom, low values (near 0) less. TFP denotes total factor productivity (US 2010 PPP base), calculated as GDP divided by an aggregation of capital (K) and labor (L). Using a Cobb–Douglas production function, $TFP = GDP/\left(K^{\alpha}L^{1-\alpha}\right)$.

Table 1 Descriptive statistics

	$lnCO_2$	lnEC	lnEF	lnGDP	$lnGDP^2$	lnTFP
Mean	1.642	4.498	2.030	9.415	89.342	1.364
Median	1.683	4.359	2.077	9.231	85.209	1.243
Maximum	2.341	5.257	2.172	10.679	114.033	2.572
Minimum	0.673	3.567	1.593	8.279	68.547	0.094
Std. Dev	0.402	0.531	0.144	0.841	15.978	0.881
Skewness	−0.337	0.066	−1.455	0.196	0.244	0.061
Kurtosis	2.176	1.479	4.415	1.408	1.428	1.396
Jarque–Bera	6.139	12.627	56.700	14.548	14.685	14.018
Probability	0.046	0.002	0.000	0.001	0.001	0.001

*, **, and ** denote the significance at the 1%, 5%, and 10% levels, respectively

Per capita carbon emissions data (excluding land-use change) came from Our World in Data's'CO_2 Emissions'dataset.[1] Per capita energy consumption data were sourced from the Joint Center for History and Economics website.[2] GDP and TFP data originated from the Long-Term Productivity Database website.[3] The economic freedom index was obtained from The Rafael del Pino Foundation.[4] Datasets were chosen for historical depth and reliability. Preprocessing involved taking natural logarithms of all variables to stabilize variance and normalize distributions. Equation (1) thus becomes:

$$lnCO_{2t} = \alpha_1 + \alpha_2 \ln GDP_t + \alpha_3 \ln GDP_t^2 + \alpha_4 \ln EC_t + \alpha_5 \ln EF_t + \alpha_6 \ln TFP_t + u_t \tag{2}$$

where'ln'is the natural logarithm, α_0 is the intercept, α_i (i = 1,…,5) are slope coefficients, and ut is the error term. Table 1 presents descriptive statistics, offering insights into variables'central tendencies, dispersion, and distributions.

The descriptive statistics reveal unique distributional features for each variable. $LnCO_2$ shows slight left skewness (mean 1.642, median 1.683). Its small standard deviation (0.402) suggests data clustering near the mean, while kurtosis (2.176) indicates a moderately peaked distribution with low outlier probability. LnEC exhibits slight right skewness (mean 4.498, median 4.359). Moderate standard deviation (0.531) implies some dispersion; lower kurtosis (1.479) suggests a flatter peak than $lnCO_2$, potentially indicating more outliers. LnEF has a near-symmetric distribution (mean/median ~2.030). Negative skewness (−1.455) indicates a longer left tail. Notably, its very low standard deviation (0.144, lowest overall) signifies high data concentration. High kurtosis (4.415) points to a sharper peak than $lnCO_2$ or lnEC, implying fewer extreme values.

[1] Global Carbon Budget (2023); Population based on various sources (2023) – with major processing by Our World in Data, Retrieved January 19, 2024, from https://ourworldindata.org/co2-emissions

[2] Bergeaud, A., Cette, G. and Lecat, R. (2016):"Productivity Trends in Advanced Countries between 1890 and 2012,"Review of Income and Wealth, vol. 62(3), pages 420–444, Retrieved January 20 2024, from http://www.longtermproductivity.com/download.html

[3] Kander, A., Warde, P., & Malanima, P. (2014). Power to the people: energy in Europe over the last five centuries, Retrieved January 20 2024, from https://histecon.fas.harvard.edu/energyhistory/energydata.html

[4] Prados de la Escosura, L. (2023). Economic freedom in retrospect (No. 236). EHES Working Paper. Retrieved January 21 2024, from https://frdelpino.es/investigacion/en/category/01_social-sciences/02_world-economy/02_economic-freedom-world-economy/

LnGDP displays left skewness (mean 9.415, median 9.231). Its relatively high standard deviation (0.841, compared to others except $\ln GDP^2$) suggests wider data spread. Kurtosis (1.408) indicates a less peaked distribution than $\ln CO_2$ or lnEF, possibly with more outliers. LnGDP^2 has the highest mean and median values. Its negative skewness (−0.244) implies a longer left tail. The exceptionally high standard deviation (15.978, highest overall) indicates very wide data dispersion. Low kurtosis (0.636, should be 1.428 as per table) suggests a flatter distribution than others, implying higher outlier likelihood. *(Correction Note: Kurtosis for lnGDP2 in the table is 1.428, not 0.636 as stated in the original text)*. Finally, lnTFP appears relatively symmetric with moderate variability, not heavily skewed by outliers. Figure 1 provides visual boxplots to complement these statistics.

Figure 1 visually confirms the distributional traits. LnCO_2 and lnGDP show left-skewed distributions (longer lower tails). However, $\ln CO_2$ has less variability and fewer potential outliers than lnGDP (smaller box, fewer points outside whiskers), suggesting periods of lower-than-average CO_2 are less extreme or frequent than for GDP. LnEC and lnTFP are right-skewed (longer upper tails), implying both are more prone to periods of higher-than-average values. LnTFP's higher kurtosis (tighter box relative to whiskers) suggests fewer potential outliers and more concentration around its mean compared to lnEC. LnEF and $\ln GDP^2$ contrast: lnEF is negatively skewed (long left tail) with significantly less variability (very small box) and high kurtosis (implying few outliers), while $\ln GDP^2$ is positively skewed (long right tail) with vast dispersion (very large box/whisker range) and higher likelihood of extreme values. This indicates economic freedom has been relatively stable with few extreme deviations, whereas squared GDP shows significant volatility and potential for extreme values.

3.2 Econometric methodology

This subsection details the specific econometric techniques employed to analyze the relationships described in the model. Given the long time series and the potential for structural changes and evolving dynamics, a suite of advanced methods was selected. These include tests designed to handle stationarity and cointegration in the presence of structural breaks, causality analysis robust to such breaks, and methods to capture time-varying coefficients and frequency-dependent relationships. To provide a clear overview of the analytical steps, Fig. 2 presents a flowchart summarizing the approach. The subsequent subsections elaborate on each specific technique.

Figure 2 outlines the study's research design. Data collection is followed by unit root testing using the Enders and Lee (2012) method, which employs Fourier functions to capture smooth structural breaks without needing prior specification. Long-run relationships are then explored via the Yılancı et al. (2023) cointegration test, capable of handling both smooth and sharp breaks by enhancing the Gregory and Hansen (1996) approach with Fourier functions across three models (FC, FC/T, FCS). Fully Modified OLS (FMOLS) is used for robust long-run estimation, addressing endogeneity and serial correlation common in time-series. To track relationship evolution over the extensive study period, time-varying coefficient analysis is performed using a recursive evolving window, revealing shifts due to policy, technology, or regulations. Causality is assessed with the Nazlioglu et al. (2016) Fourier Toda-Yamamoto test, accommodating non-stationarity and structural changes via bootstrap simulations. This is supplemented

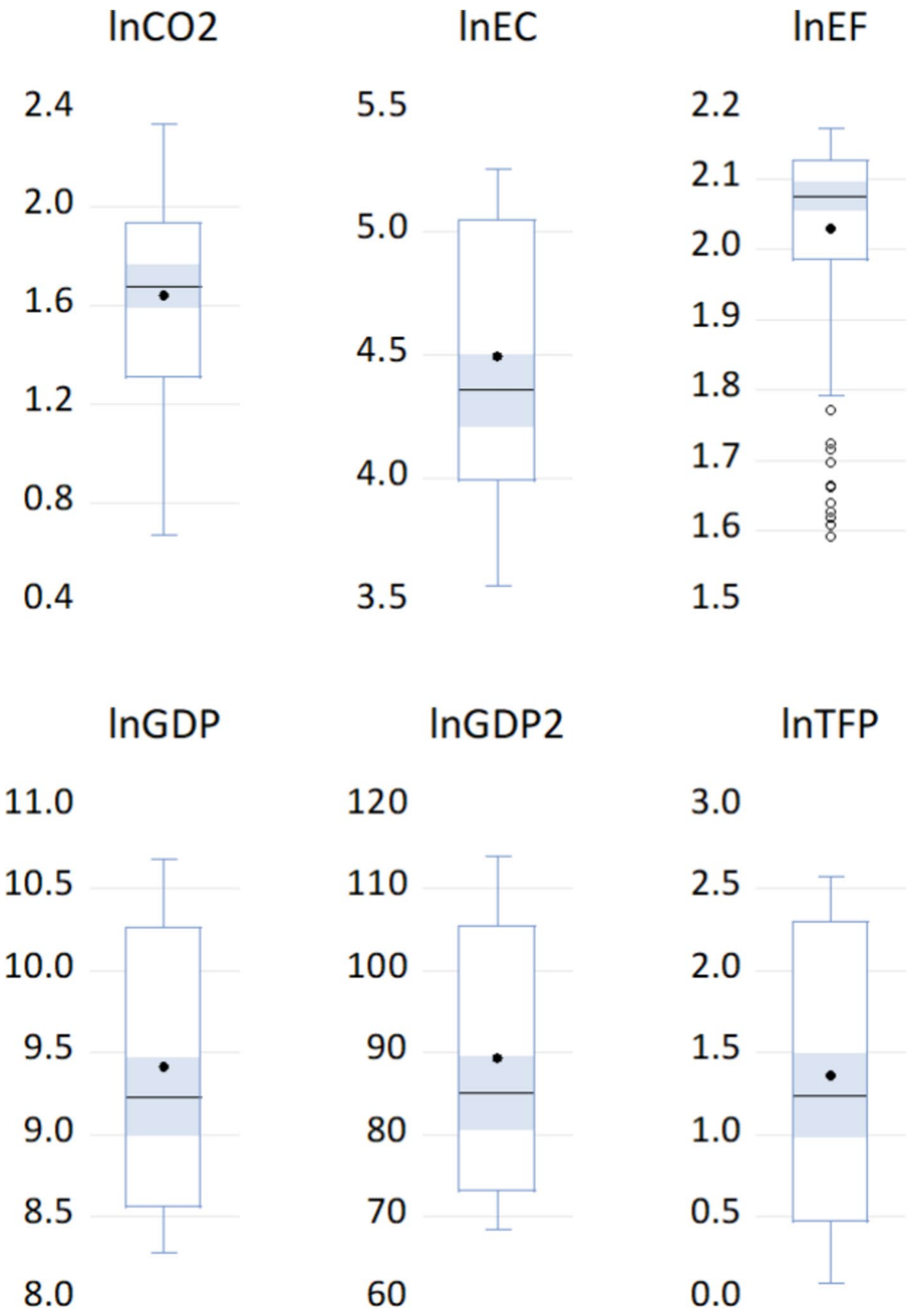


Fig. 1 Boxplots of the series

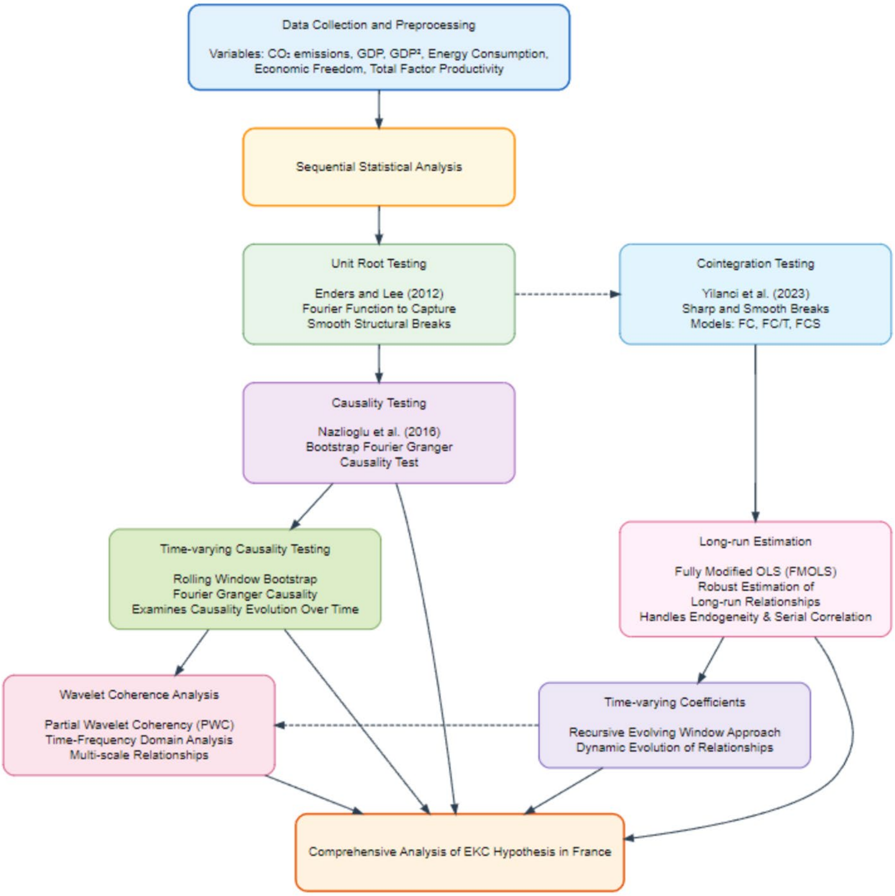


Fig. 2 Methodology flowchart

by time-varying rolling window causality analysis. Finally, partial wavelet coherency (PWC) investigates co-movements across multiple time/frequency scales, offering insights into short-, medium-, and long-term dynamics.

3.2.1 The unit root test with a fourier function

This study employs the innovative unit root test from Enders and Lee (2012) to assess stationarity while considering potential structural breaks. While several tests incorporate breaks using dummy variables (e.g., Zivot & Andrews, 1992; Lumsdaine & Papell, 1997; Narayan & Popp, 2010), they typically only capture sharp breaks (due to binary dummies) and often require pre-specifying the number of breaks, potentially lowering test power. The Enders and Lee (2012) approach enhances the standard Augmented Dickey-Fuller (ADF) test by adding a Fourier function. This modification cleverly models smooth, gradual structural changes without needing to know their location or quantity beforehand. The Fourier Function Augmented Dickey-Fuller (FADF) test is based on estimating:

$$\Delta Y_t = \beta_1 + \beta_2 Y_{t-1} + \sum_{i=1}^{k} \delta_i \Delta Y_{t-i} + \lambda f_t + u_t \tag{3}$$

Here, Y denotes the time series under consideration, and the term f_t is the Fourier function capturing smooth breaks. Following Ludlow and Enders (2000), the f_t is defined as:

$$f_t = \gamma_1 \sin(2\pi kt/T) + \gamma_2 \cos(2\pi kt/T) \tag{4}$$

where k is a specific frequency, γ_1 and γ_2 are the coefficients associated with the sine and cosine terms, respectively. t is the trend term, and T is the sample size. The optimal frequency "k" is determined endogenously by estimating Eq. (3) for k = 1, 2, …, 5 and choosing the k that minimizes the sum of squared residuals (SSR), ensuring the best fit (Enders & Lee, 2012). To address potential autocorrelation, lagged values of the dependent variable are included as regressors, and the optimal lag length is determined using the Akaike information criterion (AIC). The significance of the Fourier term ($H_0 : \gamma_1 = \gamma_2 = 0$) is checked using an F-test with critical values from Enders and Lee (2012). If significant (indicating smooth breaks), the FADF test proceeds by testing the unit root null $H_0 : \beta_1 = 0$ using a t-test (critical values also in Enders & Lee, 2012). If the F-test is insignificant, standard ADF is used.

3.2.2 The cointegration test with a sharp and smooth breaks

We utilize the recent cointegration test by Yılancı et al. (2023) which uniquely identifies both sharp and smooth structural changes in long-run relationships. It advances the Gregory and Hansen (1996) test (which used a dummy for one sharp break) by integrating a Fourier function to model multiple smooth breaks alongside potential abrupt shifts (dummy variable). This flexibility allows a more thorough analysis of relationships by accommodating gradual and sudden changes, without needing to pre-specify break locations or numbers. The test offers three models: FC, FC/T, and FCS. Model FC examines cointegration without a deterministic trend:

$$Y_t = \beta_0 + \beta_1 D_t + \phi f_t + \alpha_1 X_t + u_t \tag{5}$$

where Y_t and X_t represent the dependent and independent variables, respectively. β_0 is the intercept, captures the break's effect on the intercept via dummy Dt (Dt = 1 for t > TB, 0 otherwise, where TB is the break time), f_t is the Fourier function for smooth breaks, and α_1 is the long-run coefficient.

β_1 represents the effect of the structural break on the constant term. represents the long-run coefficient associated with the independent variable X_t.

Model FC/T adds a linear trend term (t):

$$Y_t = \beta_1 + \beta_1 D_t + \gamma t + \phi f_t + \alpha_1 X_t + u_t \tag{6}$$

Model FCS allows the slope coefficient to change after the break:

$$Y_t = \beta_1 + \beta_1 D_t + \phi f_t + \alpha_1 X_t + \alpha_2 X_t D_t + u_t \tag{7}$$

where α_1 is the pre-break slope and α_2 reflects the change post-break. The optimal frequency (k) and break date (TB) are found by estimating the chosen model for all combinations and selecting the pair minimizing the test statistic (ADF test on residuals). This minimum statistic tests the null of no cointegration against the alternative of a long-run equilibrium.

3.2.3 Fourier toda-yamamoto causality test

To assess causality while accounting for structural breaks, we use the Fourier Toda-Yamamoto (FTY) test from Nazlioglu et al. (2016). While Enders and Jones (2016) introduced breaks into causality tests, their VAR-based method requires stationary variables. The FTY test, building on Toda and Yamamoto (1995)'s lag-augmented VAR, advantageously works with non-stationary variables without differencing, preserving level information. It handles variables of potentially different integration orders. Its key innovation is adding a Fourier function to capture multiple smooth structural breaks during causality analysis. The test equation is:

$$Y_t = \alpha_0 + \sum_{i=1}^{p+d\max} \alpha_i Y_{t-i} + \sum_{i=1}^{p+d\max} \alpha_i X_{t-i} + \gamma f_t + u_t \tag{8}$$

Here, p is the optimal VAR lag length, dmax is the maximum integration order of variables (from unit root tests), and f_t is the Fourier function. Optimal frequency k for f_t is chosen (e.g., from 1 to 5) by minimizing SSR. Causality from X to Y is tested using a Wald test on the coefficients of the first p lags of X. Critical values are obtained via bootstrap simulations, suitable for small samples or non-normal data. Incorporating the Fourier function and bootstrap makes FTY robust for causality testing amidst potential breaks.

3.2.4 Partial wavelet coherency

Complementing Fourier methods, this study uses partial wavelet coherency (PWC) to analyze variable co-movement across time scales and frequencies (short-, medium-, long-term dynamics) (Goodell et al., 2022). PWC excels at extracting simultaneous time–frequency information, detecting periodic signals while balancing temporal/spectral precision (Hu & Si, 2021). It effectively identifies evolving trends and discontinuities (Frimpong et al., 2021). PWC acts like partial correlation: it isolates the relationship between two variables (y, x) by controlling for others (Z), revealing their specific connection across multiple time scales/locations (τ). The squared PWC ($\rho^2_{y,x\cdot z}$) is calculated as (Hu & Si, 2021):

$$\rho^2_{y,x\cdot z} = \frac{\left|1 - R^2_{y,x,z}(s,\tau)\right|^2 R^2_{y,x}(s,\tau)}{\left(1 - R^2_{y,z}(s,\tau)\right)\left(1 - R^2_{x,z}(s,\tau)\right)} \tag{9}$$

"."denotes variable exclusion. $R^2_{y,x}$ shows the bivariate wavelet coherency between Y and X, while $R^2_{y,z}$, $R^2_{x,z}$, $R^2_{y,x,z}$ represent the multiple wavelet coherency between the correspingding variables y–z, y-w, z-x, z-w, respectively.

$$R^2_{y,x}(s,\tau) = \frac{\overrightarrow{W}^{y,x}(s,\tau)^{y,x}\overline{\overrightarrow{W}(s,\tau)}}{\overrightarrow{W}^{y,y}(s,\tau)\overrightarrow{W}^{x,x}(s,\tau)}$$
$$R^2_{y,z}(s,\tau) = \frac{\overrightarrow{W}^{y,z}(s,\tau)\overrightarrow{W}^{z,z}(s,\tau)^{-1}\overline{\overrightarrow{W}^{y,z}(s,\tau)}}{\ddot{W}^{y,y}(s,\tau)}$$
$$R^2_{x,z}(s,\tau) = \frac{\overrightarrow{W}^{x,z}(s,\tau)\overrightarrow{W}^{z,z}(s,\tau)^{-1}\overline{\overrightarrow{w}^{x,z}(s,\tau)}}{\overrightarrow{w}^{x,x}(s,\tau)}$$
$$R^2_{y,x,z}(s,\tau) = \frac{\overrightarrow{w}^{y,z}(s,\tau)\overrightarrow{w}^{z,z}(s,\tau)^{-1}\overline{\overrightarrow{w}^{x,z}(s,\tau)}}{\overrightarrow{w}^{y,x}(s,\tau)}$$

In the above equations, $\leftrightarrow$ and $^{-}$ represent the smoothing operator and complex conjugate operator, respectively. $\overrightarrow{w}^{\alpha,\beta}$ denotes the smoothed auto-wavelet power spectra when α and β are equal, and it represents the cross-wavelet power spectra when α and β are not equal.

4 Empirical results

As a prerequisite for cointegration analysis, we first examine the integration levels of the variables, seeking to determine whether they possess unit roots, indicating non-stationarity. In addition to the Fourier ADF unit root test, the traditional ADF test, the Phillips-Perron, and the Zivot-Andrews (ZA) test were also conducted for comparison. The choice of the ZA test was made in part due to the recognition of potential structural breaks that could have affected the integration levels. Table 2 presents the results of various unit root tests, providing insights into the time-series properties of the variables.

Initially, the FADF test was applied. However, the F-test for the Fourier terms was insignificant for all variables (Table 2), suggesting smooth structural breaks are not a dominant feature. Consequently, we rely on standard unit root tests. Both ADF and PP tests yield p-values exceeding conventional levels, failing to reject the unit root null hypothesis for all variables in levels. To account for potential sharp breaks, the Zivot-Andrews (ZA) test (Model C, allowing intercept and slope breaks) was used. The ZA statistics also remained below the 10% critical value (−4.82) for all series. Thus, based on ADF, PP, and ZA tests, we conclude all six variables ($\ln CO_2$, lnEC, lnEF, lnGDP, $\ln GDP^2$, lnTFP) are non-stationary I(1) processes. This satisfies the prerequisite for cointegration analysis. The breaks identified (1960 for CO_2, GDP, GDP^2, TFP; 1967 for EC; 1949 for EF) offer historical context. 1960 might

Table 2 The findings of the unit root tests

Series	Fourier ADF			ADF	Philips-Perron	ZA	
	k*	F test	Test Stat	Test Stat	Test Stat	Test Stat	TB
$\ln CO_2$	1	4.78	−3.748 [4]	−1.869 (0.346) [9]	−2.06 (0.261)	−4.486 [4]	1960
lnEC	1	3.812	−2.828 [3]	−1.087 (0.72) [7]	−1.151 (0.694)	−3.317 [3]	1967
lnEF	5	3.546	−1.667 [0]	−1.716 (0.421) [9]	−1.956 (0.306)	−4.553 [2]	1949
lnGDP	1	2.197	0.174 [0]	−0.315 (0.918) [4]	−0.178 (0.937)	−3.521 [4]	1960
$\ln GDP^2$	1	2.276	0.405 [0]	−0.176 (0.937) [4]	0.006 (0.957)	−3.415 [4]	1960
lnTFP	5	2.621	−0.106 [0]	−0.455 (0.895) [7]	−0.428 (0.900)	−3.958 [3]	1960

Numbers in the parentheses show the p-values, and numbers in the brackets show the optimal lag lengths which are determined using AIC. The critical value for the F- and the ZA unit root test at the 10% level are 6.25, and −4.82, respectively

Table 3 The Results of Yilanci et al. (2023)'s Cointegration Test

	Test Stat	Optimal Freq	Location of Breaks
Model FC	−6.318***	6	1981
Modl FC/T	−7.221**	4	1915
Model FCS	−7.139	3	1925

The critical values which obtained using 10,000 simulations at the 1, 5, and 10% levels for the Model FC, Model FC/T and Model FCS are −6.9196, −6.3699, −6.0919; −7.442, −6.857, −6.550; and −8.342, −7.725, and −7.430, respectively. See note of Table 1.

reflect post-WWII boom impacts or early industrial shifts. 1967 aligns with the Oil Embargo's influence on EC. 1949 likely captures post-WWII economic/policy restructuring effects on economic freedom. The shared 1960 break for growth/TFP variables points towards common factors like the shift from agriculture to industry or technological advancements.

Following the confirmation of non-stationarity in all variables through unit root tests, we proceed with the Yılancı et al. (2023) cointegration test to investigate potential long-run equilibrium relationships among these variables. The Yılancı et al. (2023)'s test which is superior to conventional cointegration tests due to its ability to accommodate both sharp and smooth structural breaks by incorporating a Fourier function and a dummy variable to capture shifts and changes in the data. This enhanced specification provides a more robust assessment of the long-run relationship between variables. Table 3 provides the findings of the test, employing three distinct models to accommodate different specifications of the cointegration relationship and potential structural breaks.

The Yilanci et al. (2023) test results are in Table 3. Model FC and Model FC/T statistics (−6.318***, −7.221**) are significant at the 10% and 5% levels respectively, indicating cointegration. Model FCS (−7.139) is insignificant. Complementary tests (ARDL Bounds test, Bayer-Hanck—see Appendix 1) also support the presence of a cointegrating relationship. These findings confirm a stable long-run equilibrium exists among the variables, despite short-term fluctuations.

The presence of cointegration allows us to proceed with further analysis to understand the long-run dynamics between these variables and their impact on carbon emissions (InCO2). Hence, we explore the direction and magnitude of the relationship using FMOLS method which is suitable for addressing endogeneity issues arising from potential feedback mechanisms between variables and autocorrelation patterns that could be present in the data:

Table 4 presents FMOLS long-run estimates. LnEC, lnEF, and lnGDP have statistically significant positive coefficients, implying they are positively associated with $\ln CO_2$ in the long run. The lnEC coefficient (0.891*) suggests a 1% rise in EC corresponds to roughly a 0.891% increase in CO_2 emissions, reflecting historical fossil fuel reliance (see Fig. 3). The lnEF coefficient (0.268**) indicates that greater economic freedom has historically correlated with higher emissions. The lnGDP coefficient (8.100*) captures the emission-increasing effect of economic expansion. However, the significant negative coefficient for $\ln GDP^2$ (−0.440*) suggests decoupling at higher income levels, supporting the EKC hypothesis for France over the full period. This implies emissions growth may slow or reverse as GDP rises further. In contrast, lnTFP's coefficient (0.042) is statistically insignificant, suggesting technological progress, as measured by TFP, did not have a clear, independent long-run impact on CO_2 emissions within this model, possibly offset by other factors like EC or growth itself. Robustness checks using DOLS and CCR (Appendix 2) confirm these general findings.

Table 4 The Results of FMOLS Model

Variables	Coefficients	*p*-values
lnEC	0.891*	0.000
lnEF	0.268**	0.053
lnGDP	8.100*	0.000
lnGDP^2	−0.440*	0.000
lnTFP	0.042	0.855
Intercept	−39.950*	0.000

See note of Table 1

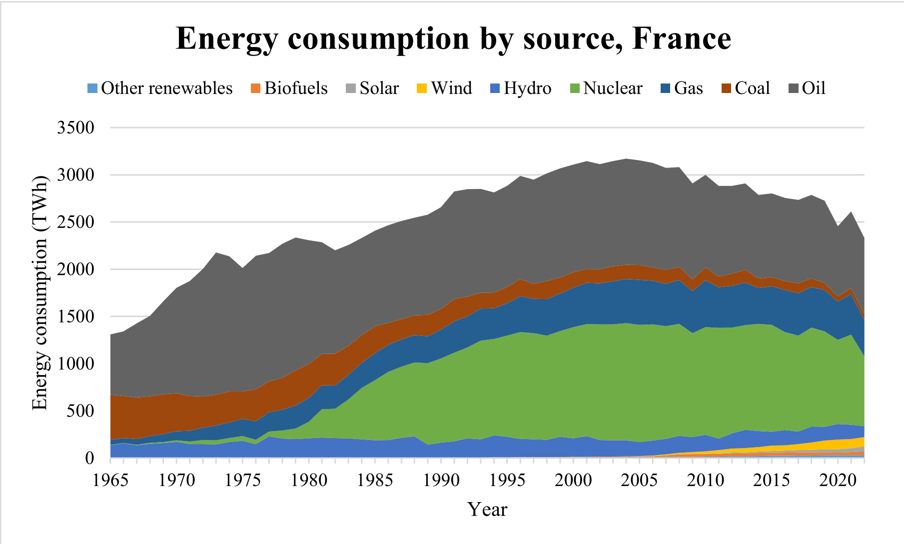


Fig. 3 Energy consumption by source, France. Note: Other renewables include geothermal, biomass and waste energy

4.1 (Data source: Energy Institute—Statistical Review of World Energy (2023))

Having established the existence of a cointegrating relationship among the variables, we now employ the Fourier Toda-Yamamoto causality test to investigate the direction of causal effects among the variables in the French context. The results are provided in Table 5[5]:

Table 5 shows FTY causality results. No significant causality runs from lnEC, lnGDP, lnGDP^2, or lnTFP to lnCO_2 at conventional levels. However, significant causality exists from lnEF to both lnCO_2 (1% level) and lnEC (1% level). This implies changes in economic freedom may Granger-cause changes in both carbon emissions and energy consumption. Interestingly, significant causality also runs from lnCO_2 to lnEF (5% level), suggesting a feedback loop where emission levels might influence policies affecting economic freedom (e.g., via environmental regulations). Furthermore, significant bidirectional causality exists

[5] Optimal lag is found as 1, while the optimal frequency is found as 1.

Table 5 The results of fourier toda-yamamoto test model

Direction	Wald	Bootstrap p-val
lnEC↛lnCO2	0.018	0.891
lnEF↛lnCO2	14.468*	0.002
lnGDP↛lnCO2	0.798	0.358
lnGDP2↛lnCO2	1.396	0.238
lnTFP↛lnCO2	0.765	0.371
lnCO2↛lnEC	1.409	0.22
lnEF↛lnEC	8.349*	0.007
lnGDP↛lnEC	1.212	0.265
lnGDP2↛lnEC	1.879	0.17
lnTFP↛lnEC	0.718	0.384
lnCO2↛lnEF	7.827**	0.013
lnEC↛lnEF	8.891*	0.009
lnGDP↛lnEF	0.658	0.405
lnGDP2↛lnEF	0.495	0.463
lnTFP↛lnEF	1.513	0.205
lnCO2↛lnGDP	0.056	0.799
lnEC↛lnGDP	0.0001	0.989
lnEF↛lnGDP	12.927*	0.002
lnGDP2↛lnGDP	3.786***	0.058
lnTFP↛lnGDP	0.02	0.89
lnCO2↛lnGDP2	0.061	0.801
lnEC↛lnGDP2	0.0001	0.99
lnEF↛lnGDP2	12.663*	0.002
lnGDP↛lnGDP2	3.831***	0.052
lnTFP↛lnGDP2	0.033	0.852
lnCO2↛lnTFP	0.065	0.784
lnEC↛lnTFP	0.074	0.784
lnEF↛lnTFP	15.776*	0.001
lnGDP↛lnTFP	2.533	0.111
lnGDP2↛lnTFP	2.531	0.109

See note of Table 1

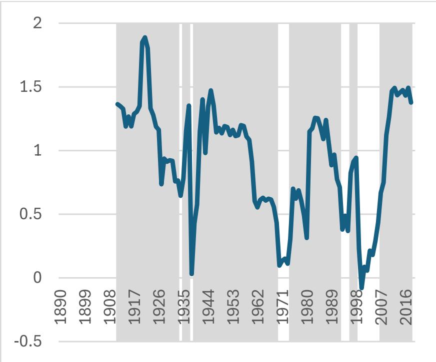
between lnEF and lnEC (lnEF—> lnEC at 1%, lnEC—> lnEF at 1%), indicating a mutual influence between economic freedom and energy consumption patterns. Significant causality also runs from lnEF to lnGDP (1% level) and $lnGDP^2$ (1% level), and from lnEF to lnTFP (1% level). GDP growth (lnGDP) and its square ($lnGDP^2$) show feedback causality ($lnGDP^2$—> lnGDP at 10%, lnGDP—> $lnGDP^2$ at 10%). These results highlight economic freedom's central role in influencing emissions, energy use, and economic activity in France.

While the Fully Modified OLS (FMOLS) model provides valuable insights into the long-run relationships between variables, it assumes that the coefficients remain constant over time. However, this assumption may not hold due to the dynamic nature of relationships between variables, which can evolve in response to sudden shifts in economic policies, technological advancements, or changes in environmental regulations. To account for these dynamic changes, we extend our analysis by estimating the coefficients and conducting causality tests within a time-varying framework. This is achieved by employing the recursive evolving window approach, which allows us to examine how the relationships between variables evolve over time. We determine the subsample size (*ss*) by following Phillips et al. (2015) as follows:

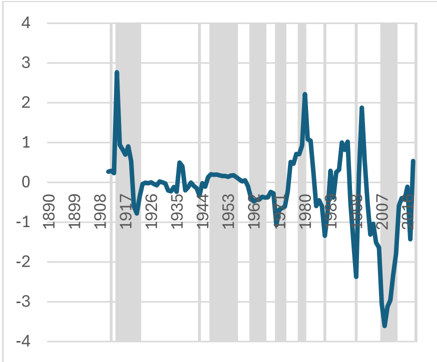
$$ss = \left\{ T\left(0.01 + 1.8/\sqrt{T}\right) \right\} \tag{10}$$

The dynamic evolution of the relationships between carbon emissions and the explanatory variables over the 1890–2019 period is illustrated through the time-varying coefficients presented in Fig. 4. Examining the impact of energy consumption (lnEC), Fig. 4a shows a persistently significant positive influence on carbon emissions across almost the entire timeframe, although the magnitude of this effect fluctuates considerably. During the early phases of rapid industrialization (approximately 1910–1932), the coefficient reached a peak near 1.8, indicating a strong link between energy use and emissions, likely reflecting reliance on fossil fuels. However, in later periods, particularly after the 1970 s, the coefficient, while remaining positive, declined significantly, suggesting a weakening relationship possibly due to France's gradual shift towards nuclear power and other cleaner energy sources, partly driven by oil crises and increasing environmental awareness, as also suggested by the energy mix evolution in Fig. 3. Figure 4b reveals a distinct trajectory for the influence of economic freedom (lnEF), which initially exerted a positive impact during the 19 th and early twentieth centuries but transitioned to displaying a negative and statistically significant effect from the late twentieth century onwards. Notable negative dips occurred around 1986, 1999, and between 2006–2011, potentially indicating that periods of increased economic freedom later coincided with the implementation of stricter environmental regulations, a transition towards a service-based economy, or major economic events like the 2008 financial crisis temporarily reducing emissions, thus suggesting a decoupling dynamic in these later phases.

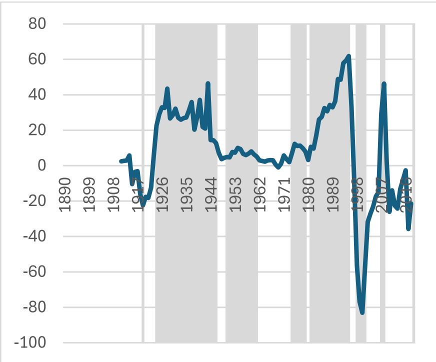
The influence of economic growth (lnGDP), shown in Fig. 4c, was significantly positive during specific historical intervals, including the interwar period (1925–1945, with coefficients ranging from 20 to 50) and the post-World War II economic boom (1950–1961, coefficient around 10), reflecting periods of intense industrial activity driving emissions. This positive impact remained significant from 1980 onwards, peaking in 1995, possibly linked to the expansion of the service sector alongside continued industrial growth, before experiencing a sharp negative dip around 2000 (coefficient −85), which might be associated with the implementation of significant environmental policies like the Kyoto Protocol. Following the 2008 financial crisis, the lnGDP coefficient largely lost statistical significance. The squared term of economic growth (lnGDP^2, Fig. 4d) displayed a complex pattern potentially indicative of EKC dynamics at certain times; it was briefly significantly positive in 1919, then significantly negative between 1925–1945 (average coefficient −2.5), suggesting diminishing returns or early decoupling effects following initial industrialization. This negative significance persisted from 1950–1961 (coefficients near zero) and again from 1980 through 1995 (lowest dip −3), consistent with an EKC turning point being reached due to regulation or efficiency gains. However, a significant positive spike around 2000 (coefficient 4.2) suggests that rapid expansion in potentially energy-intensive sectors during that specific growth phase temporarily reversed the decoupling trend, followed by a return to a significant negative coefficient (−2.2) around the 2008 crisis. Finally, the impact of total factor productivity (lnTFP), depicted in Fig. 4e, varied substantially over time: it showed a small negative impact near World War I, a significant positive spike in 1921 (coeff 5.8) possibly linked to post-war recovery, a decline during the Great Depression, a



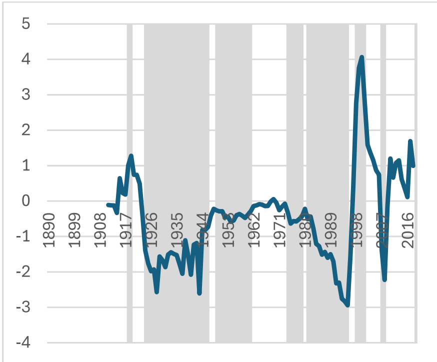
(a) LnEC



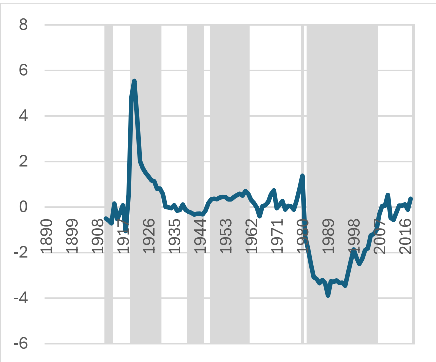
(b) LnEF



(c) LnGDP



(d) $LnGDP^2$



e) LnTFP

Fig. 4 Time-Varying Coefficients. *(The shaded areas represent statistically significant coefficients at 10% level.)*

modest positive impact during World War II and the post-war boom (1949–1961, avg coeff ~0.5), and notably, a significant negative impact between 1981 and 2005 (coeffs ranging −1.9 to −0.2, lowest −4.0 in 1990), perhaps reflecting efforts towards energy efficiency following the 1970 s energy crises and the shift towards a service economy.

Overall, the fluctuating signs and significance levels of the lnGDP and lnGDP^2 coefficients across different sub-periods strongly suggest that the standard inverted U-shaped EKC hypothesis does not consistently hold for France over the entire 1890–2019 timeframe. While periods consistent with EKC dynamics are observable (e.g., 1925–1945, 1980–1995), the relationship is frequently interrupted or altered by historical events, policy shifts, and structural economic changes, highlighting the complex and dynamic nature of the link between economic growth and carbon emissions in the long run.

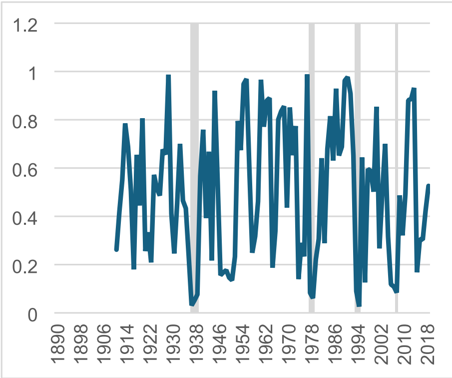
To reveal the changes in the results of the causality test, we also analyze the causality relationship in a time-varying framework. We present the results in Fig. 5.

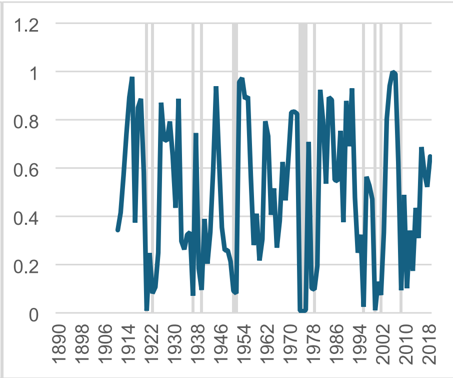
Figure 5 presents the results from the time-varying Fourier Toda-Yamamoto causality tests, revealing intricate and evolving causal interdependencies among the variables between 1890 and 2019. Although the magnitude of statistically significant causal links is generally modest (averaging around 0.1), the observed patterns and shifts offer valuable insights into the dynamic interplay shaped by France's economic history. There are instances where causality runs unidirectionally from carbon emissions (lnCO_2) to energy consumption (lnEC), notably during periods like 1936–1940, 1978–1980, and around 2009 (Fig. 5a), suggesting that emission levels might have influenced energy demand during times of economic stress or recovery efforts. Conversely, Fig. 5b shows periods where energy consumption Granger-causes carbon emissions (e.g., 1920 s, 1950 s, and during the 1970 s oil crises), indicating that energy use patterns likely drove emission levels during phases of growth or energy market disruptions.

Significant causality from carbon emissions to economic freedom (lnCO_2 →lnEF) is observed between 1915 and 1940 and during shorter post-WWII intervals (Fig. 5c), potentially reflecting how rising emissions during industrialization or crisis periods might have prompted policy responses affecting economic freedom. Figure 5d demonstrates reverse causality (lnEF →lnCO_2) during specific periods, implying that shifts in the economic freedom regime may have influenced emission outcomes at certain times. Regarding economic growth, Fig. 5e indicates periods where emissions Granger-cause GDP (lnCO_2 →lnGDP), particularly during WWII, the post-war boom, and post-crisis recoveries (1990 s, post-2008), suggesting emissions coincided with or perhaps even spurred growth-related activities. Figure 5f shows the reverse causality (lnGDP →lnCO_2) occurring in some periods, consistent with the initial stages of the EKC framework where growth drives emissions. The relationships involving squared GDP (Figs. 5g and 5 h) show intermittent bidirectional causality, offering only inconsistent support for stable EKC dynamics over the long haul. Causality involving total factor productivity reveals limited influence from emissions to TFP (lnCO_2 →lnTFP, Fig. 5i), but more frequent instances where TFP Granger-causes emissions (lnTFP →lnCO_2, Fig. 5j), suggesting that technological progress, potentially related to energy efficiency or industrial structure, has often played a role in shaping emission levels over time. Collectively, this time-varying analysis underscores the complex, shifting nature of causal relationships, heavily influenced by the specific historical and economic context of different eras.

Next, to reveal the coherency between the variables, we employ a recently suggested partial wavelet coherency test and present the results in Fig. 6:

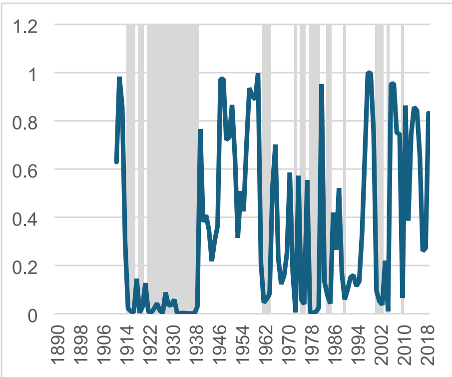
Figure 6 displays the partial wavelet coherency (PWC) results, illustrating the time–frequency co-movement and lead-lag dynamics between carbon emissions (lnCO_2)

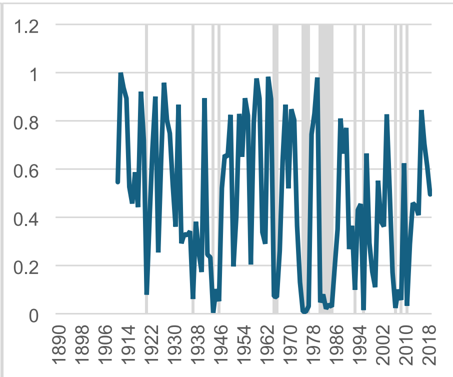




(a) $\ln CO_2 \nrightarrow \ln EC$

(b) $\ln EC \nrightarrow \ln CO_2$



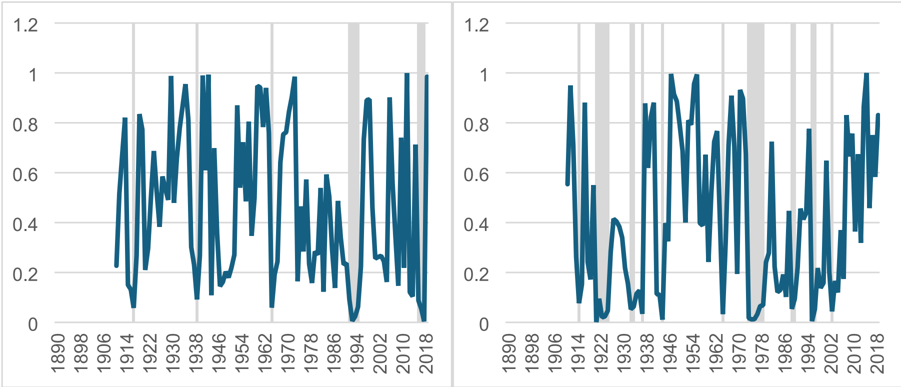


(c) $\ln CO_2 \nrightarrow \ln EF$

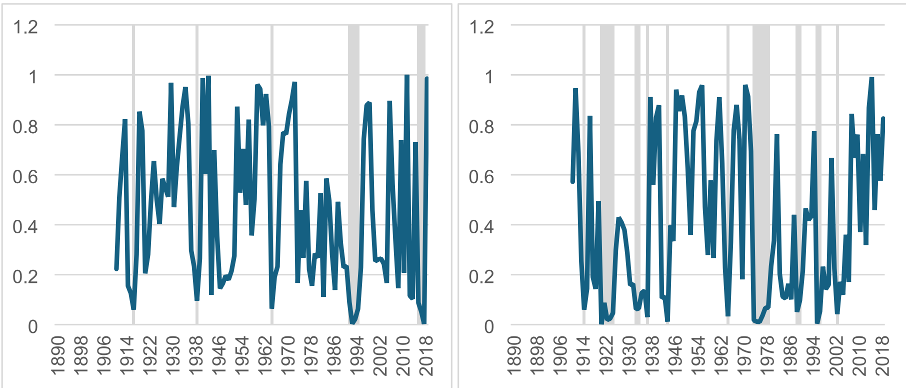
(d) $\ln EF \nrightarrow \ln CO_2$

Fig. 5 Time-Varying Fourier Toda-Yamamoto Test. *(The shaded areas represent statistically significant coefficients at the 10% level.)*

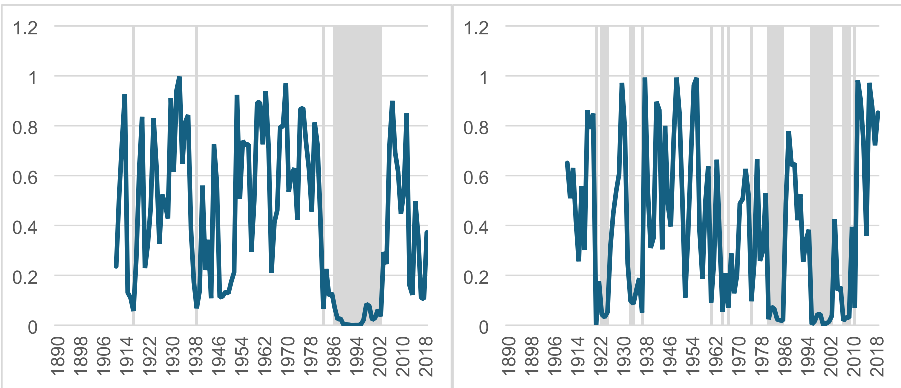
and each explanatory variable, after controlling for the influence of the other variables in the model. Statistically significant relationships (coherence >0.5) are indicated by regions enclosed by contours, with phase arrows depicting the lead-lag structure (rightward: in-phase; leftward: anti-phase; upward: $\ln CO_2$ lags predictor; downward: $\ln CO_2$ leads predictor). A strong positive coherence (mostly in-phase, rightward arrows) is evident between $\ln CO_2$ and lnEC across multiple time scales (Fig. 6a), with $\ln CO_2$ generally leading lnEC (arrows pointing somewhat down-right), particularly in more recent periods, suggesting changes in emissions might often precede or drive energy consumption patterns. The relationship between $\ln CO_2$ and lnEF (Fig. 6b) exhibits complex dynamics; at the 6–12 year cycle band around periods 20–40, $\ln CO_2$ appears to lead lnEF (down-right arrows), perhaps reflecting policy responses to emissions, while in later periods (around 100–120) at similar frequencies, the relationship inverts with lnEF



e) $\ln CO_2 \nrightarrow \ln GDP$ (f) $\ln GDP \nrightarrow \ln CO_2$



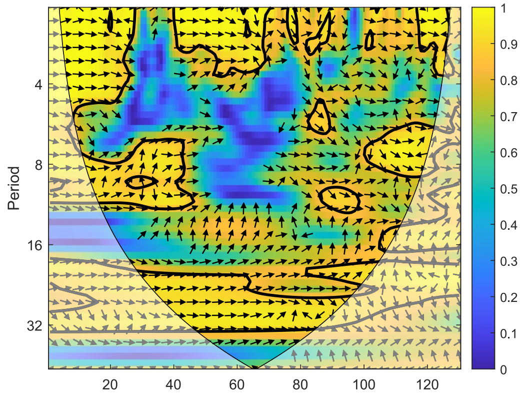
(g) $\ln CO_2 \nrightarrow \ln GDP^2$ (h) $\ln GDP^2 \nrightarrow \ln CO_2$



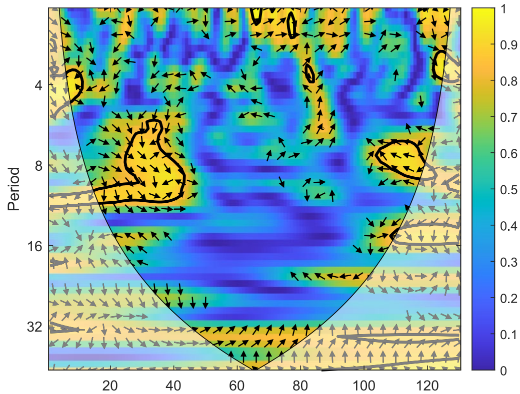
(i) $\ln CO_2 \rightarrow \ln TFP$ (j) $\ln TFP \rightarrow \ln CO_2$

Fig. 5 (continued)

Fig. 6 The Results of Partial Wavelet Coherency. (The variables after "|" are the exogenous variables. We look for wavelet coherency between the variables before ~ and after this symbol.)



(a) $\ln CO_2$~lnEC | lnEF, lnGDP, $\ln GDP^2$, lnTFP



(b) $\ln CO_2$~lnEF | lnEC, lnGDP, $\ln GDP^2$, lnTFP

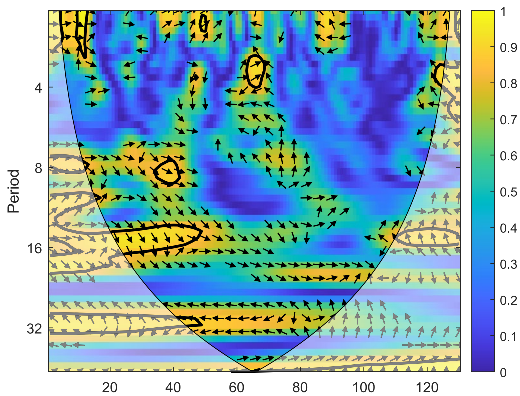
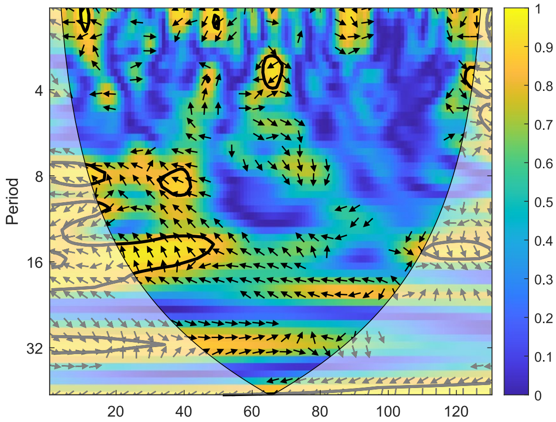
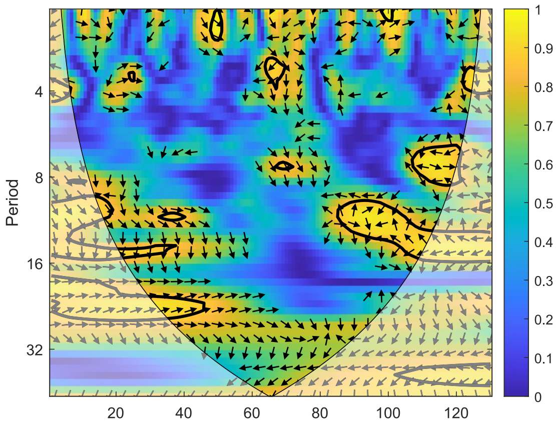


Fig. 6 (continued)

(c) $\ln CO_2$~$\ln GDP$ | $\ln EC$, $\ln EF$, $\ln GDP^2$, $\ln TFP$



(d) $\ln CO_2$~$\ln GDP^2$ | $\ln EC$, $\ln EF$, $\ln GDP$, $\ln TFP$



(e) $\ln CO_2$~$\ln TFP$ | $\ln EC$, $\ln EF$, $\ln GDP$, $\ln GDP^2$

leading $\ln CO_2$ (up-right arrows), possibly indicating that changes in economic freedom regimes influenced emissions in the longer run.

Significant coherence between $\ln CO_2$ and $\ln GDP$ (Fig. 6c) is primarily observed at lower frequencies (16-year scale) during earlier periods (around 20–50), with $\ln CO_2$ leading (down-right arrows), consistent with early-stage EKC dynamics where emissions might drive or coincide with long economic growth cycles. However, coherence is less consistent across other scales and time periods. The PWC between $\ln CO_2$ and $\ln GDP^2$ (Fig. 6d) reveals a notable positive phase relationship (arrows pointing somewhat up-right) at the

6–12-year scale around periods 20–50, indicating that $\ln CO_2$ lags behind $\ln GDP^2$. This suggests a potential decoupling dynamic where emissions trail accelerated economic growth rates, possibly due to efficiency improvements or structural changes becoming effective within those medium-term cycles. Figure 6e shows strong positive coherence between $\ln CO_2$ and lnTFP at longer cycles (> 16-year scale) around periods 35–45, with $\ln CO_2$ leading (down-right arrows), perhaps implying that periods of rising emissions coincided with or were followed by productivity increases possibly linked to technology investments or industrial expansion. The lead-lag relationship varies elsewhere; $\ln CO_2$ also leads at the 15-year scale around period 30 and the 4–8-year scale around period 70, while significant coherence around period 100 (12-year scale) lacks a clear, consistent phase direction. Overall, the PWC analysis provides a nuanced understanding of how the correlations and lead-lag relationships between carbon emissions and economic factors in France have varied across different time horizons and historical eras.

5 Discussion

This empirical investigation explored the long-run connections between CO_2 emissions and key economic indicators (EC, economic freedom, GDP, GDP^2, TFP) in France from 1890–2019. Non-stationarity was confirmed, and cointegration analysis (Yilanci et al., 2023 test, supported by ARDL/Bayer-Hanck) established a long-run equilibrium relationship. FMOLS estimation revealed positive long-run associations between CO_2 emissions and EC, economic freedom, and GDP. The EC elasticity (0.891) confirms energy use as a major emissions driver, consistent with Kongkuah (2023) on ecological footprints. Positive freedom linkage (0.268) suggests liberalization historically correlated with higher emissions.

The EKC hypothesis receives qualified support. The positive GDP coefficient (8.100) reflects the growth-emission link, while the negative GDP^2 coefficient (−0.440) indicates potential decoupling at higher incomes, aligning with the EKC premise for the overall period. This resonates with findings for other nations (Kongkuah et al., 2022; Ozgur et al., 2022) and earlier French studies using different methods but accounting for breaks (Can & Gozgor, 2016). However, our time-varying analysis shows this inverted U-shape is only evident during specific historical phases, not consistently throughout the 130 years. This temporal variability aligns with Destek et al. (2020), who found non-linear patterns (M/N-shapes) in G7 countries, confirming the EKC's validity only for specific periods (pre-1973 for France in their study, partially matching our findings of earlier peaks). Our results also echo Azam et al. (2023) who found EKC support alongside evidence of policy interventions decoupling growth and emissions, particularly in later periods corresponding to our findings of structural shifts and energy transitions. The partial decoupling observed aligns with Schröder and Storm (2020), who noted high-income economies might show weak decoupling, requiring systemic changes for deep reductions. The variability highlights the importance of dynamic modeling (like Fourier/rolling-window methods used here and by Destek et al.) to capture temporal complexities.

Regarding specific drivers, the long-run positive impact of the EC on emissions is consistent with Bella (2018) and reflects historical fossil fuel reliance. The diminishing impact of EC after the 1970 s mirrors France's strategic shift towards nuclear energy (NE). This observation is corroborated by Pata and Samour (2022), who employed Fourier transforms to demonstrate NE's significant role in reducing CO_2 emissions.

However, consistent with Pata and Samour (2022), our analysis also suggests a limited long-term mitigating impact from renewables relative to NE, underscoring Bella's (2018) call for broader energy diversification strategies.

The positive long-run association between economic freedom and emissions corresponds with Bjørnskov's (2024) framework, which highlights the potential for economic freedom to increase emissions in the absence of robust regulatory oversight. Nevertheless, our time-varying results reveal periods where economic freedom negatively correlates with emissions, suggesting that liberalization *can* coincide with environmental improvements under specific circumstances (e.g., effective environmental policies). This finding is consistent with Neagu (2019), who demonstrated that economic complexity, often enhanced by economic freedom, can facilitate shifts towards less carbon-intensive economies.

The absence of a significant long-run impact from TFP on emissions contrasts with the work of Chimeli and Braden (2005) and Amri (2018), both of whom emphasized TFP's crucial role in achieving sustainable growth. However, our time-varying analysis *does* reveal significant TFP influence during specific phases of technological or economic transition, a finding that partially aligns with Destek et al. (2020) regarding the role of innovation. This suggests that the potential environmental benefits of TFP might be context-dependent, potentially requiring complementary policies or alignment with energy transitions to be fully realized. Finally, the causality analysis underscores the influence of EF on both CO_2 emissions and EC, while also indicating a feedback loop where emission levels may impact economic freedom, pointing towards complex policy interactions.

Methodologically, the use of advanced techniques (Fourier tests, PWC) accounting for breaks and time-variation aligns with approaches in Destek et al. (2020) and Pata and Samour (2022), reinforcing the need for such methods in environmental econometrics. The study's long historical scope (1890–2019) provides a comprehensive view, similar to Destek et al. (2020)'s long analysis of G7 nations, capturing major transitions and complementing findings on non-linearities. The results also align with Bella (2018) and Azam et al. (2023) on the critical influence of historical context (policy, energy shifts) on emission dynamics.

Our findings offer a robust basis for designing policies to decouple economic growth from carbon emissions in France: The persistent positive EC-CO_2 link underscores the need for aggressive energy efficiency standards (industrial, commercial, residential) and incentives (tax credits, loans) for retrofitting and adopting renewables, reducing fossil fuel dependence. Higher economic freedom correlating with higher emissions historically suggests a need for balanced regulation. Market liberalization should be paired with strong environmental safeguards like carbon pricing or emissions trading to ensure economic policies support sustainability. While TFP's overall impact was inconsistent, periods of negative influence suggest technology can mitigate emissions if directed appropriately. Prioritize green R&D, foster public–private partnerships for low-carbon tech diffusion, and incentivize industries towards cleaner production via grants/subsidies. The dynamic growth-emissions relationship (EKC periods) implies structural shifts matter. Encourage transition to service/knowledge economies via investment in education, digital infrastructure, and skills. Support gradual transition of energy-intensive sectors to cleaner alternatives, aligning economic strategy with sustainability. Structural breaks and time-varying causality highlight the dynamic system. Implement comprehensive monitoring/evaluation systems using real-time data analytics to quickly identify trends and recalibrate policies, ensuring responsiveness to economic and technological shifts.

6 Conclusion

This research confirmed a long-run equilibrium among CO_2 emissions, EC, economic freedom, economic growth, and TFP in France (1890–2019). Historically, EC, freedom, and growth positively correlated with emissions, while overall TFP lacked significant long-run impact. The EKC hypothesis finds only partial, period-specific support; an inverted U-shape between growth and emissions emerged intermittently but was not consistent across the entire 130 years. This underscores the complex, dynamic nature of the development-environment relationship in France, shaped by factors beyond income.

Several key trends emerged from the analysis. First, the influence of Energy Consumption (EC) on emissions lessened over time, reflecting France's energy transition and gains in efficiency. Second, the impact of economic freedom evolved; while initially correlated with higher emissions, it demonstrated a negative association in recent decades, pointing to the increasing significance of environmental regulation. Third, the link between economic growth and emissions was variable, conforming to Environmental Kuznets Curve (EKC) patterns only periodically, not consistently throughout the study period. Collectively, these findings highlight the necessity for nuanced interpretations of the EKC hypothesis and acknowledge its contextual limitations.

This study provides a critical historical foundation for understanding France's growth and environmental sustainability dynamics. The qualified support for the EKC necessitates future research into the specific conditions (policy, technology, energy mix) under which decoupling occurs. Exploring other environmental indicators (water, biodiversity) would also broaden understanding. Potential future research could involve country-specific longitudinal studies with more variables (trade, FDI, energy prices) or investigate differential impacts of various technology types beyond aggregate TFP. Methodologically, dynamic panel models or machine learning could offer further insights.

In summary: France's energy transition has reduced EC's impact; economic freedom's environmental effect evolved due to policy; the EKC holds only sporadically; structural shifts significantly influenced the emissions path. This nuanced picture stresses the importance of energy diversification, regulation, and innovation for sustainable growth. Addressing these findings via targeted policies—enhancing efficiency, balancing freedom with regulation, promoting green tech, facilitating structural shifts, and adopting adaptive frameworks—is crucial for France to achieve significant carbon reductions and a sustainable future.

7 Appendix 1. The Results of Cointegration Tests

Table 6 Results of the ARDL Bounds Test

	Test Stat	1% Critical Value	
		I(0)	I(1)
f(GDP, GDP2, EC, EF, TFP)	4.789*	3.06	4.15

See note of Table 1

Table 7 Results of the Bayer-Hanck Cointegration Test

	Test Stat	Critical Values		
		10%	5%	1%
EG-J:	13.125**	8.242	10.419	15.701
EG-J-Ba-Bo-	19.776**	15.804	19.888	29.85

See note of Table 1

8 Appendix 2

Table 8 The results of long-run coefficients

Variables	DOLS		CCR	
	Coefficients	*p*-values	Coefficients	*p*-values
lnEC	0.889	0.000*	0.885	0.000*
lnEF	0.236	0.100	0.264	0.051***
lnGDP	7.594	0.000*	8.118	0.000*
lnGDP2	−0.414	0.000*	−0.440	0.000*
lnTFP	0.046	0.848	0.038	0.865
Intercept	−37.443	0.000*	−40.030	0.000*

See note of Table 1.

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Declarations

Conflict of interest The authors declare that there are no conflicts of interest associated with this manuscript. There are no financial or non-financial competing interests to report regarding the study design, data collection and analysis, decision to publish, or preparation of the manuscript. The authors have no financial or proprietary interests in any product or company mentioned in this article that could create a potential conflict of interest. The research presented received no specific grant from any funding agency, commercial or not-for-profit sectors. It has not been influenced in any way by any funding sources. The views expressed here are those of the authors and do not necessarily represent the views of any affiliated institutions or funders. The authors have no financial or non-financial interests to disclose that are directly or indirectly related to the research described in this manuscript.

References

Akadiri, S. S., Alola, A. A., & Usman, O. (2021). Energy mix outlook and the EKC hypothesis in BRICS countries: A perspective of economic freedom vs. economic growth. *Environmental Science and Pollution Research, 28*(7), 8922–8926.

Amri, F. (2018). Carbon dioxide emissions, total factor productivity, ICT, trade, financial development, and energy consumption: Testing environmental Kuznets curve hypothesis for Tunisia. *Environmental Science and Pollution Research, 25*, 33691–33701.

Ang, J. B. (2007). CO2 emissions, energy consumption, and output in France. *Energy Policy, 35*(10), 4772–4778.

Aydin, M., & Degirmenci, T. (2024). The role of greenfield investment and investment freedom on environmental quality: Testing the EKC hypothesis for EU countries. *International Journal of Sustainable Development & World Ecology, 31*, 684.

Azam, W., Khan, I., & Ali, S. A. (2023). Alternative energy and natural resources in determining environmental sustainability: A look at the role of government final consumption expenditures in France. *Environmental Science and Pollution Research, 30*(1), 1949–1965. https://doi.org/10.1007/s11356-022-22334-z

Balado-Naves, R., Baños-Pino, J. F., & Mayor, M. (2018). Do countries influence neighbouring pollution? A spatial analysis of the EKC for CO2 emissions. *Energy Policy, 123*, 266–279.

Bayer, C., & Hanck, C. (2013). Combining non-cointegration tests. *Journal of Time Series Analysis, 34*(1), 83–95.

Bella, G. (2018). Estimating the tourism induced environmental Kuznets curve in France. *Journal of Sustainable Tourism, 26*(12), 2043–2052. https://doi.org/10.1080/09669582.2018.1529768

Bergeaud, A., Cette, G., & Lecat, R. (2016). Productivity Trends in Advanced Countries between 1890 and 2012. *Review of Income and Wealth, 62*(3), 420–444.

Bjørnskov, C. (2024). Economic freedom and the greenhouse gas Kuznets curve. *European Journal of Political Economy, 82*, Article 102530.

Can, M., & Gozgor, G. (2016). Dynamic Relationships Among CO2 Emissions, Energy Consumption, Economic Growth, and Economic Complexity in France. *SSRN Electronic Journal*, 70373. https://doi.org/10.2139/ssrn.2756638

Can, M., & Gozgor, G. (2017). The impact of economic complexity on carbon emissions: Evidence from France. *Environmental Science and Pollution Research, 24*, 16364–16370.

Carlsson, F., & Lundström, S. (2003). The effects of economic and political freedom on CO2 emissions. *Economic Studies, Department of Economics, School of Economics and Commercial Law, Göteborg University: Gothenburg, Sweden*, 79.

Carlsson, F., & Lundström, S. (2001). *Political and economic freedom and the environment: The case of CO2 emissions*. Goteborg University, Goteborg.

Chimeli, A. B., & Braden, J. B. (2005). Total factor productivity and the environmental Kuznets curve. *Journal of Environmental Economics and Management, 49*(2), 366–380.

Ciarlantini, S., Madaleno, M., Robaina, M., Monteiro, A., Eusébio, C., Carneiro, M. J., & Gama, C. (2023). Air pollution and tourism growth relationship: Exploring regional dynamics in five European countries through an EKC model. *Environmental Science and Pollution Research, 30*(15), 42904–42922.

Destek, M. A., Shahbaz, M., Okumus, I., Hammoudeh, S., & Sinha, A. (2020). The relationship between economic growth and carbon emissions in G-7 countries: Evidence from time-varying parameters with a long history. *Environmental Science and Pollution Research, 27*(23), 29100–29117. https://doi.org/10.1007/s11356-020-09189-y

Enders, W., & Jones, P. (2016). Grain prices, oil prices, and multiple smooth breaks in a VAR. *Studies in Nonlinear Dynamics & Econometrics, 20*(4), 399–419.

Enders, W., & Lee, J. (2012). A unit root test using a Fourier series to approximate smooth breaks. *Oxford Bulletin of Economics and Statistics, 74*, 574–599.

Ercan, H., Savranlar, B., Polat, M. A., Yıgıt, Y., & Aslan, A. (2024). The impact of technological innovations on the environmental Kuznets curve: Evidence from EU-27. *Environmental Science and Pollution Research, 31*(13), 19886–19903.

Fang, X., & Gao, S. (2023). An empirical study on relationship between island ecological environment and socio-economic development from perspective of environmental Kuznets curve (EKC). *Ocean & Coastal Management, 244*, Article 106819.

Farooq, S., Ozturk, I., Majeed, M. T., & Akram, R. (2022). Globalization and CO2 emissions in the presence of EKC: A global panel data analysis. *Gondwana Research, 106*, 367–378.

Frodyma, K., Papież, M., & Śmiech, S. (2022). Revisiting the environmental Kuznets curve in the European Union countries. *Energy, 241*, Article 122899.

Global Carbon Budget. (2023). Population based on various sources (2023) – with major processing by Our World in Data, Retrieved January 19 2024, from https://ourworldindata.org/co2-emissions

Gregory, A. W., & Hansen, B. E. (1996). Residualbased tests for cointegration in models with regime shifts. *Journal of Econometrics, 70*(1), 99–126.

Grossman, G. M., & Krueger, A. B. (1991). Environmental Impacts of a North American Free Trade Agreement. In *NBER working aper series* (Issue 3914). National Bureau of Economic Research. https://www.nber.org/papers/w3914

Hu, W., & Si, B. (2021). Improved partial wavelet coherency for understanding scale-specific and localized bivariate relationships in geosciences. *Hydrology and Earth System Sciences, 25*(1), 321–331.

Işik, C., Ahmad, M., Pata, U. K., Ongan, S., Radulescu, M., Adedoyin, F. F., & Ongan, A. (2020). An evaluation of the tourism-induced environmental Kuznets curve (T-EKC) hypothesis: Evidence from G7 Countries. *Sustainability, 12*(21), 9150.

Islam, H. (2025). Nexus of economic, social, and environmental factors on sustainable development goals: The moderating role of technological advancement and green innovation. *Innovation and Green Development, 4*(1), Article 100183.

Iwata, H., Okada, K., & Samreth, S. (2010). Empirical study on the environmental Kuznets curve for CO2 in France: The role of nuclear energy. *Energy Policy, 38*(8), 4057–4063.

Jiang, Q., Khattak, S. I., & Rahman, Z. U. (2021). Measuring the simultaneous effects of electricity consumption and production on carbon dioxide emissions (CO2e) in China: New evidence from an EKC-based assessment. *Energy, 229*, Article 120616.

Joshi, P., & Beck, K. (2018). Democracy and carbon dioxide emissions: Assessing the interactions of political and economic freedom and the environmental Kuznets curve. *Energy Research & Social Science, 39*, 46–54.

Kander, A., Warde, P., & Malanima, P. (2014). Power to the people: energy in Europe over the last five centuries, Retrieved January 20 2024, from https://histecon.fas.harvard.edu/energyhistory/energydata.html

Karimi, M. S., Khezri, M., Khan, Y. A., & Razzaghi, S. (2022). Exploring the influence of economic freedom index on fishing grounds footprint in environmental Kuznets curve framework through spatial econometrics technique: Evidence from Asia-Pacific countries. *Environmental Science and Pollution Research, 29*(4), 6251–6266.

Khan, M. M., Zaman, K., Irfan, D., Awan, U., Ali, G., Kyophilavong, P., & Naseem, I. (2016). Triangular relationship among energy consumption, air pollution and water resources in Pakistan. *Journal of cleaner production, 112*, 1375–1385.

Kongkuah, M. (2023). Impact of Belt and Road countries' renewable and non-renewable energy consumption on ecological footprint. *Environment, Development and Sustainability, 26*, 8709. https://doi.org/10.1007/s10668-023-03068-5

Kongkuah, M., Yao, H., & Yilanci, V. (2022). The relationship between energy consumption, economic growth, and CO2 emissions in China: The role of urbanisation and international trade. *Environment, Development and Sustainability, 24*(4), 4684–4708. https://doi.org/10.1007/s10668-021-01628-1

Kuznets, S. (1955). Economic Growth and Economic Inequality. *American Economic Review, 45*, 1–28.

Liu, P., Ur Rahman, Z., Jóźwik, B., & Doğan, M. (2024). Determining the environmental effect of Chinese FDI on the Belt and Road countries CO2 emissions: An EKC-based assessment in the context of pollution haven and halo hypotheses. *Environmental Sciences Europe, 36*(1), 48.

López, R., & Toman, M. A. (Eds.). (2006). *Economic development and environmental sustainability: New policy options*. OUP Oxford.

Ludlow, J., & Enders, W. (2000). Estimating non-linear ARMA models using Fourier coefficients. *International Journal of Forecasting, 16*(3), 333–347.

Lumsdaine, R. L., & Papell, D. H. (1997). Multiple trend breaks and the unit-root hypothesis. *Review of Economics and Statistics, 79*(2), 212–218.

Ma, X., Ahmad, N., & Oei, P. Y. (2021). Environmental Kuznets curve in France and Germany: Role of renewable and nonrenewable energy. *Renewable Energy, 172*, 88–99.

Makarov, I., & Alataş, S. (2024). Production-and consumption-based emissions in carbon exporters and importers: A large panel data analysis for the EKC hypothesis. *Applied Energy, 363*, Article 123063.

Mamkhezri, J., Muhamad, G. M., & Khezri, M. (2022). Assessing the spatial effects of economic freedom on forest-products, grazing-land, and cropland footprints: The case of Asia-Pacific countries. *Journal of Environmental Management, 316*, Article 115274.

Marques, A. C., Fuinhas, J. A., & Nunes, A. R. (2016). Electricity generation mix and economic growth: What role is being played by nuclear sources and carbon dioxide emissions in France? *Energy Policy, 92*, 7–19.

Mehmood, U., & Tariq, S. (2020). Globalization and CO2 emissions nexus: Evidence from the EKC hypothesis in South Asian countries. *Environmental Science and Pollution Research, 27*(29), 37044–37056.

Moalla, M. (2024). Testing the EKC Hypothesis Considering Trade Openness, Urbaniza-tion, and Financial Development in Indonesia. *International Business and Accounting Research Journal, 8*(2), 136–145.

Mohamed, E. F., Abdullah, A., Jaaffar, A. H., & Osabohien, R. (2024). Reinvestigating the EKC hypothesis: Does renewable energy in power generation reduce carbon emissions and ecological footprint? *Energy Strategy Reviews, 53*, Article 101387.

Mu, H. (2024). Green investment, energy efficiency, and economic growth: Does economic freedom matter? Evidence from BRICS countries. *Technological and Economic Development of Economy, 30*(1), 218–237.

Mutascu, M. (2018). A time-frequency analysis of trade openness and CO2 emissions in France. *Energy Policy, 115*, 443–455.

Mutascu, M., Pereau, J., & Ursu, E. (2016). *A Wavelet Analysis of the Environmental Kuznets Curve in France* (Vol. 33). Retrieved from https://econpapers.repec.org/RePEc:grt:wpegrt:2016-10

Narayan, P. K., & Popp, S. (2010). A new unit root test with two structural breaks in level and slope at unknown time. *Journal of Applied Statistics, 37*(9), 1425–1438.

Nazlioglu, S., Gormus, N. A., & Soytas, U. (2016). Oil prices and real estate investment trusts (REITs): Gradual-shift causality and volatility transmission analysis. *Energy Economics, 60*, 168–175.

Neagu, O. (2019). The link between economic complexity and carbon emissions in the European Union countries: A model based on the Environmental Kuznets Curve (EKC) approach. *Sustainability (Switzerland), 11*(17), 4753. https://doi.org/10.3390/su11174753

Ofozor, C. A., Abdul-Rahim, A. S., & Sulaiman, C. (2022). Impact of poverty, population density, and trade openness on deforestation: fresh evidence from Nigeria. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1102, No. 1, p. 012037). IOP Publishing.

Omri, E., & Saadaoui, H. (2023). An empirical investigation of the relationships between nuclear energy, economic growth, trade openness, fossil fuels, and carbon emissions in France: Fresh evidence using asymmetric cointegration. *Environmental Science and Pollution Research, 30*(5), 13224–13245.

Omri, E., Saadaoui, H., & Bazin, D. (2024). Are renewable energy resources, oil price, and trade openness helping France achieve its environmental targets? Evidence from an asymmetric analysis. *The Journal of Economic Asymmetries, 30*, Article e00371.

Ozcan, B., & Ulucak, R. (2021). An empirical investigation of nuclear energy consumption and carbon dioxide (CO2) emission in India: Bridging IPAT and EKC hypotheses. *Nuclear Engineering and Technology, 53*(6), 2056–2065.

Ozgur, O., Yilanci, V., & Kongkuah, M. (2022). Nuclear energy consumption and CO2 emissions in India: Evidence from Fourier ARDL bounds test approach. *Nuclear Engineering and Technology, 54*(5), 1657–1663. https://doi.org/10.1016/j.net.2021.11.001

Ozturk, I., Sharif, A., Godil, D. I., Yousuf, A., & Tahir, I. (2023). The dynamic nexus between international tourism and environmental degradation in top twenty tourist destinations: New insights from quantile-on-quantile approach. *Evaluation Review, 47*(3), 532–562.

Ozturk, I., Farooq, S., Majeed, M. T., & Skare, M. (2024). An empirical investigation of financial development and ecological footprint in South Asia: Bridging the EKC and pollution haven hypotheses. *Geoscience Frontiers, 15*(4), Article 101588.

Pata, U. K., & Naimoglu, M. (2024). How renewable and nuclear energy-related research and development expenditures pave the way for curbing carbon emissions in France?. *Energy & Environment*, 0958305X241258798.

Pata, U. K., & Samour, A. (2022). Do renewable and nuclear energy enhance environmental quality in France? A new EKC approach with the load capacity factor. *Progress in Nuclear Energy, 149*, Article 104249.

Prados de la Escosura, L. (2023). *Economic freedom in retrospect (No. 236)*. EHES Working Paper.

Rej, S., Bandyopadhyay, A., Murshed, M., Mahmood, H., & Razzaq, A. (2022). Pathways to decarbonization in India: The role of environmentally friendly tourism development. *Environmental Science and Pollution Research, 29*(33), 50281–50302.

Ridwan, M., Raihan, A., Ahmad, S., Karmakar, S., & Paul, P. (2023). Environmental sustainability in France: The role of alternative and nuclear energy, natural resources, and government spending. *Journal of Environmental and Energy Economics, 2*(2), 1–16.

Saud, S., Haseeb, A., Zaidi, S. A. H., Khan, I., & Li, H. (2024). Moving towards green growth? Harnessing natural resources and economic complexity for sustainable development through the lens of the N-shaped EKC framework for the European Union. *Resources Policy, 91*, Article 104804.

Selden, T. M., & Song, D. (1994). Environmental quality and development: Is there a Kuznets curve for air pollution emissions? *Journal of Environmental Economics and Management, 27*(2), 147–162.

Shahbaz, M., Nasir, M. A., & Roubaud, D. (2018). Environmental degradation in France: The effects of FDI, financial development, and energy innovations. *Energy Economics, 74*, 843–857.

Shahnazi, R., & Shabani, Z. D. (2021). The effects of renewable energy, spatial spillover of CO2 emissions and economic freedom on CO2 emissions in the EU. *Renewable Energy, 169*, 293–307.
Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. *World Development, 32*(8), 1419–1439.
Toda, H. Y., & Yamamoto, T. (1995). Statistical inference in vector autoregressions with possibly integrated processes. *Journal of Econometrics, 66*(1–2), 225–250.
Tsurumi, T., & Managi, S. (2010). Decomposition of the environmental Kuznets curve: Scale, technique, and composition effects. *Environmental Economics and Policy Studies, 11*, 19–36.
UN. (2025b). Goal 7: Ensure Environmental Sustainability. https://www.un.org/millenniumgoals/environ.shtml (Accessed 15 January 2025).
UN. (2025a). Agenda 21. https://www.un.org/millenniumgoals/environ.shtml Data. (Accessed 15 January 2025).
Uzar, U. (2024). The impact of freedom of expression and belief on CO2 emissions: An examination of the group of seven. *Journal of Environmental Management, 367*, Article 121952.
Uzar, U., & Eyuboglu, K. (2024). *Democracies use more renewable energy. In Natural Resources Forum*. Blackwell Publishing Ltd.
Voumik, L. C., Nafi, M. D. S., Bekun, F. V., & Haseki, M. I. (2023). Modeling energy, education, trade, and tourism-induced environmental Kuznets curve (EKC) hypothesis: Evidence from the Middle East. *Sustainability, 15*(6), 4919.
Wang, Z., Gao, L., Wei, Z., Majeed, A., & Alam, I. (2022). How FDI and technology innovation mitigate CO2 emissions in high-tech industries: Evidence from province-level data of China. *Environmental Science and Pollution Research, 29*(3), 4641–4653.
Wood, J., & Herzog, I. (2014). Economic freedom and air quality. *Fraser Institute, Vancouver, Canada, April*.
Yılancı, V., Akan, T., & Işık, A. H. (2023). Time-varying disaggregation of the income-emissions nexus: New evidence from the United Kingdom. *Journal of Environmental Management, 348*, 119202.
Zivot, E., & Andrews, D. W. K. (1992). Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. *Journal of Business & Economic Statistics, 20*(1), 25–44.

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