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ORIGINAL PAPER

Probing the carbon neutrality drive of environmental-related technologies and energy transition in France and Germany: a novel time–frequency technique

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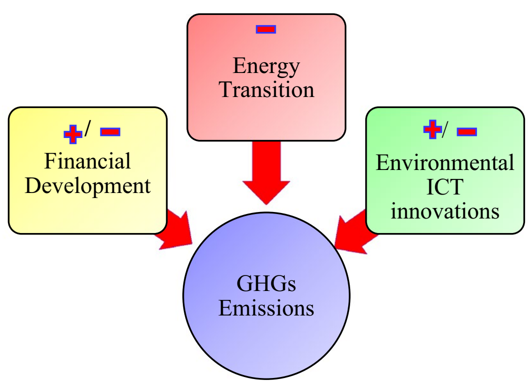
Abstract
This study presents a rare comparative analysis of the factors influencing environmental quality through greenhouse gas (GHG) emissions in the European Union member states' largest economies, i.e., France and Germany. By considering the unique economic, energy, and environmental characteristics of both countries, the finding unveils a novel perspective in the literature. The research utilizes a recently developed wavelet local multiple correlation (WLMC) technique with quarterly dataset spanning from 1990/Q1 to 2020/Q4. The results demonstrate that environmental-related information and communication technologies innovations, energy transition, and financial development play significant roles in limiting the growth of GHGs emission, particularly in the medium and long term. The wavelet-based Granger causality analysis reveals evidence of feedback causality among the variables in both countries in the medium and long term. Moreover, there are slight differences in the short-term relationships given that the observations are generally similar in later period. Overall, the findings offer a deeper understanding and policy insights regarding the time and frequency dynamics of GHG drivers in France and Germany.

Graphical abstract



Keywords Environmental sustainability · Energy transition · Environmental-related ICT innovations · France · Germany

Abbreviations

BRICS	Brazil, Russia, India, China and South Africa
CWT	Cross-wavelet transformation
DWT	Discrete wavelet transformation
EICTI	Environmental-related ICT innovations
EU	European Union
FDV	Financial development
DOLS	Dynamic ordinary least squares
ENTS	Energy transition
FMOLS	Fully modified ordinary least squares
GHGS	Greenhouse gas emissions
NARDL	Nonlinear autoregressive distributed lag
NDCs	Nationally determined contributions
WLMC	Wavelet local multiple correlation

Extended author information available on the last page of the article

Introduction

The European Union (EU), with its recently launched European Green Deal, is committed to achieving reduction of greenhouse gas emissions in 2030 by at least 55% relative to 1990 emission level and eventually attaining carbon neutral by 2050 (European Commission 2022). With the EU's Climate Target Plan (CTP), decarbonizing the region by 2050 is expected to offer several opportunities through a committed effort by member countries. Besides reducing greenhouse gas (GHG) emissions, it also offers opportunity to tackle energy poverty and energy import dependency, creating jobs and growth while improving health and wellbeing. On this path, even before the coronavirus (COVID-19) scourge in 2020, the EU maintained a consistent decline in GHG emissions compared to the 1990 emission, thus indicating the effectiveness of the members states' nationally determined contributions (NDCs) toward emission reduction. Specifically, between 1990 and 2020, GHG emissions in the EU reduced by 32% across the sectors except in the transportation sector where there was a 7% increase in GHG emissions in the same period (World Economic Forum 2022). In achieving this milestone, member countries have noticeably scaled up investment in environmental-related technologies and innovations, expanded energy financing opportunities, and deliberately increased share of renewable and clean energy mix according to the EU's and NDC-related programs. Besides these factors, empirical studies that examined the case of the EU countries both with panel and country-specific approaches and across sectors have identified other driving factors responsible for either mitigation or surge in GHG emissions (Andrés and Padilla 2018; Bekun et al. 2019; Saint Akadiri et al. 2019; Jäger-Waldau et al. 2020; Mielcarek-Bocheńska and Rzeźnik 2021).

Given this motivation, this study considers the objective of examining the drivers of GHG emissions in France and Germany. Importantly, the investigation explores the comparative impacts of environmental-related information and communication technologies (ICT) innovations, energy transition, and financial development on the GHG emissions in the economies. The selection of these case (France and Germany) is explained by (i) the economic importance of the two economies based on their relatively high gross domestic products (GDPs) compared to the rest of the EU member states (World Economic Forum 2023), (ii) the obvious disparity in the countries' energy profiles: While energy consumption especially electric power is dominated by nuclear energy source in France, Germany's electricity energy is mostly sourced from fossil energy fuels with significant dependency on energy imports from outside the EU, and (iii) the population size and other demographics of the countries, i.e., both are the largest by population in the EU (EU 2023). Moreover, this investigation also offers novel contribution in terms of the empirical approach.

The findings from this investigation have the potential to support both countries in achieving various Sustainable Development Goals (SDGs), particularly SDG-13 (enhancing environmental quality) and SDG-7 (energy transition). This investigation makes substantial contributions to the existing literature in two aspects. Firstly, it goes beyond the prevailing studies (e.g., Ali et al. 2021; Fethi and Rahuma 2019; Li et al. 2020; Shahbaz et al. 2013) that primarily focuses on the influence of technological innovations on renewable energy and environmental quality. However, it is important to note that not all technological innovations are directly linked to environmental issues. This implies that examining the overall impact of technology might not be entirely suitable for this context. Therefore, assessing the specific impact of environment-related information and communication technology innovations could serve as a more suitable indicator of the transition to clean energy and environmental quality. Given the absence of prior empirical research on the influence of environment-related information and communication technology innovations (EICTI), financial development (FDV), and energy transition (ENTS) on environmental quality in the cases of France and Germany, this study aims to fill this significant gap in the literature. Secondly, our study emphasizes the significance of EICTI innovations and provides insights into the interplay of this variable and its influence on environmental quality. Moreover, the research comprehensively examines the impact of all these factors simultaneously, utilizing recently available data for France and Germany. While some recent studies (e.g., Alola et al. 2023; Adebayo et al. 2023; Ullah et al. 2023; Olanrewaju et al. 2023) have explored the drivers of GHG emissions, such as financial development, economic growth, human capital, technological innovation, and globalization, on environmental quality in the cases of Germany and France, none have specifically investigated the impact of EICTI innovations. This study aims to address this gap and contribute valuable insights in this area.

Moreover, to overcoming the limitations in the conventional bivariate wavelet techniques such as continuous wavelet coherence, continuous wavelet transformation, partial wavelet coherence, and multiple wavelet coherence approaches, the recently developed wavelet local multiple correlation (WLMC) is employed in this study. The WLMC approach, introduced by Polanco-Martínez et al. (2020), performs a multivariate analysis of the dynamic relationships over time horizons to demonstrate its advantage over the above-mentioned conventional approaches and even over cross-wavelet transformation (CWT) and discrete wavelet transformation (DWT). Thus, this approach also provides the advantage of examining the fluctuations and volatility of the variables as revealed in Shah et al. (2022). Clearly, given the significant contribution to literature and empirical approach, the result of this investigation offers reliable policy dimension.

The other sections of the study are orderly presented for guidance and clarity. Specifically, Sect. "Literature review" details the literature coverage relevant to this investigation. Sect. "Theoretical framework, data and methods" presents detail description of the dataset and the empirical approaches. The results of the investigation are discussed and compared with the literature in Sect. "Findings and discussion". Finally, the study is concluded with summary of the study and policy highlight in sect. "Conclusions and policy directions".

Literature review

In recent decades, policymakers and stakeholders in the energy and environment-related sectors have paid significant attention to the role of economic indicators in proposing policies toward limiting CO_2 emissions and other GHGs emissions. As a result, significant studies have been documented mostly in energy and environmental literature, informing the public about ecological quality/deterioration drivers. Though several studies (Ali et al. 2021; Fethi and Rahuma 2019; Li et al. 2020; Shahbaz et al. 2013) have outline significant policy ramifications, a consensus has not been reached regarding policy recommendations. These mixed conclusions can be attributed to the difference in the characteristics of the examined cases, technique(s) employed, and the time frame.

The study of Çitil et al. (2023), with the motive of drafting a precise policy for carbon neutrality for the G-20 nations, explores the drivers of air quality within the framework of environmental Kuznets curve (EKC) using data spanning from 1990 to 2019. The quantile regression via the method of moment approach result shows that in the higher quantiles, the emissions intensification role of economic growth and dirty fuel is more pronounced, while in the lower and middle tails, the emissions mitigating role of clean energy and financial development is observed. In a same approach as Çitil et al. (2023), the study of Kirikkaleli et al. (2023) documents the emissions intensification role of economic growth and dirty fuel as well as the emissions-decreasing role of globalization, innovation, and clean energy. Similarly, by considering the Nordic nations, Alola and Adebayo (2022) adopted the nonlinear autoregressive distributed lag (ARDL) to evaluate the drivers of GHGs emissions using data from 1990 and 2019. The drivers of GHGs emissions considered in the study are green technologies, export intensity, and green energy. It is also highlighted that the decrease in the growth of GHGs emissions in the Nordic nations is caused by the intensification of green technologies, export intensity, and green energy while economic progress promotes GHGs emissions.

The case of Malaysia was explored by Zhang et al. (2021) with the use of the fully modified ordinary least square (FMOLS) and ARDL to explore the drivers of GHGs emissions. The authors also consider the time and frequency in their analysis using wavelet coherence over the period from 1970 to 2018. The study result shows that in short and long term, economic expansion and energy use contribute to the upsurge in GHGs while green energy and globalization promote the decrease of GHGs. Besides, the study unveils an insignificant financial development-GHGs emissions nexus which affirms the stand of He et al. (2021), who documented that the insignificant financial development-GHGs emissions connection can be attributed to the immaturity of the financial sector of a nation. Within the context of the BRICS nations, Adebayo et al. (2023) used the cross-sectional ARDL (CS-ARDL) to evaluate the role of green energy, natural resources, and financial development on CO_2 emissions between 1990 and 2018. The result gathered from this study disclosed emissions mitigating role of green energy, innovation, and financial development while nonrenewable energy boosts the growth of CO_2 emissions.

Policymakers and scholars have focused on the rising energy requirements of information and communication technology (ICT) devices. Every endeavor to mitigate climate change should take into account the ICT sector's carbon footprint because ICT equipment is utilized in practically every aspect of the economy. Meanwhile, by employing data from 1985 to 2018, Batool et al. (2022) examined the effects of ICT, renewable energy use, and financial development on CO_2 emissions in several emerging East and South Asian nations. By using the pooled mean group (PMG) approach for panel data analysis, the findings demonstrate that while IT and financial growth have little immediate influence on CO_2 emissions, they have a favorable long-term impact on ecological deterioration. In addition, renewable energy has a favorable long-term and short-term impact on environmental integrity. Similarly, by examining 16 developing nations between 2000 and 2018, Haldar and Sethi (2022) investigated the direct effects of ICT on the environment and the indirect consequences through interactions with sustainable energy, financial development, and innovation. The research's findings demonstrate that rising internet use and using sustainable energy substantially cut CO_2 emissions while dramatically boosting the use of nonrenewable energy sources. Thus, the study posits that internet use and innovation working together lower CO_2 emissions.

Evaluation of the literature

The synopsis of studies can be summed up as follows: (i) energy transition has a generally mitigating role on GHGs emissions; (ii) financial development impact GHGs emissions positively or negatively; and (iii) ICT also impact GHGs emissions in either direction. Related studies have been executed for single-country cases, such as China, France, South Korea, Italy, South Africa and Nigeria, as well as different bloc such as MINTS, ASEAN nations, G7 nations, PIIGS economies, EU nations and WENA nations have been explored in this context. Despite the numerous investigations on the linkages between financial development, ICT, energy transition, and ecological degradation, none of these studies have considered the role of environmental-related ICT innovations. Hence, the current investigation bridges this gap in the literature by exploring the impact of environmental-related ICT innovations, energy transition, and financial development on GHGs emissions. Additionally, this study conducts a comparative analysis by focusing on the two largest economies in the European Union, i.e., France and Germany. This approach allows for valuable insights into the differences and similarities between these nations. More so, the study utilizes a time-varying technique proposed by Polanco-Martínez et al. (2020) to identify the correlation between variables over different periods and frequencies. Additionally, wavelet-based causality, in line with the studies of Adebayo (2022) and Mishra et al. (2020), is employed to capture causality between GHG emissions and its drivers at various frequencies. This comprehensive methodology enhances the understanding of the intricate relationships between the studied variables.

Theoretical framework, data, and methods

Theoretical framework and model

To achieve the Paris Agreement goal and essentially restricting the global temperature, a shift from fossil fuel-based energy to clean energy is necessary. Energy transition has been identified as the solution to mitigate the adverse effects of global warming and climate change resulting from the economic trajectory of both developing and developed nations. Promoting a sustainable future necessitates a focus on reducing GHGs and facilitating energy transition, requiring key policy initiatives from policymakers worldwide. Environment-related information and communication technology innovations (EICTI) represent a crucial area of research and policy development, given the rapid global shift toward digitalization. Amid the pressing challenge of climate change, ICT solutions like smart grids, energy-efficient buildings, and renewable energy technologies offer promising avenues to lower GHGS and transition toward low-carbon economies. The application of ICT innovations also presents an opportunity for improved environmental monitoring, management, and more effective decision-making, fostering sustainable resource utilization. ICT innovations further enhance demand-side management strategies, empowering consumers to actively manage energy consumption and reduce waste, thereby promoting energy efficiency. This interconnected relationship between EICTI, energy transition, and GHGS creates a path to address environmental concerns and achieve sustainable development goals. Thus, EICTI is expected to promote ecological quality by decreasing GHGs emissions.

Likewise, financial development (FDV) plays a crucial role as a facilitating tool in transitioning to a carbon-free economy by providing essential funding and investment opportunities for renewable energy and energy-efficient technologies. Concurrently, energy transition policies can significantly shape FDV by encouraging sustainable investments and divesting from carbon-intensive industries. Acknowledging the importance of FDV for a sustainable future can foster the adoption of policies that incentivize GHG emissions reduction, such as carbon pricing and renewable energy subsidies. Moreover, it contributes to the creation of job opportunities via renewable energy development, promoting economic growth while simultaneously curbing GHG emissions.

In line with the above perspective, incorporating these indicators (EICTI, ENTS, FDV) in a GHGs impact model can well mimic the environmental impact framework presented by Holdren and Ehrlich (1974). Thus, we propose the study model by formulating the following economic function:

$$\mathrm{GHGs_t} = f\left(\mathrm{EICTI_t}, \mathrm{ENTS_t}, \mathrm{FDV_t}\right) \quad (1)$$

Data

The current study tends to explore the drivers of GHGs emissions via a comparative analysis between France and Germany over the quarterly period 1990/Q1 to 2020/Q4. The dependent variable is GHGs emissions, while environmental ICT innovations, energy transition and financial development are the drivers of GHGs emissions. Table 1 presents detailed information about the variables, including sources and measurements. Based on the research of Shahbaz et al. (2020), we apply the quadratic match-sum method to transform the raw data into quarterly intervals. The strategy can be modified to address the seasonality problems. The quadratic match-sum technique, which is particularly good at avoiding the problem of small data, helps

Table 1 Data source and measurements

Sign	Variables	Measurement	Source
EICTI	Environmental ICT innovations	Number of patients in environmental-related ICT	OECD
ENTS	Energy transition	Share of primary energy from renewables	BP
FDV	Financial development	Index	IMF
GHGS	Greenhouse gas emissions	Total GHG emissions measured in tons of carbon dioxide equivalents	WB

reduce point-to-point volatility when dealing with seasonal concerns. This method aims to fit every observation of the underpinning annual time series into a local quadratic polynomial before applying the fitting polynomial to populate all observations of higher frequency. Also, the quadratic match-sum approach may efficiently adjust the data with seasonal oscillations due to the fall in point-to-point data changes (Balcilar et al. 2019). The Eviews 12 software program can be employed to implement this strategy, which is superior than earlier interpolation methods. Moreover, the indicators are logged. This is done to ensure the indicators align with normal distribution. Furthermore, the analysis flow of the study is presented in Fig. 1.

Methods

The present analysis evaluates the time and frequency nexus between CO_2 emissions and FDV, ENT, and EICTI in Germany and France. In order to achieve this, this inquiry uses the wavelet multiple local correlation (WLMC) developed by Polanco-Martínez et al. (2020). Wavelet correlation has only been applied to bivariate situations since its conception. This has made a multivariate wavelet connection necessary. As a result, Polanco-Martínez et al. (2020) created an updated wavelet correlation multivariate. This article aims to apply the WLMC method to analyze the time and frequency intersection between GHG emissions, financial development, renewable energy, and environmental ICT developments "interactively" (i.e., across time) across multiple time periods. This method improves our ability to understand the basic connections between these indications. Standard statistical approaches that do not take into consideration this progression make it hard to grasp these characteristics and the pattern of their relationship properly over time.

The multiple regression reasoning provides the cornerstone for the WLMC. The WLMC idea was created by Fernández-Macho (2019) and applied in the current study. For instance, R is an n-dimensional multivariate time series factor at the time $t = 1, 2 \ldots$T. According to Fernández-Macho (2018), local regression for fixed $s \in [1 \ldots T]$, can be used for some $r \in R$to reduce the weighted square error, as demonstrated below:

$$W_w = \sum_t \theta(t - w)\left[E_w\left(R_{-i,t}\right) - r_{it}\right]^2 \quad (2)$$

$$Z_r^2 = 1 - \frac{Z_w RR_\tau}{TWRR_\tau}, = 1, 2, 3 \ldots .T \quad (3)$$

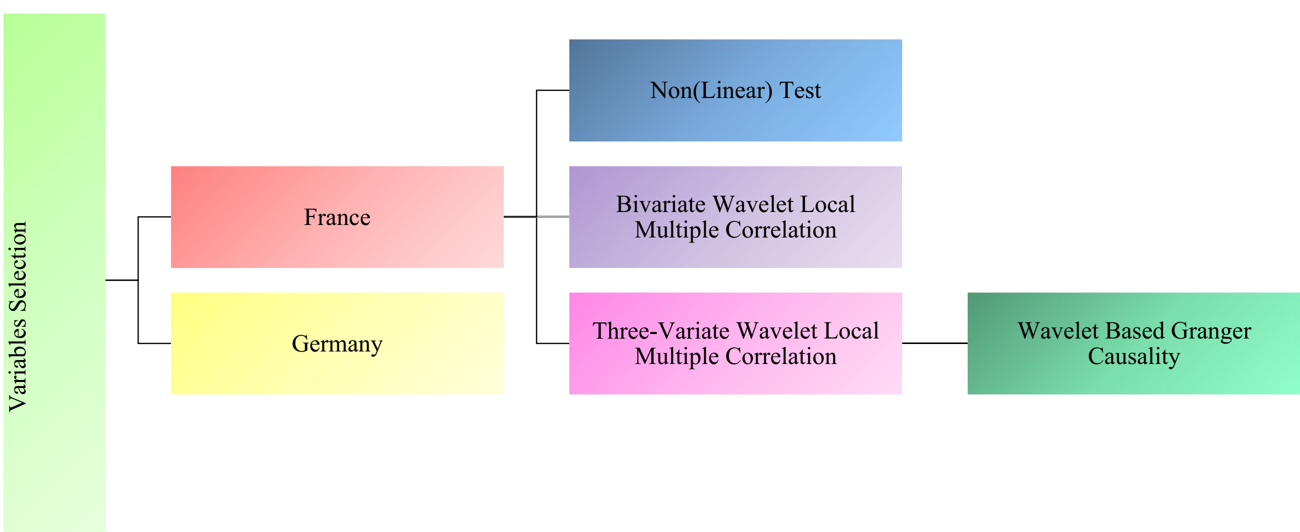


Fig. 1 Flow of the analysis

ZwRRr and TWRRr are examples of the residual and total weighted sum of squares in Eq. 3. After multivariate regression comes WLMC in the estimation procedure. The square root of the regression coefficient of determination may be used to determine the WLMC ∂R(∂k), for each wavelet scale k, for the linear mixture of series:

$$\hat{\partial} W_r(\theta_k) = \sqrt{Z_r^2}, k = 1, \ldots Kr = 1, \ldots T \quad (4)$$

Equation 4 shows the WLMC in the following manner.

$$\hat{\partial} W_r(\theta_k) = corr(\vartheta((t-r))^{1/2} W_{ik,} \sqrt{Z_r^2}, \vartheta(t-r))^{1/2} W_{ik} \quad (5)$$

Figure 1 shows the flow of the study.

Findings and discussion

The results of the priori test, i.e., (non)linearity test, validate the use of the WLMC analysis.

Pre-estimation results

Statistical summaries such as mean, median, standard deviation, and normality properties of the included factors are provided in Table 2, for both countries. From these outputs, one can argue that Germany has a higher GHGS compared to France, as indicated by a higher mean value. Similarly, Germany is also leading France in terms of environmental-related ICT innovations with a mean value of 4.8239, compared to the 2.9625 mean of France. France has a higher energy transition mean (5.4356) compared to Germany's mean (5.2796). On the aggregate side, a higher value of ENTS, EICTI, and GHGS has been observed in Germany, while France is performing better in terms of FDV only from the included factors during the period studied. Additionally, except for ENTS in France, all the variables are negatively skewed in both countries, as revealed by the skewness statistics. The Jarque–Bera statistics for each variable for both countries confirm that none of the included factors in our study follow the normal distribution. The statistical properties of the variables can be further confirmed in Fig. 2. The results regarding the stationarity properties of the variables are shown in the lower panel of Table 2. The null hypothesis (series contains a unit root) is tested by using ADF and PP tests after taking the first difference of the variables. The results provided show that the null hypothesis is rejected by both applied tests, which confirm that all series are stationary at first difference. Table 3 provides a summary of the correlation between the variables and GHG emissions, indicating a negative correlation between GHGs and FDV, EICTI, and ENTS.

The current study utilized the nonlinearity test proposed by Broock et al. (1996), to assess the nonlinear nature of the data series. The obtained results, as presented in Table 4, indicate that the null hypothesis of linearity is rejected at a 1% level of significance for all examined data series, across different embedding dimensions (M2, M3, M4, M5, M6), suggesting that ENTS, FDV, ICTI, and GHGS possess nonlinear characteristics for both France and Germany. These findings imply that the linear Granger causality approach is inadequate and may produce inconsistent outcomes in the presence of nonlinearity due to misspecification errors. Consequently, a more efficient and reliable alternative, such as the wavelet approach, may be more suitable for developing long-term, time and frequency-based policies.

Table 2 Descriptive statistics and stationarity tests results

	France				Germany			
	LnENTS	LnFDV	LnEICTI	LnGHGS	LnENTS	LnFDV	LnEICTI	LnGHGS
Mean	5.4356	− 0.4024	2.9625	19.870	5.2796	− 0.3558	4.8239	20.610
Median	5.4042	− 0.3183	3.0644	19.897	5.3285	− 0.3201	4.9497	20.625
Maximum	5.8511	− 0.1657	4.4515	20.026	6.5460	− 0.2426	5.3885	20.803
Minimum	5.1031	− 0.9120	1.2877	19.661	3.9384	− 0.6727	3.5631	20.360
Std. Dev	0.2067	0.2231	0.7252	0.1079	0.8834	0.1020	0.4406	0.1043
Skewness	0.4350	− 1.0255	− 0.7304	− 0.3526	− 0.0495	− 1.3359	− 0.7924	− 0.4210
Kurtosis	2.0969	2.7154	3.0266	1.8963	1.4916	3.8327	2.8420	2.6824
Jarque–Bera	8.1253	22.153	11.029	8.8623	11.804	40.466	13.107	4.1851
Probability	0.0172	0.0000	0.0040	0.0119	0.0027	0.0000	0.0014	0.1233
Δ ADF	− 3.375*	− 3.221*	− 6.142***	− 4.811***	− 3.802**	− 3.9876**	− 3.890**	− 3.504**
Δ PP	− 7.539***	− 5.171***	− 9.253***	− 6.405***	− 5.606***	− 5.8828***	− 6.887***	− 6.127***

***P < 1%, **P < 5% and *P < 10%

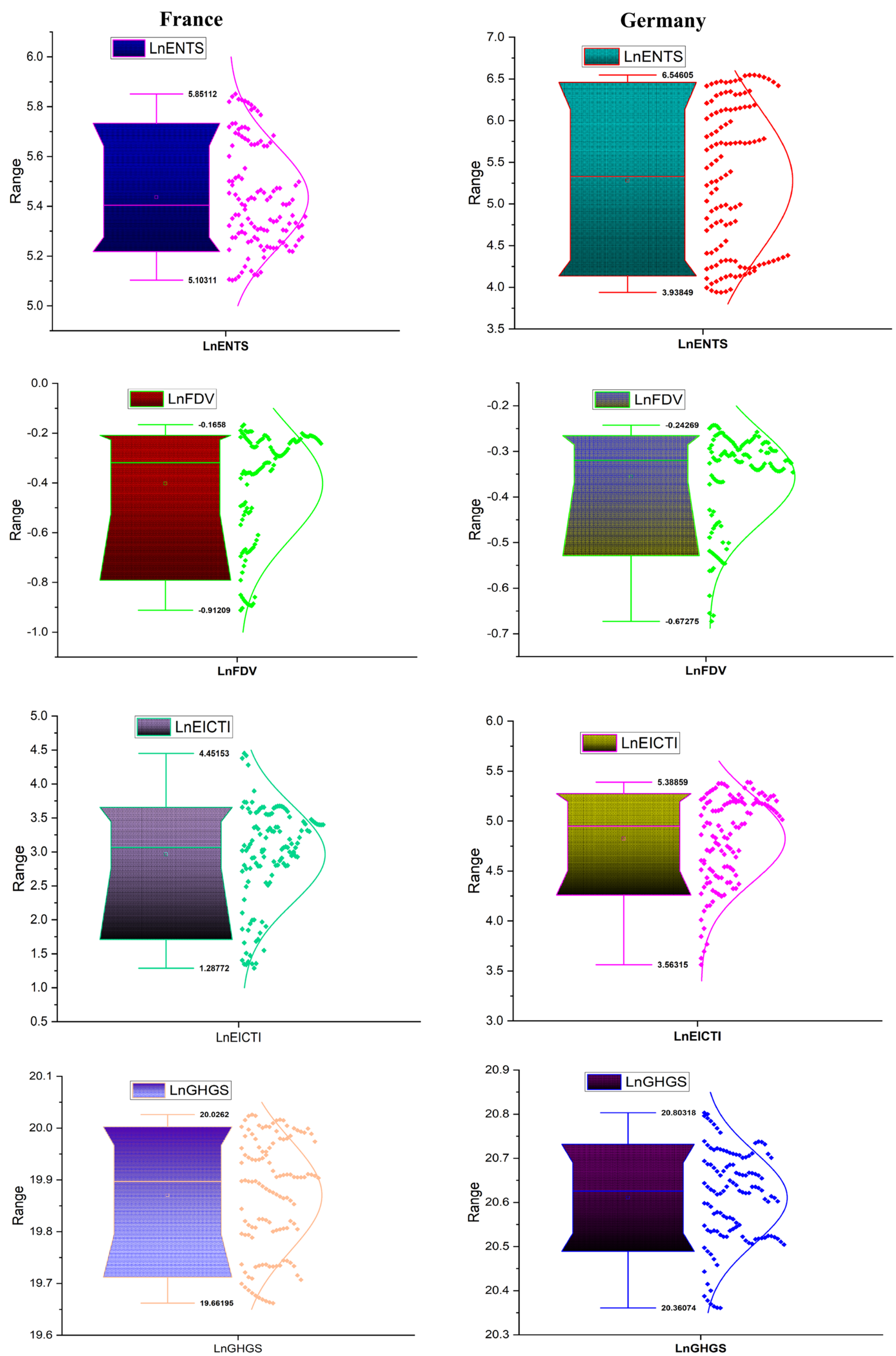


Fig. 2 Box plot of variables used

WLMC results

Next, the WLMC analysis was conducted to assess the interconnection between variables in both countries, and the outcomes are illustrated in Figs. 3, 4, 5, 6, 7, 8, and 9. The bivariate level of analysis was employed to determine the degree of correlation between the two variables at different time frequencies and provide an overview of the relevant factors associated with the multivariate concept. The WLMC figures depict the correlation nexus of the variables through black lines, while the horizontal scale denotes periods and the vertical scale indicates frequencies ranging from 1 to 16. The correlation strength is displayed through a color scheme, with heated colors representing the most severe time dependences and cooler colors representing the least severe ones. A blank area indicates an absence of correlation between the variables. The vertical bar displays correlation statistics, ranging from lower/negative (blue) to higher/positive (red) correlation. These findings offer valuable insights into the correlation between variables, which may inform future policy development and decision-making in both countries.

Table 3 Pearson correlation results

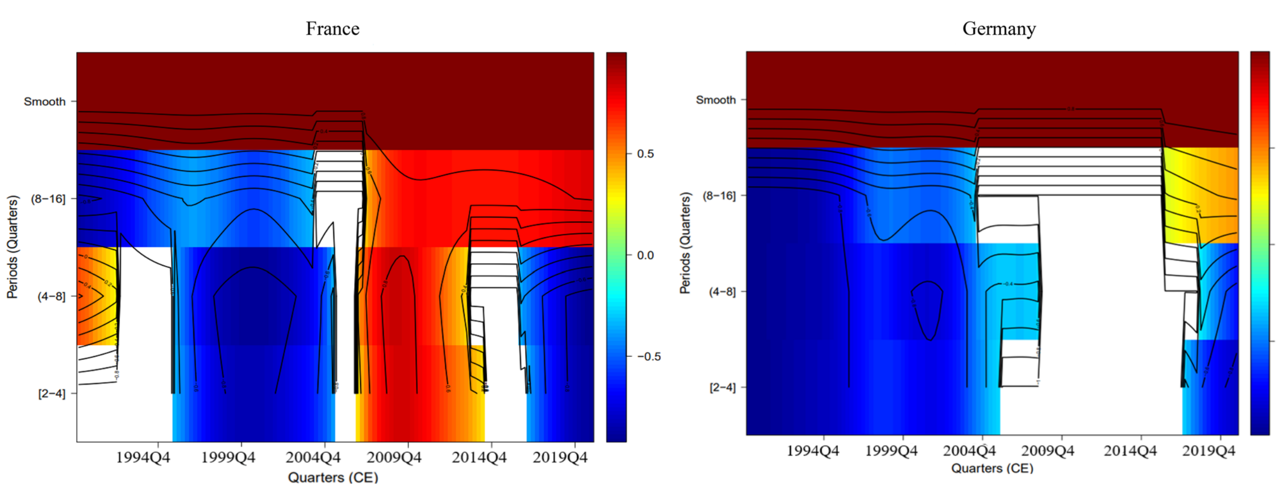
	France				Germany			
	EICTI	ENTS	FDV	GHGS	EICTI	ENTS	FDV	GHGS
EICTI	1.000				1.000			
ENTS	0.605***	1.000			0.519***	1.000		
FDV	0.818***	0.498***	1.000		0.681***	0.536***	1.000	
GHGS	– 0.672***	– 0.811***	– 0.743***	1.000	– 0.503***	– 0.930***	– 0.494***	1.000

***P < 1%

Table 4 Non(linearity) test results

	France				Germany			
	LnENTS	LnFDV	LnICTI	LnGHGS	LnENTS	LnFDV	LnEICTI	LnGHGS
M2	0.2050***	0.1767***	0.1729***	0.1879***	0.2041***	0.2041***	0.2041***	0.2041***
M3	0.3489***	0.2917***	0.2879***	0.3130***	0.3446***	0.3446***	0.3446***	0.3446***
M4	0.4496***	0.3668***	0.3601***	0.3980***	0.4416***	0.4416***	0.4416***	0.4416***
M5	0.5198***	0.4129***	0.4047***	0.4564***	0.5089***	0.5089***	0.5089***	0.5089***
M6	0.5685***	0.4440***	0.4339***	0.4970***	0.5565***	0.5565***	0.5565***	0.5565***

Note: ***P < 1%



a: ENTS Vs GHGS

b: ENTS Vs GHGS

Fig. 3 ENTS Vs GHGS

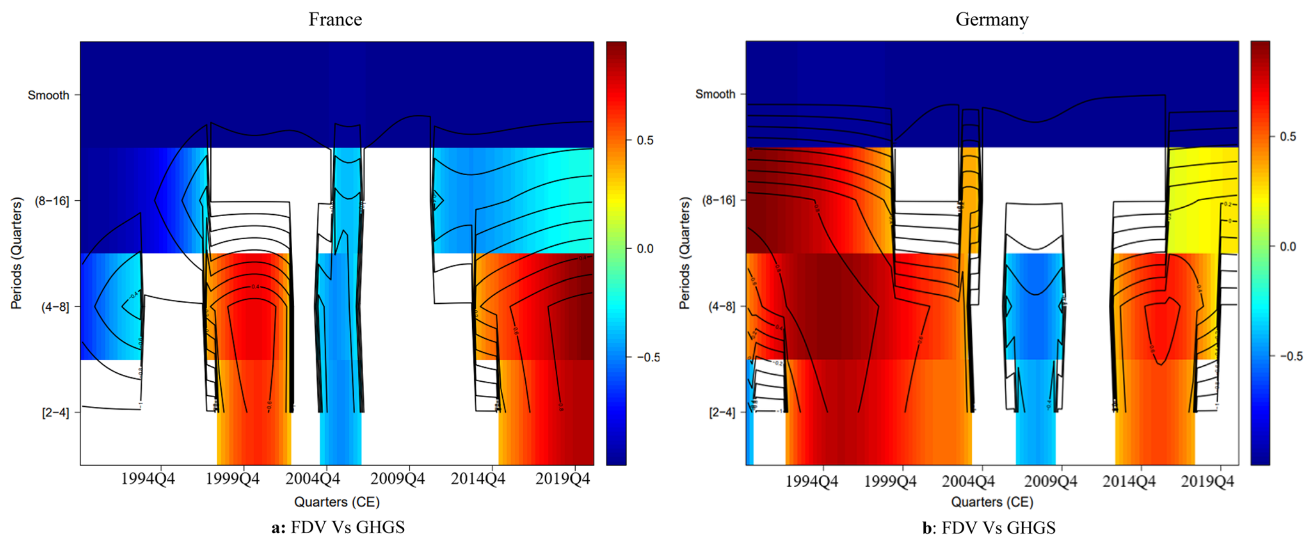


Fig. 4 FDV Vs GHGS

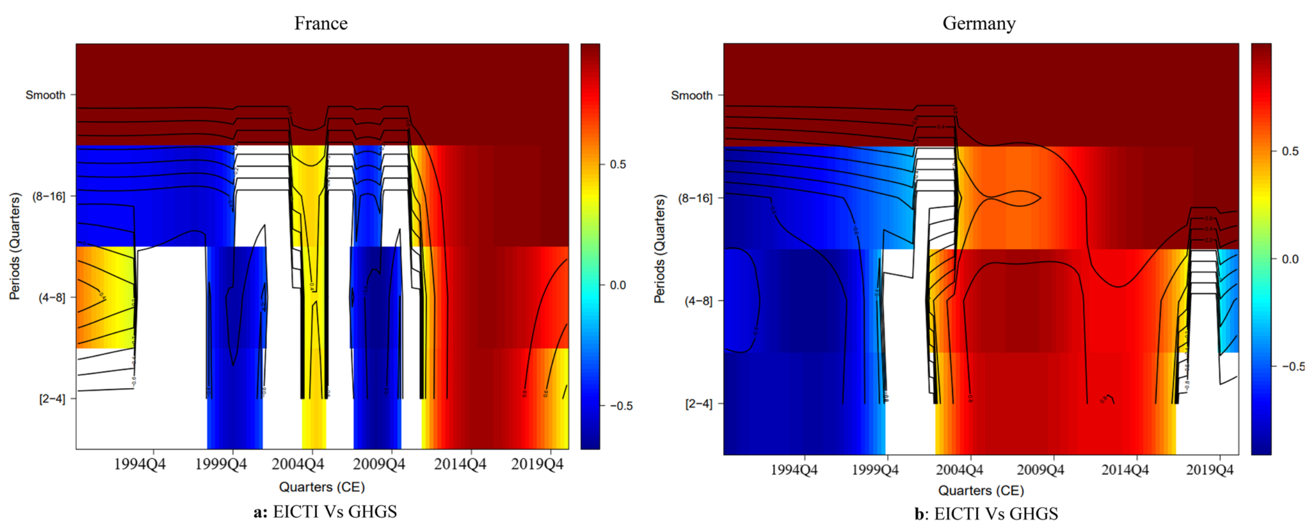


Fig. 5 EICTI Vs GHGS

Bivariate relationships

The bivariate case of WLMC between energy transition (ENTS) and greenhouse gas emission (GHGS) is displayed in Fig. 3. As shown for France in Fig. 3a, there is strong negative connectedness between ENTS and GHGS in short- to long-term frequency domains for the period 1992 to 2007. From 2008 to 2020, the long-term correlation between ENTS and GHGS in France turned positive, while the short-, and medium-term relations between these variables remain negative from 2014 to 2020. From this outcome, it can be advocated that the nexus between ENTS and GHGS in France is mixed across different times and frequencies, however, the negative connectedness is more prevalent. France is committed to reducing GHGS emissions through a comprehensive energy transition plan. One key aspect of this plan is the development of nuclear energy, which already accounts for a significant portion of France's electricity generation. According to the IEA, the share of renewable energy in France's total energy mix had reached approximately 18% by 2020. This expansion has enabled the country to reduce its reliance on carbon-intensive sources for electricity generation. As a result, the power sector's transition to renewable energy has likely contributed to a decline in GHGS (Ravigné et al. 2022). The government has also implemented measures to promote energy efficiency, including building insulation and the deployment of smart grids (Thimet and Mavromatidis 2022).

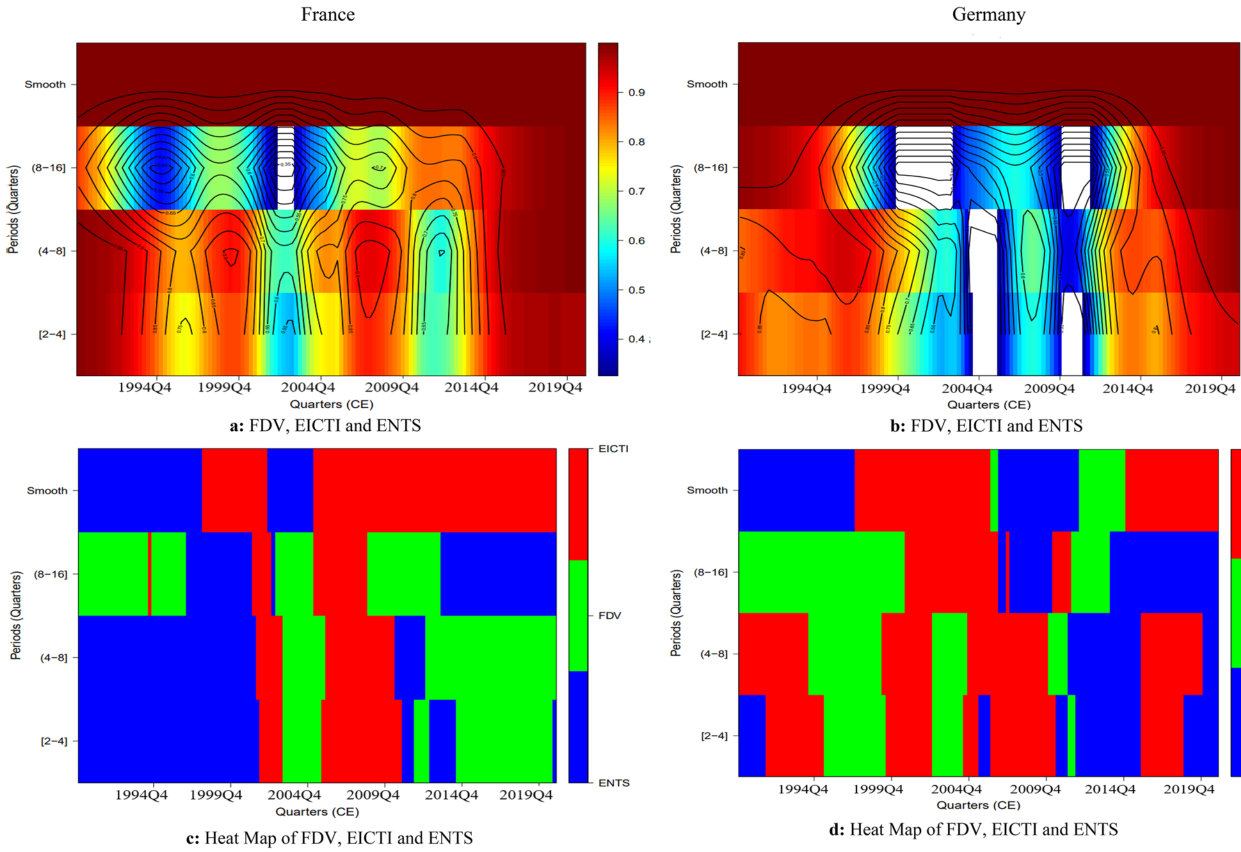


Fig. 6 FDV, EICTI and ENTS nexus plots

In contrast for the case of Germany, there is a negative correlation between ENTS and GHGS in all frequency domains throughout the analyzed period, except from 2007 to 2017 where the two variables have an insignificant connection. This implies that ENTS is a key factor in reducing GHGS in Germany as revealed by our outcomes in Fig. 3b. The shift toward renewable energy sources and increased energy efficiency has helped to significantly reduce Germany's GHGS emissions. According to Xie et al. (2023) Germany's commitment to ENTS has led to a considerable decrease in carbon emissions over the past decade. The country's energy transition policy has been pivotal in shifting away from fossil fuels and increasing the share of renewables in the energy mix, leading to a substantial increase in wind and solar installations, ultimately reducing GHGS (Thimet and Mavromatidis 2022). In 2020, the country's GHGS emissions were 42.3% lower than the 1990 baseline, largely due to the expansion of renewable energy and the phasing out of coal-fired power plants (IEA 2022).

A huge number of past studies have also demonstrated a similar (negative) effect of energy transition (renewable energy) on GHGS emissions (see, Kirikkaleli et al. 2023; Olanrewaju et al. 2023; Li et al. 2020; Zhang et al. 2021). ENTS and its connection to reducing GHGS are deeply intertwined. Unlike fossil fuels, which emit GHGS like carbon dioxide (CO_2) and methane (CH_4) when burned, renewable energy sources produce little to no direct emissions during operation (Zhang et al. 2021). This inherent characteristic of renewables makes them essential in mitigating climate change and curbing global GHGS (Li et al. 2020). Renewable energy technologies, such as solar panels and wind turbines, harness natural resources like sunlight and wind to generate electricity. This process does not involve the combustion of fossil fuels, resulting in zero direct emissions of GHGS. As renewable energy installations expand, the share of low-carbon electricity in the energy mix increases, leading to a decline in overall GHGS in the power sector (Kirikkaleli et al. 2023). Moreover, the integration of renewable energy into the grid indirectly reduces emissions. By displacing conventional power plants that rely on fossil fuels, renewables help meet peak demand periods, reducing the need for carbon-intensive electricity generation (Olanrewaju et al. 2023). The adoption of renewable energy drives innovation and cost reductions, making them increasingly competitive with fossil fuels. As renewables become more affordable and accessible, businesses and individuals are incentivized to transition away from carbon-intensive energy sources. This

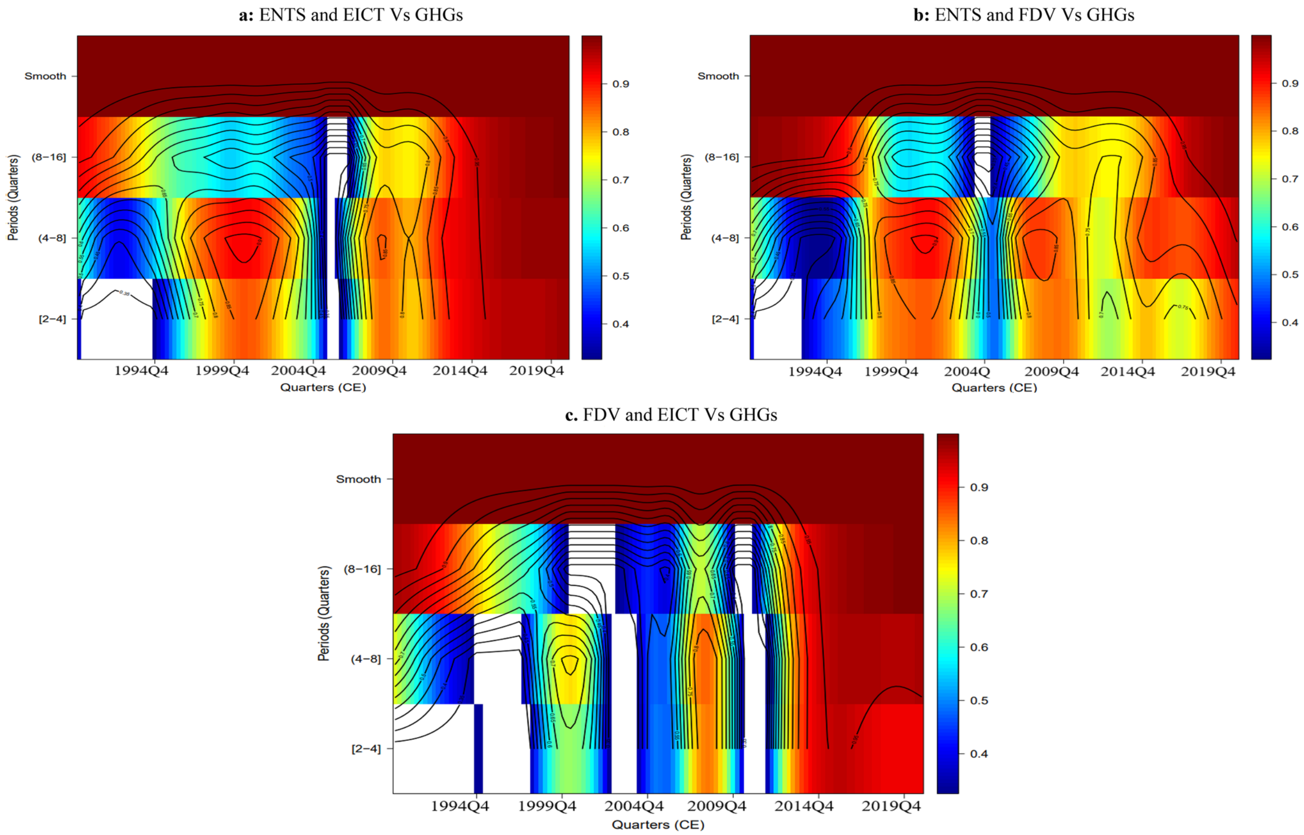


Fig. 7 ENTS and EICTI Vs GHGSF, ENTS and FDV Vs GHGS, and FDV and EICTI Vs GHGS in France

phenomenon, known as the "renewable energy learning curve," accelerates the displacement of fossil fuels in various sectors beyond electricity generation (Adebayo and Ullah 2024).

Figure 4 shows the dynamics of the relationships between financial development (FDV) and GHGS. It can be seen from Fig. 4a for the case of France that the correlation between FDV and GHGS is diverse across different times and frequencies. There is a negative correlation between the two variables in long-term frequencies (8–16) in all periods. However, positive linkages are also noted between FDV and GHGS in short-, and medium-term frequencies for the period 1998 to 2002, and 2015 to 2020, but overall, the negative interaction is more intense. France has a diversified and robust financial sector, with significant investments in renewable energy and sustainable infrastructure projects. In recent years, France has implemented various financial policies to reduce GHGS emissions, such as the Green OAT program, which issued €25 billion in green bonds for financing environmental projects. The French government has also established various incentives and tax breaks for companies that invest in sustainable and low-carbon technologies. In 2020, France was ranked 10th in the Global Green Finance Index, which assesses countries based on their support for sustainable finance initiatives and reducing GHGS emissions. French government has been supportive of green technology development through investments in research and development and the implementation of policies to encourage sustainable practices. Additionally, France has been issuing green bonds to finance environmental projects, contributing to the growth of sustainable investments, since part of the Paris Agreement, the country has committed to reducing its GHGS and adopting climate-friendly policies.

Unlike France, there are strong negative correlations between FDV and GHGS across all frequency domains in Germany, as displayed in Fig. 4b. A strong and significantly negative association between FDV and GHGS in Germany is noted for the years 1990 to 1998 and 2006 to 2011 in Germany. In addition, there is a positive connection between the two variables in the short-term (frequency 2–4) for the period 2017 to 2020; however, the negative correlations are highly prominent in all frequencies during the period analyzed. Considering the potential benefits of FDV, Germany's financial sector had made a notable stride and been actively involved in issuing green bonds to finance eco-friendly projects, with a total issuance of around €20.4 billion in 2020, making it the second largest market for green bonds globally. Similarly,

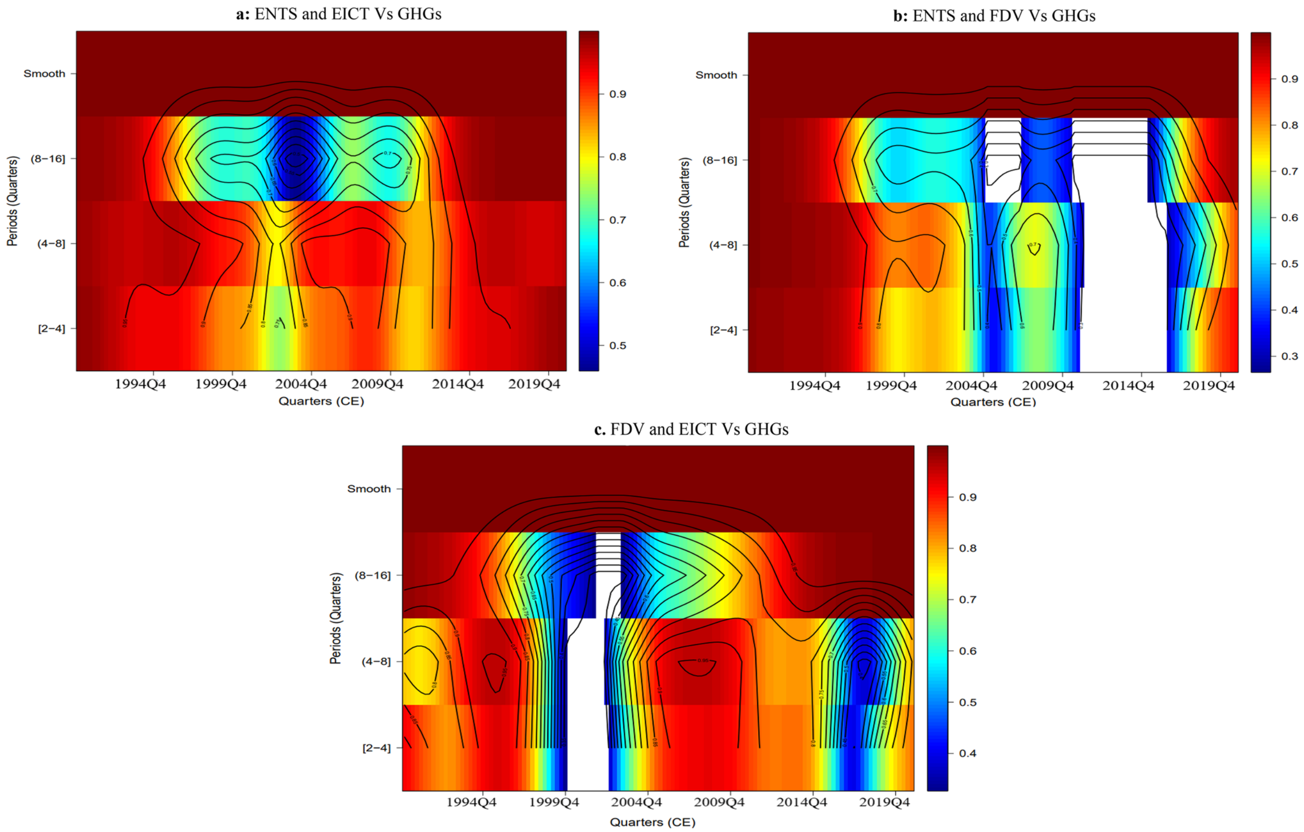


Fig. 8 ENTS and EICTI Vs GHGSF, ENTS and FDV Vs GHGS, and FDV and EICTI Vs GHGS in Germany

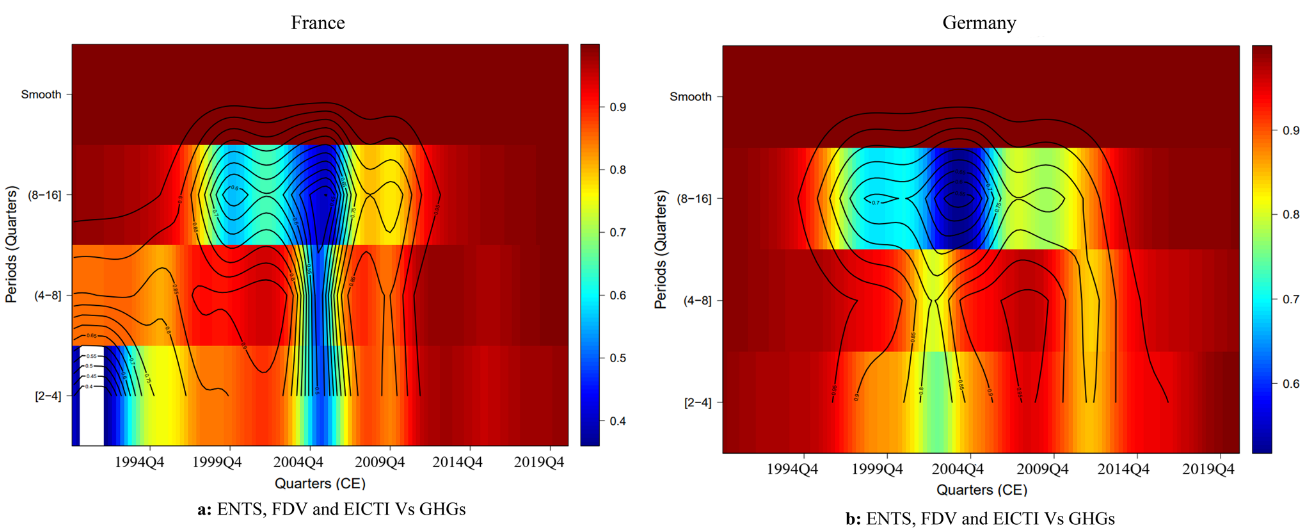


Fig. 9 Four-variate (ENTS, FDV and EICTI Vs GHGS) results

the financial sector of Germany has been actively investing in sustainable projects, with sustainable funds growing by 29% in 2020, reaching a record high of €295 billion (IEA 2022). The country has also implemented various policies to support sustainable finance, such as the Sustainable Finance Strategy and the Green Bond Standard. These efforts have contributed significantly to reducing GHGS emissions in Germany, as financial institutions have been channeling funds toward sustainable initiatives.

The studies of Çitil et al. (2023), Adebayo et al. (2023) and He et al. (2021) also revealed an identical long-term negative influence on financial development on GHGS emissions. FDV plays a crucial role in reducing GHGS emissions by providing necessary resources for investment in renewable energy and low-carbon technologies. The International Energy Agency estimates that globally, an additional $1.6 trillion in investment per year is required to reach net-zero emissions by 2050. In this regard, financial institutions are playing an active role in mobilizing the necessary resources to finance the energy transition to reach net-zero emissions targets (Alola and Adebayo 2022). An enhanced financial sector can facilitate the deployment of clean technologies and renewable energy by improving access to capital and reducing borrowing costs for green investments (Zhen et al. 2022). As financial markets become more efficient and effective, they can direct funds toward sustainable projects and green infrastructure, making it financially viable for businesses and individuals to adopt eco-friendly practices (Çitil et al. 2023; Jianguo et al. 2022). Moreover, improved financial systems can stimulate research and development in green technologies through increased funding and better risk-sharing mechanisms, fostering innovation and efficiency improvements in the clean energy sector (He et al. 2021). Similarly, well-developed financial institutions, such as green bonds and carbon markets, create incentives for companies to reduce emissions and operate more sustainably, rewarding environmentally responsible behavior. Adebayo (2022) argued that FDV helps reducing GHGS by enhancing climate policies and international cooperation, bolstering countries' capacities to mobilize resources, and facilitating the transfer of green technologies.

The bivariate case of WLMC between environment-related ICT innovations (EICTI) and GHGS is shown in Fig. 5. AS shown in Fig. 5a for France, we find a negative connectedness between EICTI and GHGS in the short, medium, and long term for the period 1990 to 2011. Meanwhile, there is a positive association between EICTI and GHGS in France from 2012 to 2020 in all frequency domains. According to the French Climate and Energy Efficiency Agency (ADEME), the EICTI measures such as improved data analytics and real-time tracking, businesses and government agencies can identify emission hotspots and implement targeted reduction measures and this approach has helped several industries achieve a 20% reduction in their carbon emissions through more effective emission management. Furthermore, the integration of smart transportation systems, electric vehicles, and ride-sharing platforms in France have collectively reduced transportation-related emissions by approximately 15% over the last decade.

The correlations between EICTI and GHGS in the case of Germany are also diverse across different periods, as shown in Fig. 5b. A strong negative connection between the two variables has been detected from 1990 to 1999 in all frequency domains. However, in the middle period analyzed, there is a positive correlation between EICTI and GHGS in all frequencies, but more intense in the long-term for the period from 2003 to 2020. According to the German Environment Agency, the implementation of EICTI technologies has contributed significantly to energy efficiency improvements in industries and buildings, leading to a reduction of approximately 15% in carbon emissions from the industrial sector over the past decade. Additionally, the adoption of EICTI solutions in the transport sector has helped lower emissions by around 8% through measures such as promoting electric mobility and optimizing transportation systems.

However, there are limited studies examining the nexus between EICTI and GHGS emissions in the literature, and we claimed that our outcomes are consistent with Ullah et al. (2023), Batool et al. (2022) and Haldar and Sethi (2022) who find that ICT development has a limiting influence on GHGS emissions. The use of digital technologies and ICT innovations in various sectors, such as transport, agriculture, and industry, has helped reduce GHGS emissions by promoting energy efficiency and renewable energy use. In the context of the energy sector, ICT innovations are enabling the integration of renewable energy sources into the grid, facilitating demand-response mechanisms, and optimizing energy consumption, resulting in significant reductions in GHG emissions (Haldar and Sethi 2022). Similarly, the implementation of energy-efficient building standards and smart home solutions enables households to manage their energy consumption effectively (Liu et al. 2023). Also, EICTI promote sustainable transportation systems by supporting the transition to electric vehicles, optimizing traffic flow, and encouraging ride sharing, resulting in reduced emissions from the transport sector (Ullah et al. 2023). These innovations encompass a range of technologies such as smart grids, intelligent transport systems, and energy-efficient buildings, which offer substantial reductions in energy consumption and GHGS emissions (Batool et al. 2022).

Multivariate relationships

Figure 6 depicts the three-variate WLMC plots showcasing the relationship among EICTI, FDV, and ENTS. This advanced approach enables us to accurately assess the correlation among these variables and identify the dominant factor. This dominant factor enhances the multi-correlation and can be utilized to describe other factors at varying frequencies (Polanco-Martínez et al. 2020). The three-variate WLMC shows a significantly high degree of positive correlation among EICTI, ENTS, and FDV at different frequencies—short, medium, and long term—throughout the analyzed period in both France and Germany, as demonstrated in Fig. 6a and b. Although the correlations among variables are lower in the short-term, they are higher in the long-term. The three-variate finding reveals a noteworthy connection among EICTI, FDV, and ENTS, which is critical in comprehending how financial development and technological advancements in countries like France and Germany are fostering environment- and energy-related innovations, ultimately leading to the development of green energy resources. This result demonstrates the asymmetrical interrelation among these factors, indicating that a robust financial sector can elevate the amount of capital and credit invested in green energy initiatives, thereby promoting technological innovations and energy transition. These findings provide valuable insights into the importance of sustainable development in the global economy and the role of financial institutions in driving it forward.

Figure 6c and d provides insights into the correlation patterns among EICTI, FDV, and ENTS, with a focus on France and Germany. In the case of France, environment-related ICT innovations (EICTI) emerge as the dominant factor, as demonstrated by the blue color in the heatmaps (see Fig. 6c). This multivariate approach enables us to assess the contribution of each element in the multiple relationships, highlighting EICTI's significance in the short and medium term. However, in the long term, financial development (FDV) takes over as the dominant factor, followed by EICTI and ENTS, respectively. Despite this shift, EICTI continues to maintain its overall dominance in the correlation patterns in France. In contrast, the correlation patterns in Germany demonstrate the dominancy of FDV across different frequencies (see Fig. 6d). This finding suggests that investments in green projects will lead to an increase in innovations and R&D activities in renewable energy technologies, ultimately promoting green energy supply and consumption (Jianguo et al. 2022). Overall, these findings emphasize the importance of understanding the role of various factors in promoting sustainable development by reducing greenhouse gas emissions, particularly in the context of financial development and technological innovations (He et al. 2021; Liu et al. 2023).

The identification of factors that are strongly associated with greenhouse gas emissions (GHGS) and over what frequency is a critical step toward addressing the challenges of climate change. To achieve this, we conducted a multivariate analysis using GHGS as a dependent factor to examine its relationship with EICTI, ENTS, and FDV. The results are presented in Figs. 7 and 8. In the case of France, Fig. 7 shows that ENTS and EICTI, ENTS and FDV, and FDV and EICTI appear to impact GHGS emissions similarly, with positive correlations observed in most frequency domains. Similar patterns of correlation are observed in the case of Germany, as shown in Fig. 8, where EICTI, ENTS, and FDV are all identically connected to GHGS emissions throughout the analyzed period. Furthermore, in the four-variate case presented in Fig. 9, the most intense positive correlation of EICTI, ENTS, and FDV to impact GHGS emissions can be observed over long-term frequencies (8–16) in both France and Germany, can be seen in Fig. 9a and b. This observation is consistent with the idea that sustained efforts are required to mitigate the impact of GHGS emissions on the environment. It is important to note that while these variables exert different impacts on GHGS emissions independently when incorporated in a multivariate context, they reveal parallel correlation patterns. These findings underscore the need for a holistic approach to addressing the challenges of climate change, one that considers the interplay of various factors that contribute to GHGS emissions. Such an approach could enable policymakers and stakeholders to identify effective strategies for mitigating the impact of GHGS emissions and promoting sustainable development. The summary of the France and Germany is shown in Fig. 10a, b, respectively.

Wavelet-based Granger causality results

Recent studies conducted by Adebayo (2022) and Arshian et al. (2020) have emphasized the reasons for the decline in GHG emissions, underscoring that energy/power-generating resources play a more significant role as contributors, rather than institutional development. While this has led to positive environmental outcomes, it has come at the expense of economic growth, raising concerns about achieving the goal of low-carbon energy generation in the long term. If climate-related measures fail to drive an energy shift, it is expected that GHGS emissions in France and Germany will continue to rise. While the bivariate approach shows a decrease in GHGS emissions due to EICTI, FDV, and ENTS, the multivariate context shows that this is not the case, as inadequate climate policies linked to financial development, technology innovations, and energy transition have prevented the government from taking full advantage of these factors. Therefore, robust policies integrating financial and technological strategies linked to the energy sector are crucial to achieve a sustainable reduction in GHGS emissions. Such policies require an innovative financing and technology solution, coupled with a clear and coherent regulatory framework.

The multivariate analysis of the relationship between EICTI, ENTS, FDV, and GHGS emissions yields nearly identical results to the bivariate analysis conducted in Figs. 3, 4, 5, highlighting the significant role of these factors

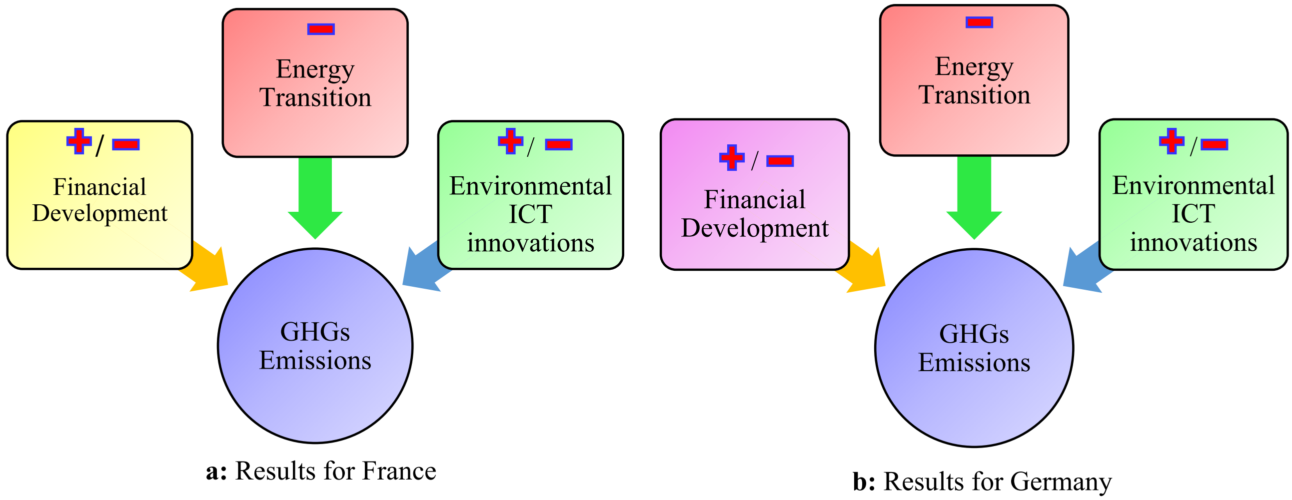


Fig. 10 **a** Results for France and **b** Results for Germany

in GHGS emissions patterns. These findings confirm the results of the bivariate analysis, emphasizing the long-term association between these variables and underscoring their importance in influencing the environmental quality of France and Germany. Furthermore, analyzing these correlations across short- and long-term frequencies can be particularly beneficial for policymakers, providing a consistent framework for promoting sustainability in the energy sector. Our multivariate approach reveals that EICTI and FDV are the dominant factors in this time-varying analysis in France and Germany, respectively. In addition to the importance of ENTS and FDV, our study revealed that EICTI also plays a significant role in reducing GHGS emissions in France (Fig. 6c). This highlights the potential of innovative technologies to achieve economic growth and environmental protection simultaneously, ultimately promoting sustainable development. However, our findings suggest that this association is a long-term process, and it may take time for EICTI and related production methods to become widely available. In contrast, FDV remains a crucial factor in reducing GHGS emissions in Germany (Fig. 6d). Therefore, it is crucial to develop comprehensive policies and initiatives that support the implementation of EICTI and FDV to reduce GHGS emissions in both France and Germany. In addition, the robustness of the findings from the WLMC approach is verified by applying the Wavelet-based Granger causality test. The findings shown in Table 5 indicated that EICTI, FDV, and ENTS are insignificant to cause GHGS emissions in the short, and medium run (rows D1 to D4), in both Germany and France. Hoverer, a significant causality in the long term has been observed from EICTI, FDV, and ENTS to GHGS emissions in France and Germany. The causal effect from EICTI, FDV and ENTS to GHGS emissions is consistent with several studies in the literature (see Alola and Adebayo 2022; Ullah et al. 2023; Wang et al. 2023; Jianguo et al. 2022; Zhen et al. 2022). The outcomes from the causality test validate the one estimated through the WLMC approach, suggesting a long-term significant correlation of EICTI, FDV, and ENTS with GHGS emissions for the sample countries.

Conclusions and policy directions

Conclusion

Reducing GHGS emissions is a critical step toward achieving sustainable development goals, since a higher level of GHGS emissions has devastating and far-reaching consequences, including sea level rise, increased frequency of extreme weather events, and loss of biodiversity. This study highlights the dynamics of relationships among environment-related ICT innovations (EICTI), financial development (FDV), energy transition (ENTS), and GHGS emissions in the case of France and Germany. A unique time and frequency-based approach named wavelet local multiple correlations (WLMC) have been employed to examine the relationships among the variables for the period 1990 to 2020.

The bivariate analysis results first show a long-term positive connectedness between EICTI, FDV, and ENTS in France and Germany. Consequently, EICTI, FDV, and ENTS are negatively linked with GHGS emissions in the long-term frequency, implying that the long-term policies targeting these factors can help promote sustainable development in both France and Germany. Moreover, the result posits that EICTI and FDV are the dominating factors in the multivariate nexus in the case of France

Table 5 Wavelet-based Granger causality results

	Dependent Variables	Germany				France			
		Independent variables							
		ENTS	FD	EICTI	GHGS	ENTS	FD	EICTI	GHGS
DI	ENTS		3.468**	0.136	0.034		3.886**	1.743	3.658***
	FD	0.003		0.774	3.697**	0.063		0.491	1.701
	EICTI	6.694***	0.051		6.025***	1.591	4.870***		3.785***
	GHGS	0.841	0.026	0.060		0.067	0.283	0.476	
D2	ENTS		7.563***	0.264	0.455		8.273***	1.123	6.555***
	FD	0.025		1.374	7.020***	0.620		1.144	3.406**
	EICTI	13.19***	0.411		11.57***	5.215***	13.28***		8.731***
	GHGS	2.046	0.286	0.415		0.692	4.458***	0.494	
D3	ENT		0.251	0.611	0.158		2.219*	0.769	2.349**
	FD	0.376		2.740**	0.441	0.991		0.261	0.299
	EICTI	2.673*	1.784		2.249*	0.870	1.931		0.477
	GHGS	0.239	0.574	0.578		3.243**	0.224	0.101	
D4	ENTS		0.529	0.215	1.516		1.654	0.599	3.998***
	FD	3.729**		4.135***	5.788***	0.828		0.316	1.731
	EICTI	1.505	0.781		1.98578	1.875	0.812		1.279
	GHGS	1.004	1.366	0.319		4.246***	1.336	0.541	
D5	ENTS		2.150*	3.732***	3.047***		2.356*	1.856	1.193
	FD	4.629***		2.210**	5.339***	1.053		2.694**	1.609
	EICTI	5.120***	0.636		4.883***	0.620	2.765**		2.367*
	GHGS	2.570**	3.842***	3.134***		1.578	3.162***	4.438***	
D6	ENTS		15.14***	9.565***	3.640***		5.851***	7.681***	4.12088
	FD	11.09***		6.205***	9.520***	6.033***		9.576***	3.437**
	EICTI	8.434***	10.26***		4.059***	6.243***	4.748***		3.408**
	GHGS	3.493***	14.32***	7.672***		6.785***	5.515***	11.24***	
Original	ENTS		4.309***	2.620**	1.277		0.176	1.952*	1.142
	FD	0.512		1.7304	0.119	0.085		0.054	1.342
	EICTI	0.380	0.930		0.223	0.658	0.656		1.278
	GHGS	0.844	0.456	0.219		0.436	1.197	1.572	

***$P < 1\%$. **$P < 5\%$ and *$P < 10\%$. The F-statistics denote the null hypothesis rejection of "no causality." "D1 and D2", "D3 and D4", and "D5 and D6" stand for short, medium, and long term, respectively

and Germany, respectively. Finally, the outcomes of the three-, and four-variate suggest that EICTI, ENTS, and FDV are identically (similar trend) affecting the GHGS in both countries. The findings suggest that a multifaceted approach that integrates financial and technological strategies linked to the energy sector is required to achieve a sustainable reduction in GHG emissions. Meanwhile, the focus of Germany and France should be on improving financial support for renewable energy projects and incentivizing technological innovations to reduce GHG emissions further.

Policy recommendations

As evidenced by the long-term outcomes of our study, EICTI, FDV and ENTS are key factors for the reduction of GHGS emissions. However, we find that the influence of these factors on GHGS emissions varies across time and frequency domains. However, the long-term effect of EICTI, FDV, and ENTS on GHGS emission is negative, so policy measures involving these factors can pave the way toward sustainable development in Germany and France. To accelerate the reduction of GHGS emissions, both Germany and France can further scale up policy measures that harness the potential of EICTI, FDV, and ENTS. Firstly, the governments in both countries can introduce attractive financial incentives and grants to stimulate private sector investments green technologies. Public–private partnerships can further expedite the integration of latest technology across sectors, leading to substantial emission reductions and sustainable economic growth. Similarly, the promotion of green finance initiatives will channel investments into low-carbon projects and EICTI innovations. By establishing green bonds and investment funds, both governments can mobilize private capital for renewable energy projects. Strengthening investment in renewable energy frameworks will drive the energy transition toward, which in long term reduces the GHGS emissions and support to reach emission-free economy goal. Secondly, smart grid integration and advanced metering systems can expedite the energy transition. By mandating energy-intensive industries and commercial buildings to adopt EICTI solutions for optimizing energy usage, the governments can effectively reduce GHGS emissions and energy wastage. Thirdly, both countries should prioritize sustainable transportation solutions, including promoting electric mobility and public transport. Financial incentives such as tax credits and subsidies for electric vehicle purchases, combined with investments in charging infrastructure and intelligent transportation systems, will enhance low-carbon transportation options. Lastly, fostering cross-border collaboration and knowledge sharing between Germany and France will leverage shared expertise and experiences in combating climate change through EICTI, FDV, and ENTS. Policy dialogues, joint research projects, and technology exchange initiatives will accelerate the development and deployment of effective solutions to reduce GHGS emissions. By adopting these policy recommendations, Germany and France can demonstrate their commitment to environmental sustainability, spur economic growth, and significantly contribute to global efforts in combatting climate change. These proactive measures will set a precedent for other nations to follow, promoting a collective response to the pressing issue of GHGS emissions and fostering a greener future.

Limitation and future study

Although this study provides valuable insights into the contributions of EICTI, FDV, and ENTS toward reducing GHGS emissions, there are some limitations that must be taken into account. One is the insufficient data on some of the factors that may impact GHGS emissions reduction, such as specific energy sources or production methods. Furthermore, the study only focused on France and Germany, and its results may not be generalizable to other countries or regions. To gain a more comprehensive understanding of the effectiveness of similar policies and initiatives in other contexts, future research should be conducted. This research should also examine the potential for cross-border collaboration to achieve GHGS emissions reduction targets.

Author contributions TSA: Methodology; Conceptualization; Formal analysisAAA: Data; Writing - original draft; Investigation; Supervision, and Corresponding.SU: Editing of the text.

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Data availability Data is readily available on request from the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

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