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Research article

Differential benefit of coal and natural gas efficiency in Denmark: How clean is the environmental-related innovation?

Tomiwa Sunday Adebayo [a], Andrew Adewale Alola [b,c,d,*]

[a] Department of Business Administration, Faculty of Economic and Administrative Science, Cyprus International University, Via Mersin-10, Turkey
[b] CREDS-Centre for Research on Digitalization and Sustainability, Inland Norway University of Applied Sciences, 2418, Elverum, Norway
[c] Adnan Kassar School of Business, Lebanese American University, Beirut, Lebanon
[d] Faculty of Economics, Administrative and Social Sciences, Nisantasi University, Istanbul, Turkey

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ABSTRACT

Inspired by Denmark's ambitious renewable energy initiatives and its commitment to achieving a substantial 70 percent reduction in greenhouse gas (GHG) emissions by 2030 and achieving net-zero emissions by 2050, this study delves deeper into examining the roles of energy source efficiency, renewable energy utilization, and environment-related technologies spanning the years from 1990 to 2021. A comprehensive array of wavelet tools, including wavelet coherence, wavelet-based ordinary least squares (WBOLS), Continuous Wavelet Transform (CWT), Granger causality, and wavelet correlation, was employed to dissect these dynamics. The primary findings underscore the potential for enhancing environmental sustainability through these key indicators. For instance, employing the WBOLS method reveals that a percent increase in renewable energy consumption translates into an approximate reduction of ~0.02%, ~0.03%, and ~0.54% in GHG emissions in the short-, medium-, and long-term, respectively. Similarly, improvements in energy efficiency yield remarkable outcomes. A one percent increase in the efficiency of natural gas utilization leads to GHG emission reductions of ~0.44%, ~0.19%, and ~0.83% in the short-, medium-, and long-term, respectively. Moreover, a 1 percent enhancement in coal energy efficiency results in GHG emission reductions of ~0.23%, ~0.19%, and ~0.91% in the short-, medium-, and long-term, respectively. Furthermore, the study indicates that a surge of 1% in innovation through environment-related technologies corresponds to GHG emission reductions of ~0.56%, ~0.10%, and ~0.02% in the short-, medium-, and long-term, respectively. The results are notably substantiated by the CWT Granger causality approach. Considering the somewhat modest impact of innovation on GHG emissions, especially in the long-term, the study recommends a deliberate emphasis on the design and formulation of environmentally-related innovations that prioritize attributes such as reliability, durability, and adaptability.

1. Introduction

Aspiring for a cleaner environment, Denmark is committed to achieving 70 percent and net-zero emissions i.e., 100 percent reduction in Greenhouse gas (GHG) emissions from 1990 level in 2030 and 2050 respectively (IEA, 2022). Alongside these nationally determined contributions (NDCs) is the target to 100 percent renewable electricity and 90 percent non-fossil sources for district heating by 2030. In line with these projections, and with respect to total electricity and aggregate primary energy utilization, Denmark now has the highest share of wind energy. Given Denmark's Green Roadmap which details 24 initiatives of the country's pathway to achieving climate goals is well-outlined through energy efficiency and mitigation of carbon dioxide (CO_2) emission approaches. Among the outlined energy efficiency and CO_2 reduction pathways include: annual reduction in energy consumption (currently, energy production and total primary energy supply has reduced by 8.63 percent and 12.16 percent from 1990 level), curb road emissions by increasing energy efficient and plug-in hybrid vehicles, expand wind energy development, increase investment in Carbon Capture Utilization and Storage (CCUS) technologies and developing 'energy islands' for offshore wind, and exploring other renewable and clean energy sources such as biomass energy potentials (The International Trade Administration, U.S. Department of Commerce, 2022). Therefore, reflecting on the study of Holdren and Ehrlich (1974) which documents

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* Corresponding author. CREDS-Centre for Research on Digitalization and Sustainability, Inland Norway University of Applied Sciences, 2418, Elverum, Norway.
E-mail addresses: twaikline@gmail.com (T.S. Adebayo), andrew.alola@hotmail.com (A.A. Alola).

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Table 1
Variables source and measurement.

Variables	Sign	Measurement	Source
Coal Efficiency	COEF	GDP, PPP (constant 2017 international $)/Coal energy in tonnes	Authors Calculation
Gas efficiency	GASEF	GDP, PPP (constant 2017 international $)/Gas energy in tonnes	Authors Calculation
Greenhouse Gas Emissions	GHG	thousand tons	(GMF, 2023)
Innovation	INNO	Environmental-related technologies % of GDP	(OECD, 2023)
Renewable Energy Consumption	REC	Per Capita (Kwh)	(OWD, 2022)

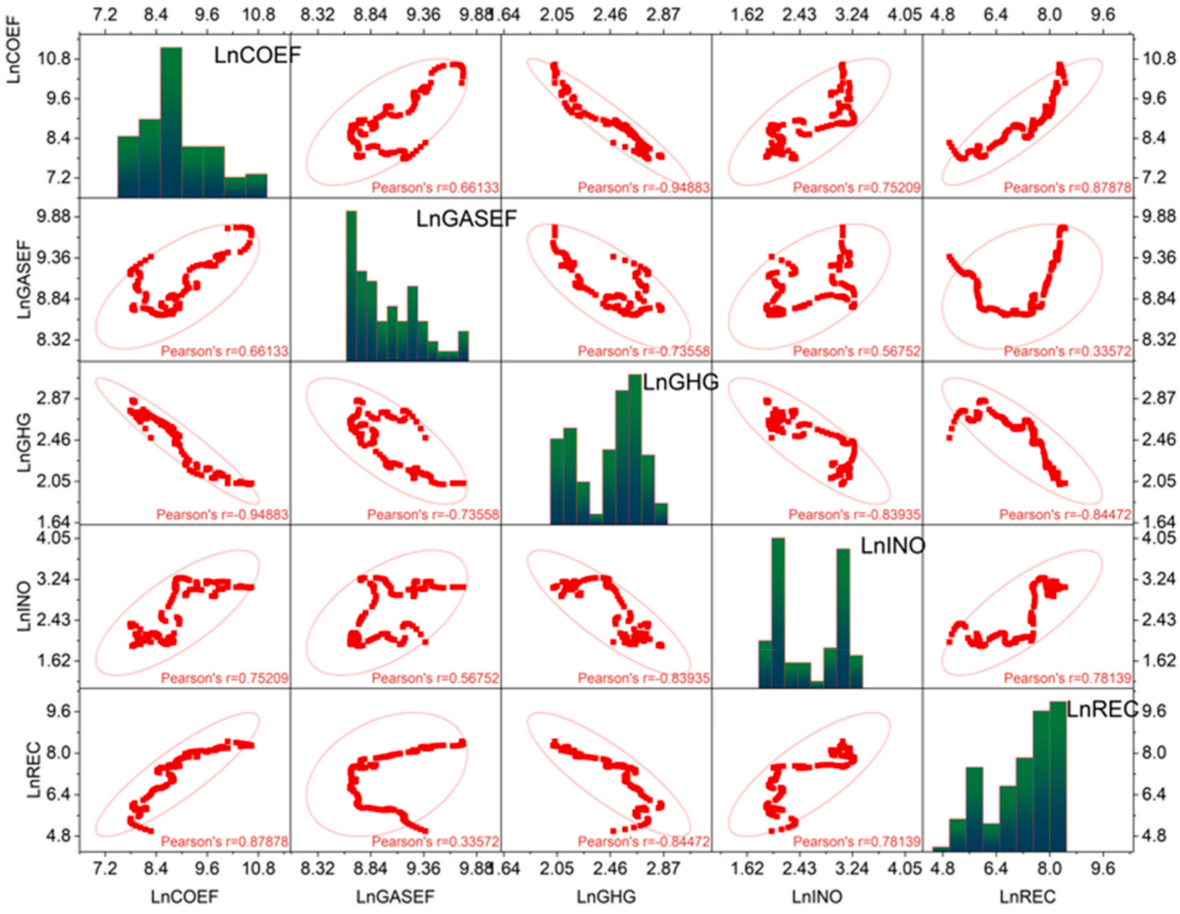
Table 2
Descriptive statistics.

	COEF	GASEF	GHG	INO	REC
Mean	8.8974	8.9974	2.4495	2.5767	7.1775
Median	8.7948	8.8985	2.5406	2.4565	7.4875
Maximum	10.636	9.7485	2.8552	3.2700	8.4536
Minimum	7.7833	8.6368	2.0199	1.9151	4.9991
Std. Dev.	0.7695	0.3166	0.2507	0.4969	0.9583
Skewness	0.6291	0.7119	−0.4186	0.0639	−0.6391
Kurtosis	2.6215	2.5194	1.7409	1.2275	2.1803
JB	9.2091	12.043	12.193	16.843	12.298
Probability	0.0100	0.0024	0.0022	0.0002	0.0021

the environmental impact of economic, population, and disruptive technologies aspects, Denmark's environmental sustainability overview offers enormous prospects.

To explore these environmental sustainability prospects, the current approach is developed with the objective of examining the environmental effects of renewable energy, coal energy efficiency, natural gas efficiency, and environmental-related technologies in Denmark. Although there are emerging studies that have addressed the environmental sustainability aspects of the Nordic states, however, focus on the specific role of energy efficiency alongside environmental-related technologies especially for the case of Denmark remained largely undocumented. Particularly, in this case, energy efficiency indicators were measured by the purchasing price parity (PPP) of Gross Domestic Product (GDP) in constant 2017 international United States Dollar ($) per tonnes of energy source. Moreover, the investigation relies on the recently developed wavelet-based empirical techniques for the preliminary tests and main estimations vis-à-vis wavelet correlation-coherence-cohesion, Continuous Wavelet Transform (CWT) Granger causality, and the wavelet-based Ordinary Least Square (WBOLS). Given the outlined novelty of the investigation and the empirical revelation on the environmental effects of energy efficiency and innovations, this study offers important policy formulation insight for the decision-makers and other relevant actors in Denmark and the Nordic neighbours.

For the other part of the manuscript, relevant literature is discussed in section 2 and the dataset alongside the empirical pathways are outlined in section 3. The findings of the investigation and comparison with



a: Scatter Plot.

Fig. 1A. The visual illustrates the (Pearson's) correlation between the variables, especially between the dependent variable GHG and the explanatory variables (REC, INO, GASEF, and COEF). As such, the direction of the relationships as enclosed spherically are also indicated by the Pearson's correlation (*r*) values.

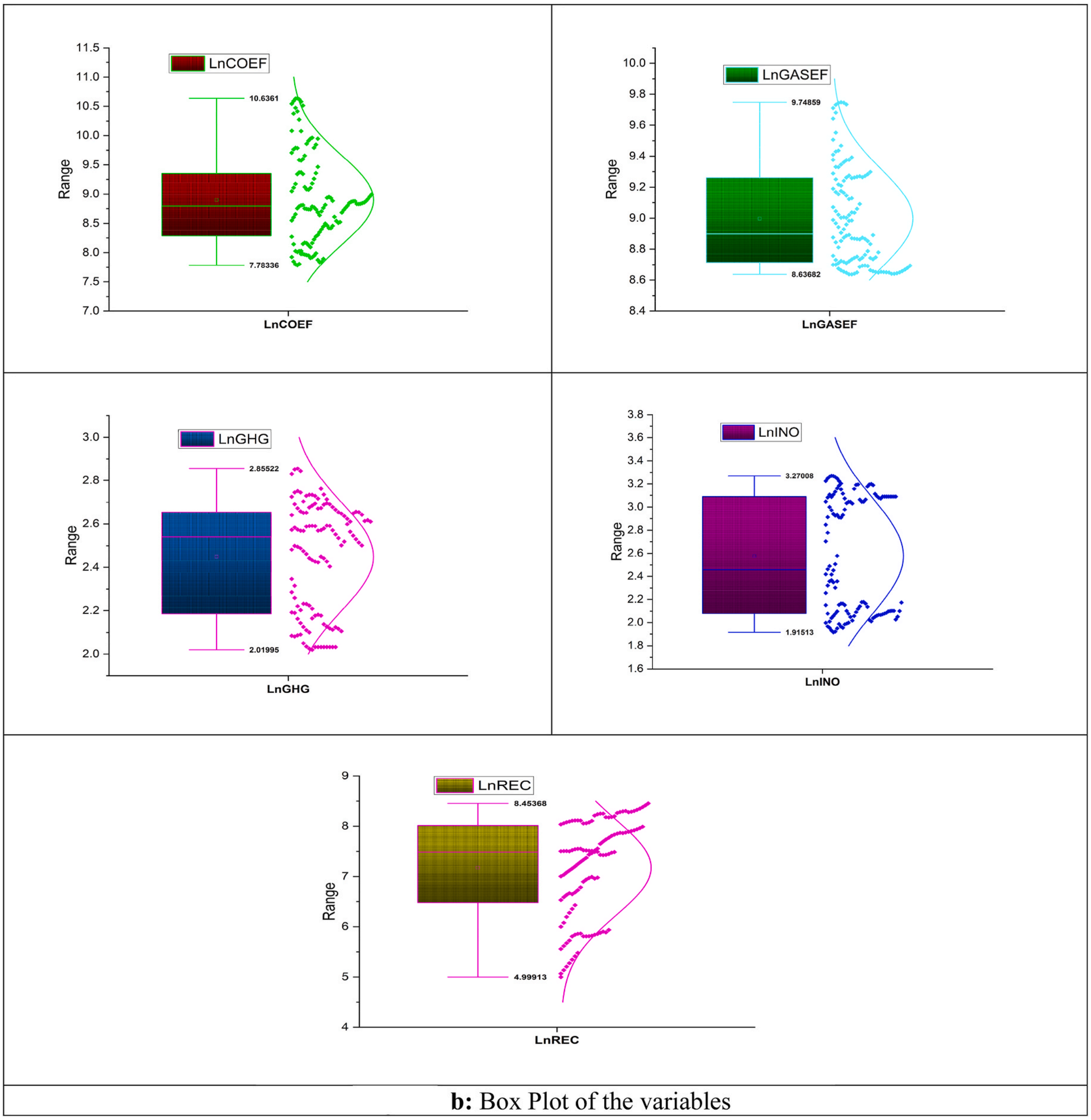


Fig. 1B. Box Plot of the variables.

related literature are documented in section 4. Lastly, the investigation is summarily concluded with result highlights, limitations, and policy recommendations in section 5.

2. Literature review

2.1. Renewable energy and GHG emissions

The extensive comprehension and consciousness prompted by climate change and global warming are profound, leading to a significant transformation in the policies of numerous nations toward fostering sustainable development and environmental preservation (Chen et al., 2023; Yan et al., 2023). During the Paris Agreement of 2015, the Glasgow Agreement of 2021, and the more recent Sharm El Sheikh Agreement of 2022, the emphasis on sustainable energy has been pronounced as a pivotal strategy to curtail GHG emissions, consequently enhancing ecological well-being. Various empirical inquiries have illuminated the significant role that green and clean energy sources play in curbing the expansion of GHG emissions (Afshan et al., 2022; Alam and Murad, 2020; Xiang et al., 2023; Zou et al., 2023). Intending to limit the expansion of GHG emissions in the Nordic economies, (Alola and Adebayo, 2022) explored the renewable energy-GHGs emissions nexus by considering the nonlinear nature of the indicators from 1990 to 2019. The results from this research documented the GHG emissions mitigating the role of green energy, which improves the ecological quality.

Similarly, Oyebanji et al. (2023) explored the drivers of CO_2 emissions by using quarterly data for Denmark. The researchers' findings underscore that the decline in CO_2 emissions within Denmark is attributed to the expansion of sustainable energy. Also, the outcome of (Kirikkaleli and Sowah, 2023) aligns with the research conducted in a few similar studies (Oyebanji et al., 2023; Alola and Adebayo, 2022). In their study, they employed Fourier-based methods spanning from 1990q1 to 2019q4 to investigate the role of sustainable energy in mitigating CO_2 emissions. The results affirm the role of sustainable energy in reducing emissions, a conclusion reinforced by the studies of (Ozturk et al., 2022; Sarkodie and Strezov, 2018; Bekun et al., 2019). Conversely, some studies documented the emissions-intensifying role of renewable energy. For instance, the study of (Pata, 2018) using Turkey as a case

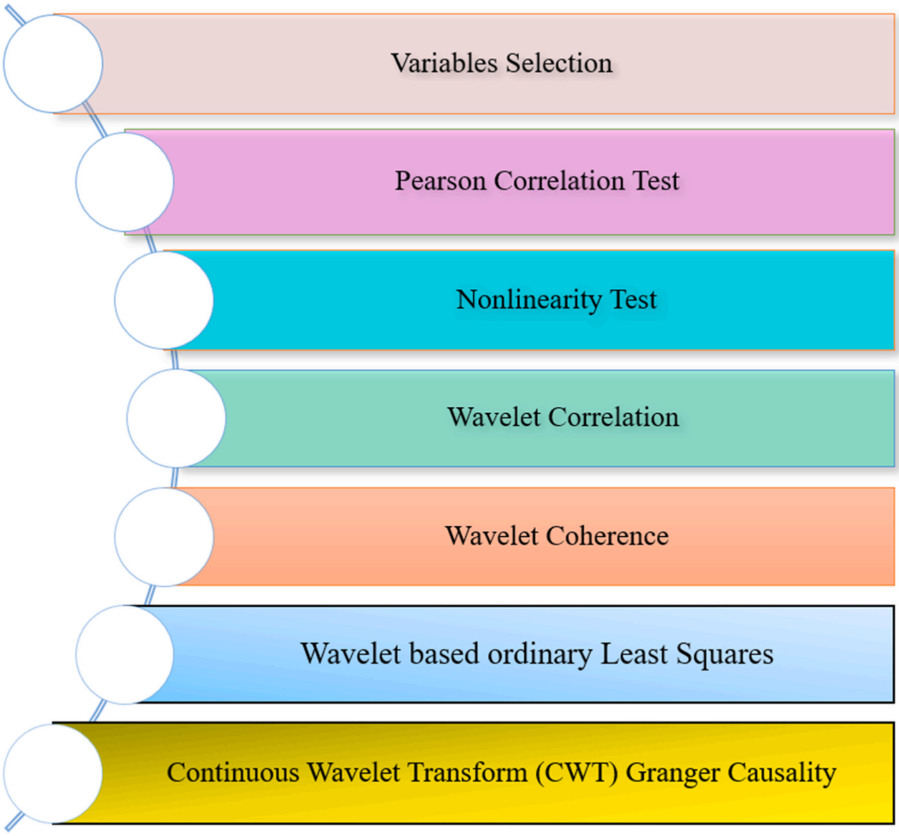


Fig. 2. Flow of the study.

Table 3
Non-linearity tests (by Broock et al., 1996).

	COEF	GASEF	GHG	INO	REC
M2	16.378*	23.623*	45.797*	44.327*	45.768*
M3	16.978*	24.478*	48.433*	46.221*	48.383*
M4	17.864*	25.795*	51.869*	49.045*	51.993*
M5	19.326*	28.001*	57.074*	53.348*	57.499*
M6	21.630*	31.188*	64.339*	59.673*	65.341*

Note: *P $<$ 0.01.

Table 4
Correlation results.

	COEF	GASEF	GHG	INO	REC
COEF	–	0.6613*	−0.9488*	0.7520*	0.8787*
GASEF	0.6613*	–	−0.7355*	0.5675*	0.3357*
GHG	−0.9488*	−0.7355*	–	−0.8393*	−0.8447*
INNO	0.7520*	0.5675*	−0.8393*	–	0.7813*
REC	0.8787*	0.3357*	−0.8447*	0.7813*	–

Note: *P $<$ 0.01.

reported that the growth of renewable energy is not sustainable and, as a result, intensifies CO_2 emissions. Likewise, the work of (Abbas et al., 2021) embarks on proposing a sustainable environment policy for the case of Pakistan using the linear ARDL and data between 1990 and 2019. The study results uncovered the insignificant renewable energy-emissions interrelationship in the long-term while renewable energy augments the growth of CO_2 emissions in the short-term.

2.2. Innovation and GHG emissions

Global markets are on the verge of the fourth industrial revolution, with technological innovation seen as the major means of achieving sustainable development (Bano et al., 2022; Chien et al., 2022; Ding et al., 2021). In this light, it is reasonable to believe that technological improvements influence ecological resilience. Moreover, eco-innovation tackles worldwide ecological problems (Wang and Su, 2020). More critically, technologies may be appropriate for reducing climate change and improving environmental sustainability. Technological progress might theoretically expand environmentally friendly manufacturing structures for long-term growth. Throughout history, several investigations have been done to analyse the impact of innovations on ecological deterioration, utilizing a variety of specifications, techniques, and metrics.

For example, (Alola and Adebayo, 2023) with the motif of deploying a sustainable development policy, used the nonlinear technique to evaluate the innovations-GHG emissions nexus. Using data from 1990 to 2021, the research results disclosed that ecological quality in Finland is attributed to innovation growth. Likewise, (F. Chen et al., 2022), in their study on the innovation-emissions interplay in 17 developing economies from 1995 to 2019, reported that the mitigation of CO_2 emissions in the selected nations is caused by the growth of innovation and, as a result, leads to improved ecological excellence. Intending to propose a sustainable policy agenda, (Hafeez et al., 2022) used the pooled mean group (ARDL-PMG) framework to evaluate the role of innovation in curbing CO_2 in the short-run as well as the long-run in Russia, Japan and China. The result obtained from this research disclosed that Russia, Japan and China could achieve ecological sustainability via innovation which lessens CO_2 emissions. Conversely, using Japan as a case, the increasing emissions role of innovation is documented by the study of (Adebayo and Kirikkaleli, 2021) using the wavelet tools. A similar result is also documented by the study of Shabbir et al. (2023).

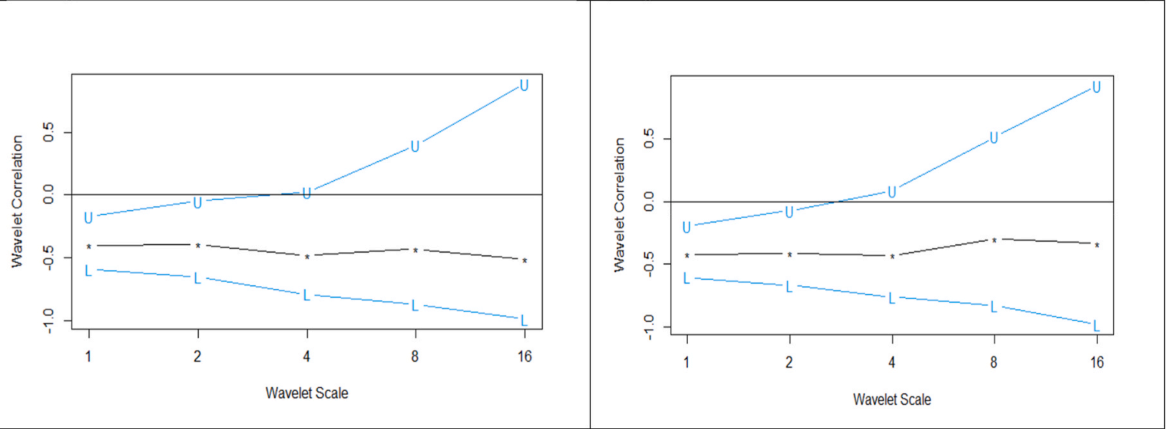


Figure 3a: Wavelet Correlation between COEF and GHGs

Figure 3b: Wavelet Correlation between GASEF and GHGs

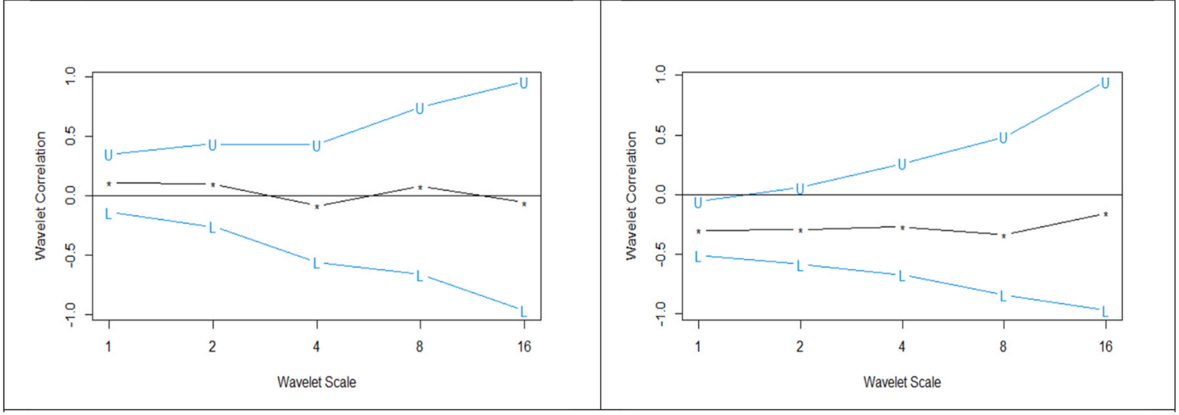


Figure 3c: Wavelet Correlation between INNO and GHGs

Figure 3d: Wavelet Correlation between REC and GHGs

Fig. 3. Wavelet Correlation between GHG emissions and COEF, GASEF, INNO and REC.

2.3. *Energy efficiency and GHG emissions*

The urge to increase energy efficiency is growing all around the globe. This call is being made for a variety of reasons. The growing price of fossil fuels is the most significant contributor, as price volatility has serious negative effects on energy demand and supply. Our planet's economic progress depends on an endless supply of energy, especially electricity generation (Akbar et al., 2022; Akram et al., 2020; Awan et al., 2022). Economic improvement is a broad concept, yet, for several advanced and developing economies, economic progress can be modeled as the advancement of the manufacturing sectors. With the advent of the world's energy crisis, energy intensity and efficiency have been the most debated themes, intending to harness these tactics to alleviate energy poverty and reduce energy consumption. According to our comprehensive literature assessment, the notion of energy efficiency is associated with GHGs emissions and has been extensively covered in the literature.

For example, with the intention of drafting ecological sustainability initiatives for 30 developing countries within the EKC framework, (Mehmood Mirza et al., 2022) investigated the role of energy efficiency in curtailing the growth of CO_2 emissions using data between 1990 and 2016. The research findings documented the emissions-lessening role of energy efficiency, which leads to improved ecological excellence. Intending to compel an emission-decreasing policy for emerging economies, (Awan et al., 2022) evaluated the role energy efficiency played in curbing the growth of CO_2 emissions utilizing data between 1996 and 2014. The research findings via the quantile regression deduced the emissions-lessening role of energy efficiency, which enhances ecological quality. A Similar investigation is also documented by the study of Shabbir et al. (2020).

2.4. *Appraisal of the literature*

Consequently, based on our analysis of the existing literature, we recognize the following gaps in research. Firstly, though empirical investigations (Alola et al., 2021; Awan et al., 2022; Ding et al., 2021; Hafeez et al., 2022) have been initiated regarding the role of energy efficiency, innovations, and renewable energy in limiting the growth of GHG emissions, no empirical study has been dedicated to the case of Denmark. Secondly, this research subdivides energy efficiency into coal efficiency and gas efficiency and then explores the influence of the two on GHG emissions respectively. The study findings will assist the government in developing more adaptable sustainability initiatives concerning energy efficiency.

Thirdly, previous studies on these associations have been restricted to conventional techniques such as fully modified OLS (FMOLS), vector autoregressive (VAR), dynamic OLS (DOLS), quantile regression (QR), dynamic ARDL, bootstrap ARDL (BARDL), VECM, bootstrap rolling window approach and many more. Therefore, we deviate from these studies by employing wavelet tools, including CWT Granger causality, wavelet cohesion, and wavelet coherence. Specifically, the novel CWT Granger causality initiated by (Olayeni, 2016) unlike the conventional causality, can detect causality between two series at various frequencies and periods. Moreover, this approach is also adaptive for nonlinear and nonstationary variables. Besides that, we deployed the wavelet-based ordinary least square (WBOLS) to identify the impact of coal efficiency and gas efficiency, along with innovation and renewable energy, on GHGs emissions at different periods. To the investigators' understanding, this is the first study to apply the WBOLS and CWT Granger causality to capture the effect of coal efficiency, gas efficiency, innovation, and renewable energy on GHG emissions. Thus, the gap in prior

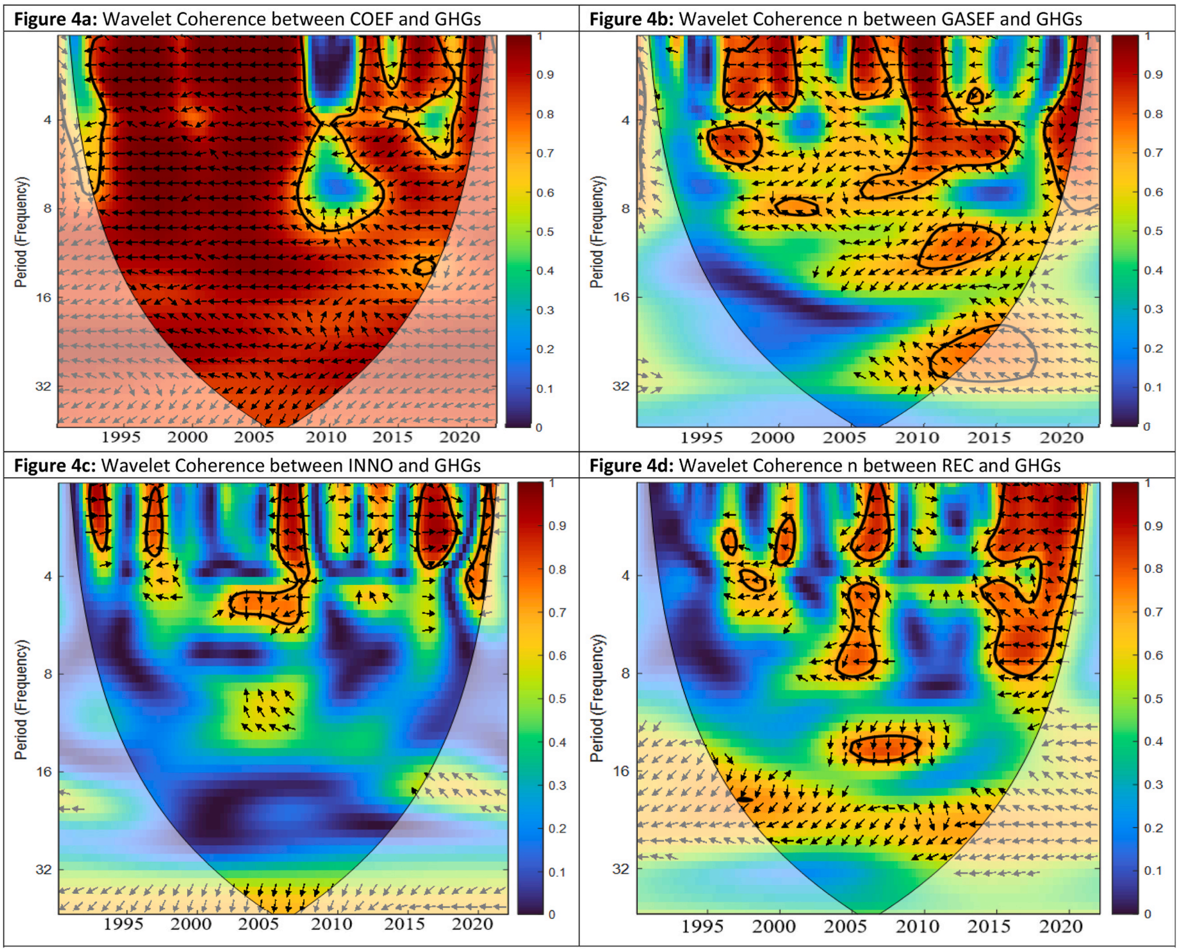


Figure 4a: Wavelet Coherence between COEF and GHGs

Figure 4b: Wavelet Coherence n between GASEF and GHGs

Figure 4c: Wavelet Coherence between INNO and GHGs

Figure 4d: Wavelet Coherence n between REC and GHGs

Fig. 4. Wavelet Coherence between GHG emissions and COEF, GASEF, INNO and REC.

literature is filled.

3. Data

In order to evaluate the role of energy efficiency (coal and gas), innovation, and renewable energy in limiting GHG emissions, this investigation used data between 1990 and 2021. The dependent variable is GHG emissions (GHGs), while the regressors are gas efficiency (GASEF), coal efficiency (COALEF), innovation (INO), and renewable energy (REC). The detailed measurement and sources of the indicators are presented in Table 1. The data are transformed from low-frequency to high-frequency data following prior studies (Tiwari et al., 2020; Kirikkaleli and Sowah, 2023). Furthermore, data are logged to ensure that it aligns with normality.

The brief statistical information regarding all the variables of investigation is shown in Table 2. GASEF (8.997) has the highest mean, which ranges from 8.636 to 8.997. This is accompanied by COEF (8.897), which ranges from 7.783 to 10.636, REC (7.177), which ranges from 4.999 to 8.453, INNO (2.576), which ranges between 1915 and 3.270, and GHG (2.44) which ranges from 2.019 to 2.855. REC is highly volatile, while GHG is less volatile than other indicators. With the exemption of REC and GHG, which are negatively skewed, all the other variables, i.e., COEF, GASEF, and INO, are skewed positively. Furthermore, all the series are platykurtic since their value is < 3. Moreover, the nonlinear distribution of the series is shown by the Jarque Bera; thus, nonlinear techniques will be suitable for this analysis. The study applies the natural logarithm to the series to alleviate skewness. In addition, Fig. 1a (scatter Plot) and Fig. 1b (box plot) show the visual information regarding the maximum, minimum, and correlation.

4. Empirical methods

In this empirical investigation, the empirical methods rest on the wavelet tools. The tools used in this study encompass wavelet coherence, wavelet-based ordinary least squares (WBOLS), wavelet correlation, and CWT Granger causality. The wavelet correlation and wavelet-based ordinary least squares are frequency domain techniques while wavelet coherence, CWT Granger, and wavelet cohesion are time-frequency domain techniques. The wavelet tools are powerful tools that can identify the association/causality between series at different frequencies and periods. Also, these techniques can uncover hidden information that timedomain techniques cannot identify (Aguiar-Conraria and Soares, 2014; Fernández-Macho, 2019; Tiwari et al., 2020).

4.1. Discrete wavelet transform

The study utilized the discrete wavelet transform to divide the series into frequency and scales. As per (Mishra et al., 2020), the scales and bands are shown by the difference in frequency. The wavelet family comprises both the mother and father wavelets which are shown below

$$\int \varphi(\mathrm{T})\mathrm{d}t = 1 \tag{1}$$

$$\int \varphi(\mathrm{T})\mathrm{d}t = 0 \tag{2}$$

The father wavelet is employed for signals and patterns at the lower frequencies, whereas the mother wavelet is employed for higher frequencies patterns and signals. The wavelet is defined as follows;

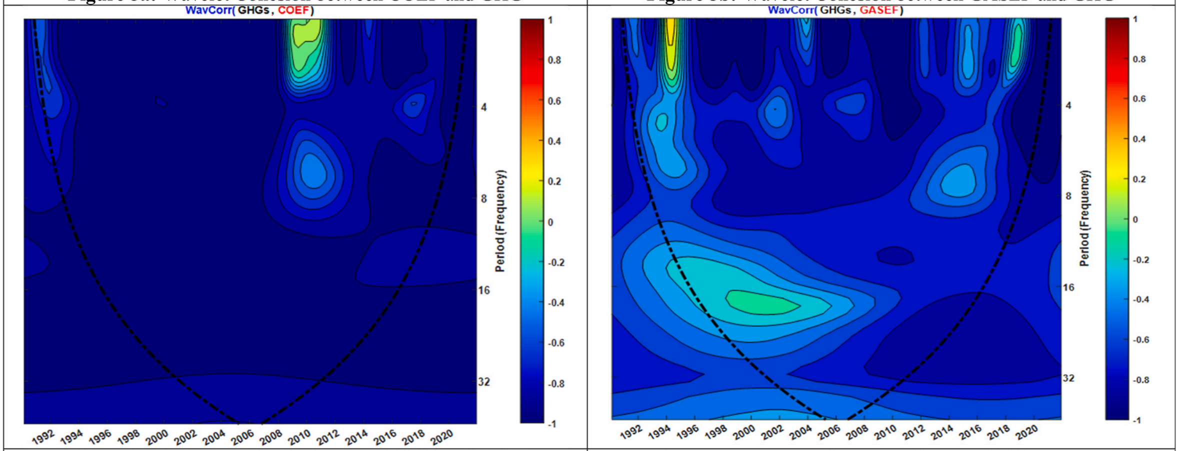


Figure 5a: Wavelet Cohesion between COEF and GHG

Figure 5b: Wavelet Cohesion between GASEF and GHG

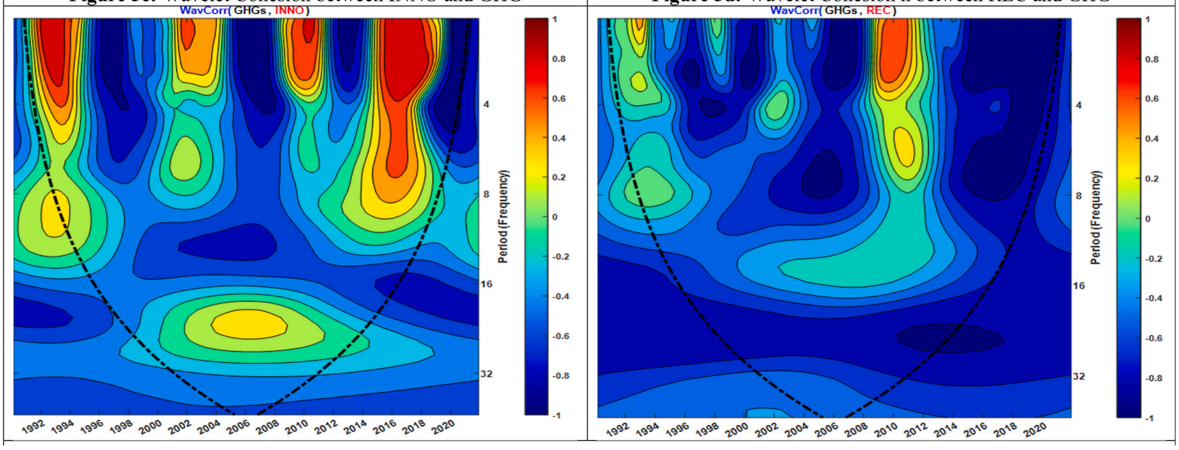


Figure 5c: Wavelet Cohesion between INNO and GHG

Figure 5d: Wavelet Cohesion n between REC and GHG

Fig. 5. Wavelet Cohesion between GHG emissions and COEF, GASEF, INNO and REC.

Table 5
Wavelet-based ordinary least Square (WBOLS).

	Variable	Coefficient	Std. Error	t-Statistic	Prob.
Short Term D2	COEF	−0.2301***	0.0156	−14.704	0.0000
	INNO	−0.5614***	0.0247	−22.727	0.0000
	REC	−0.0249**	0.0125	−1.9910	0.0487
	GASEF	−0.4412***	0.0540	−8.1665	0.0000
Medium-Term					
D4	COEF	−0.1949***	0.0171	−11.354	0.0000
	INNO	−0.0953***	0.0225	−4.2315	0.0000
	REC	−0.0319**	0.0136	−2.3476	0.0205
	GASEF	−0.1874***	0.0319	−5.8694	0.0000
Long-Term D6	COEF	−0.9129***	0.0417	−21.855	0.0000
	INNO	−0.0220	0.0212	−1.0372	0.3016
	REC	−0.5439***	0.0331	−16.409	0.0000
	GASEF	−0.8328***	0.0557	−14.946	0.0000

Note: D2, D4 and D6 denotes short, medium and long-term. ***P<1%, **P<5% and × P<1%.

$$\varphi_{j,k}(t) = 2^{j/2}\varphi\left(2^{j}t - k\right) \tag{3}$$

$$\varphi_{j,k}(t) = 2^{j/2}\psi\left(2^{j}t - k\right) \tag{4}$$

4.2. *Wavelet coherence*

According to Torrence and Webster (1999), the cross-wavelet of the two series x(t) and y(t) can be interpreted as follows:

$$W_{xy}(m,n) = W_x(m,n)W_y^{*}(m,n) \tag{5}$$

The cross-wavelet power spectrum split the series into periods, emphasizing particularly sensitive intensity across the remainder of the time series in all time-frequency realms. Wavelet coherence (WTC), due to its specific properties, can discriminate between a wide variety of areas and times when co-movement prevails between the time series. In line with (Torrence and Webster, 1999), the coefficient of the WTC is modified as follows:

$$R_n^2(s) = \frac{\left|N\left(N^{-1}W_{xy}(m,n)\right)\right|^2}{N\left(N^{-1}\left|W_x(m,n)\right|^2\right)\, N\left(N^{-1}\left|W_y(m,n)\right|^2\right)} \tag{6}$$

The WTC coefficient closer to 1 indicates a significant degree of connection, whereas values around 0 indicate no correlation.

4.3. *Wavelet cohesion*

(Rua, 2013) proposed wavelet cohesion to clarify the co-movement between series x(t) and y(t). (Rua, 2013) proposed the co-movement intensity gauge $\rho_{x_n y_n}$ as a real number on [−1, 1] by factoring for the real sections of wavelet cross-spectra, as shown below.

$$\rho_{x_n y_n} = \frac{\Re\left(W_n^{x} W_n^{y}\right)}{\sqrt{\left|W_n^{x}\right|^2 \left|W_n^{y}\right|^2}} \tag{7}$$

Moreover, unlike the WTC, the wavelet cohesion method discovers both negative and positive linkages across series but does not extract details on the lag/lead.

Figure 6a: Aggregate Causality from GHGs to COEF **Figure 6b:** Aggregate Causality from COEF to GHGs

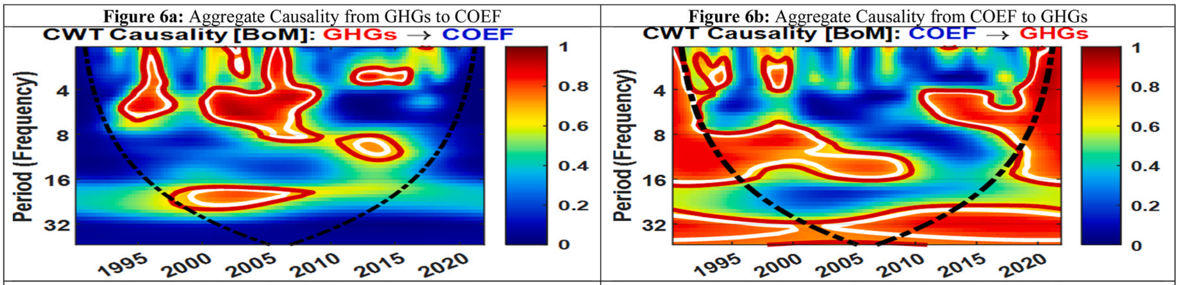


Figure 6c: In-phase Causality from GHGs to COEF **Figure 6d:** In-phase Causality from COEF to GHGs

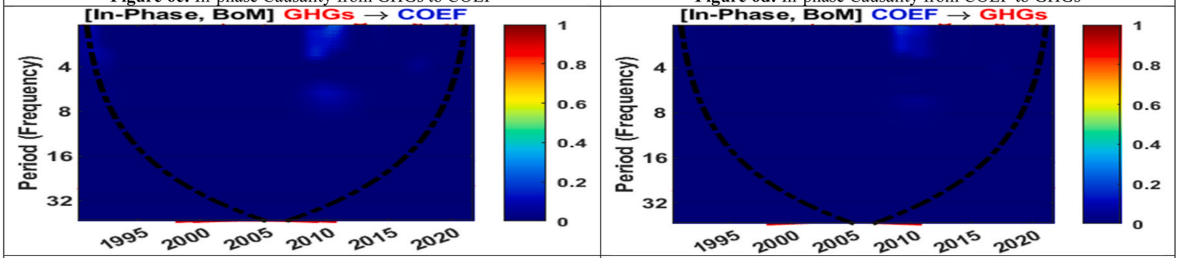


Figure 6e: Out-of-phase Causality from GHGs to COEF **Figure 6f:** Out-of-phase Causality from COEF to GHGs

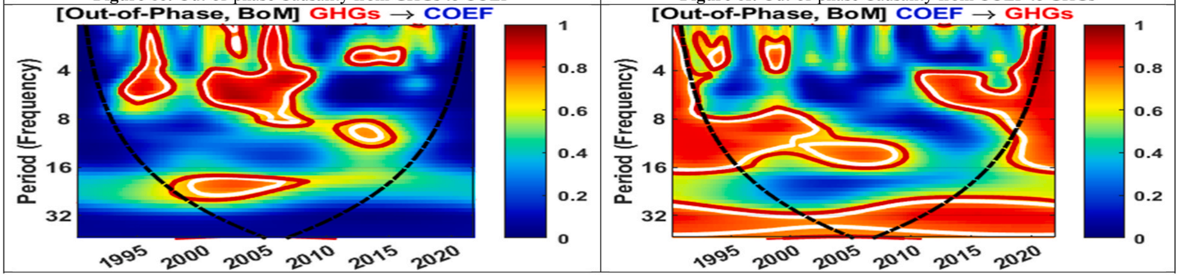


Fig. 6. Causality between GHGs and COEF

4.4. *Causality in Continuous Wavelet Transform*

By improving on the CWT-based correlation introduced by Rua (2013), Olayeni (2016) introduced the Continuous Wavelet Transform Granger causality approach. The CWT causality is presented in Equations (8) and (9) as follows.

$$G_{y\to x}(\tau,s)=\frac{\zeta\left\{s^{-1}\left|\Re\left(W^{m}_{xy}(\tau,s)\right)I_{y\to x}(\tau,s)\right|\right\}}{\zeta\left\{s^{-1}\sqrt{\left|W^{m}_{x}(\tau,s)\right|^{2}}\right\}\bullet\zeta\left\{s^{-1}\sqrt{\left|W^{m}_{y}(\tau,s)\right|^{2}}\right\}}, \tag{8}$$

Where; $W^m_x(\tau,s)$, $W^m_y(\tau,s)$ and $W^m_{xy}(\tau,s)$ are the wavelet transformation of x and $I_{y\to x}(\tau,s)$ is the series function, exemplified below:

$$I_{y\to x}(\tau,s)=\begin{cases}1,\text{ if }\varphi_{xy}(\tau,s)\in\left(0,\frac{\pi}{2}\right)\cup\left(-\pi,-\frac{\pi}{2}\right)\\ \qquad 0,\text{ otherwise}\end{cases}\text{, and}$$
$$\varphi_{xy}(\tau,s)=\tan^{-1}\left(\frac{\Im\left\{W^{m}_{xy}(\tau,s)\right\}}{\Re\left\{W^{m}_{xy}(\tau,s)\right\}}\right) \tag{9}$$

The list and pathway of the employed methods in this study is shown by Fig. 2. This depicts the entire procedures beginning from the preliminary tests to the main investigation.

5. Findings and discussion

5.1. *Preliminary test results*

This section contains the preliminary and necessary tests alongside the main empirical results. Accordingly, the results of these conditional tests are presented in the first part. Given the conditions for employing the main empirical wavelet approaches, the response of GHG emission to the explanatory variables is tested for nonlinearity evidence by employing the Broock et al. (1996) method. As noted in the result in Table 3, the null hypothesis for non-linearity in the series is rejected for the variables. Additionally, a test for correlation especially between the dependent (GHG) and the explanatory variables all reveals a negative correlation (see Table 4). This result is expected considering that efficient utilization of coal and natural gas are expected to mitigate GHG emissions. Moreover, renewable energy and innovation (proxy by environmental-related technologies) also align with expectation i.e., negative correlation with GHG emission.

5.2. *Wavelet correlation estimates*

The results of the implemented wavelet-based estimation approaches begin with the wavelet correlation as indicated in Fig. 3. In Fig. 3, the vertical and horizontal axes present the coefficient of the wavelet correlation and wavelet scales respectively. Given this visual revelation, the black discontinuous lines especially coal efficiency (Fig. 3a), natural gas efficiency (Fig. 3b), innovation (Fig. 3c) and renewable energy (Fig. 3d) are well below the negative region, thus justifying the negative relationship with the dependent variable. Wholly, this result aligns with the correlation matrix earlier indicated in Table 4.

5.3. *Wavelet coherence estimates*

Furthermore, the application of the wavelet coherence (see Fig. 4) and wavelet cohesion (see Fig. 5) techniques respectively yield a graphic representation of the relationships between GHGs and its determinants (specifically coal efficiency, gas efficiency, renewable energy and innovation. In Figs. 4 and 5, the vertical and horizontal axes present the frequency and time-frame respectively. In Fig. 4, the rightward (leftward) arrows present a positive (negative) correlation. Furthermore, the

Figure 7a: Aggregate Causality from GHGs to COEF

Figure 7b: Aggregate Causality from COEF to GHGs

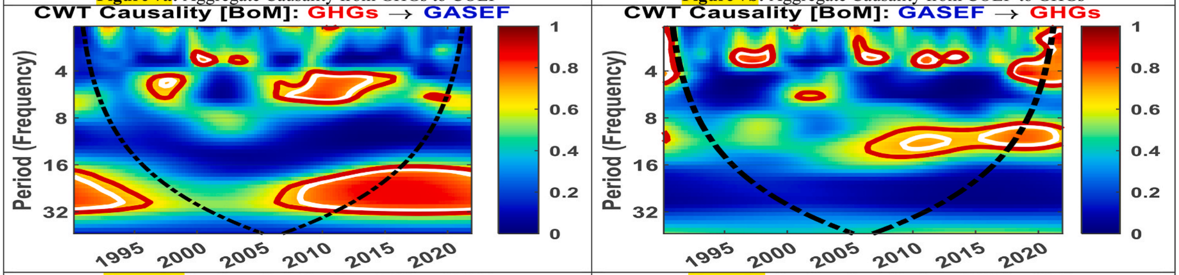


Figure 7c: In-phase Causality from GHGs to COEF

Figure 7d: In-phase Causality from COEF to GHGs

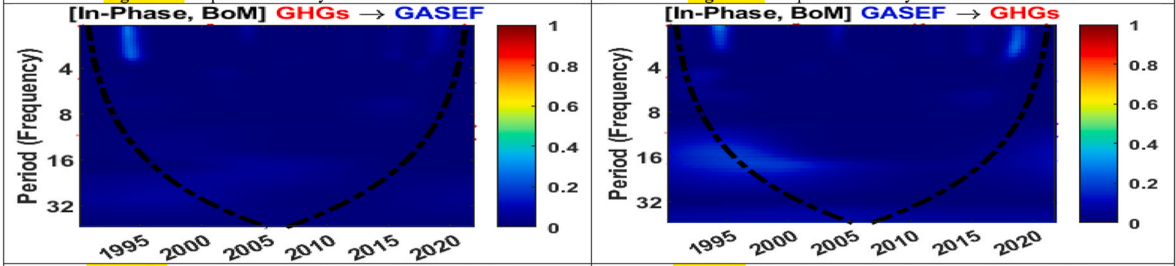


Figure 7e: Out-of-phase Causality from GHGs to COEF

Figure 7f: Out-of-phase Causality from COEF to GHGs

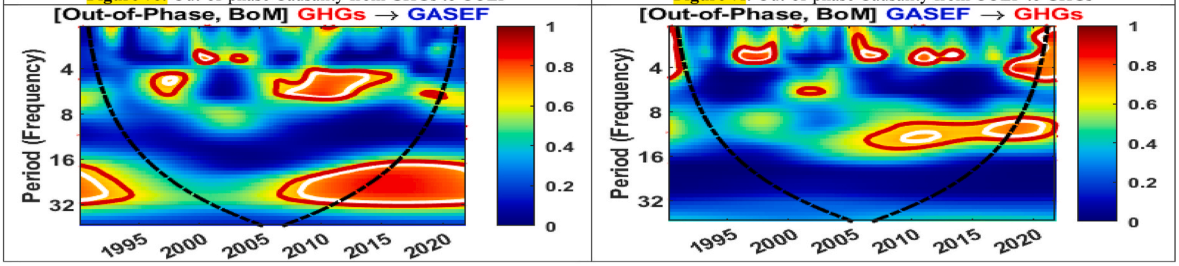


Fig. 7. Causality between GHGs and COEF

arrows facing rightward denote that the series are in-phase (positively correlated) while facing leftward also denotes that the series are out-of-phase (negatively correlated).

Fig. 4a presents the wavelet coherence (WTC) between COEF and GHGs with the leftward arrows (out-of-phase) suggesting a negative correlation. This form of interaction is also mostly indicative of the correlation between GHG and GASEF (see Fig. 4b), and between REC and GHG in the examined periods (see Fig. 4c). Meanwhile, for the interrelationship between INNO and GHG, the correlation is restricted to only the short-term period (see Fig. 4d). Compared with the wavelet correlation inference in Fig. 3, these results are in tandem.

For the wavelet cohesion (WC), Fig. 5a depicts the correlation between COEF and GHGs with evidence of negative correlations dominating across all frequencies and timeframes. Likewise, the results of the WC between GHGs and gas efficiency (see Fig. 5b) showcased proof of a negative correlation between GHGs and gas efficiency. Regarding the connection between GHGs and INNO as shown by Fig. 5c, negative connection between the series is dominant suggesting that the series move in an opposite direction. Fig. 5d showcase the correlation between GHGs and REC with a negative connection between the variables dominating which implies that REC and GHGs move in opposite path.

Moreover, all the above results also agree with the wavelet cohesion graphics in Fig. 5 where a negative correlation is evident between GHG and COEF, GASEF, and REC. Likewise, the correlation between INNO and GHG also shows a mix of negative and positive relationships across the periods.

5.4. Wavelet-based ordinary least squares (WBOLS)

Given the WBOLS result (see Table 5), renewable energy yields an expected outcome. The result reveals that renewable energy mitigates GHG emissions in all the periods. Specifically, a percent increase in the consumption of renewable energy attains ~0.02 percent, ~0.03 percent, and ~0.54 percent decrease in GHG emissions in the short-, medium-, and long-term in Denmark. The significantly high long-term impact of renewable energy on the emission of GHGs as compared to the short- and medium-term is a positive development for Denmark. This evidence is in line with the country's 2030 energy and environment-related commitment i.e., to increase renewable energy contribution in total energy by more than 50 percent and reducing GHG emissions by 70 percent (International Energy Agency, 2022). Moreover, Denmark is famous for renewable energy development and utilization as the current electricity supply in the country constitutes 67 percent renewables with wind and biomass energy contributing 46.8 percent and 11.2 percent respectively (The International Trade Administration, U.S. Department of Commerce, 2022). The (positive) role of renewable energy in environmental sustainability has been largely unanimous for several examined (Bekun et al., 2019; Adebayo and Kirikkaleli, 2021; Usman et al., 2022).

Additionally, still on Table 5, efficient use of natural energy source mitigates GHG emissions in al the periods, and the impact is more pronounced in the long-term. Specifically, a percent increase in the efficiency of natural gas source reduces GHG emissions in the short-, medium-, and long-term by ~0.44 percent, ~0.19 percent, and ~0.83 percent respectively. This is not far from expectation given that natural gas is relatively not as environmentally damaging compared to oil fossil and coal energy sources. Moreover, environmental tolerance would naturally be further advance by improvement in natural gas efficiency. Relating this outcome to the literature, according to Alola and Adebayo (2022) there is significant evidence that innovative utilization of natural gas and other energy sources such as nuclear and oil energy benefits the environment in Finland. However, without the application of technological innovation or environmental-related approach to natural gas, studies also reveals that natural gas source hampers environmental

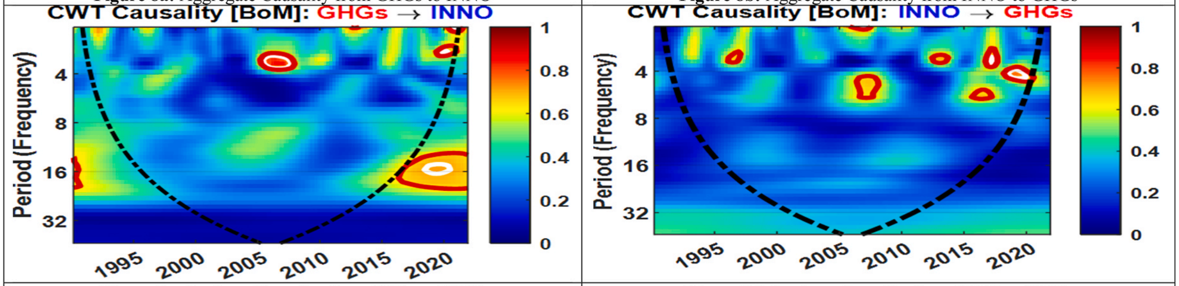


Figure 8a: Aggregate Causality from GHGs to INNO

Figure 8b: Aggregate Causality from INNO to GHGs

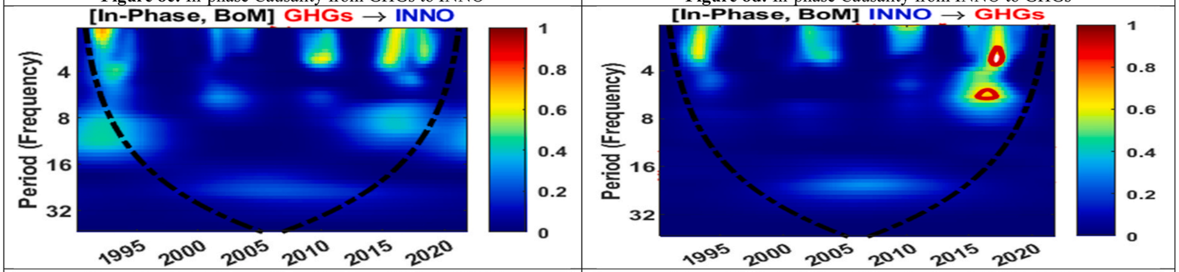


Figure 8c: In-phase Causality from GHGs to INNO

Figure 8d: In-phase Causality from INNO to GHGs

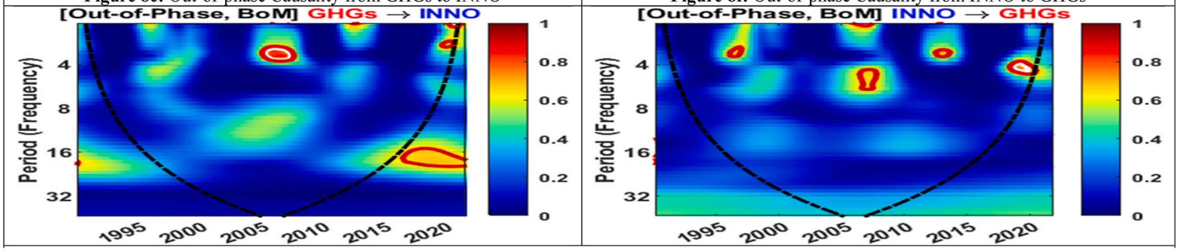


Figure 8e: Out-of-phase Causality from GHGs to INNO

Figure 8f: Out-of-phase Causality from INNO to GHGs

Fig. 8. Causality between GHGs and INNO.

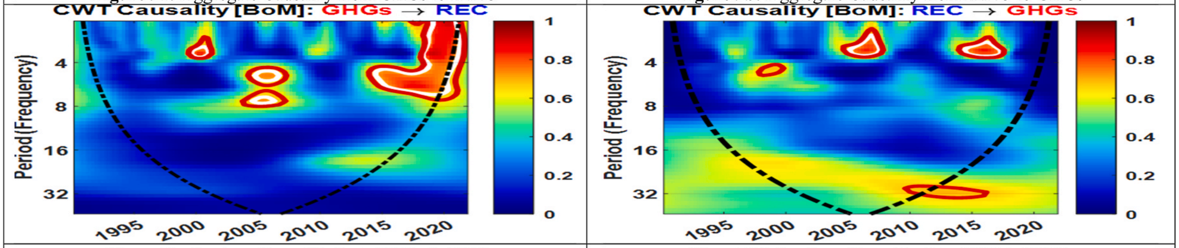


Figure 9a: Aggregate Causality from GHGs to INNO

Figure 9b: Aggregate Causality from INNO to GHGs

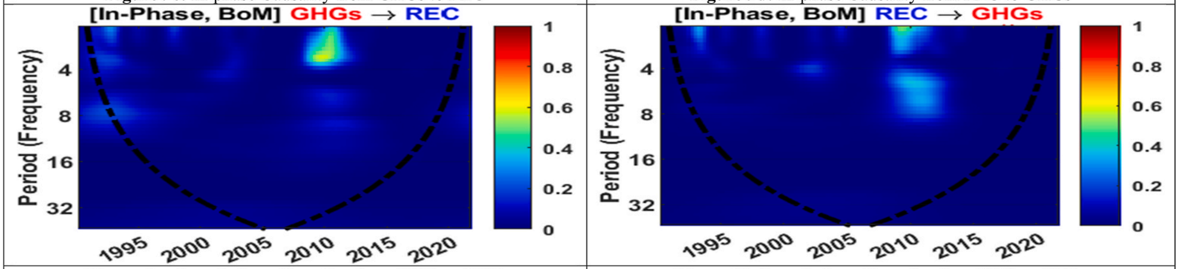


Figure 9c: In-phase Causality from GHGs to REC

Figure 9d: In-phase Causality from REC to GHGs

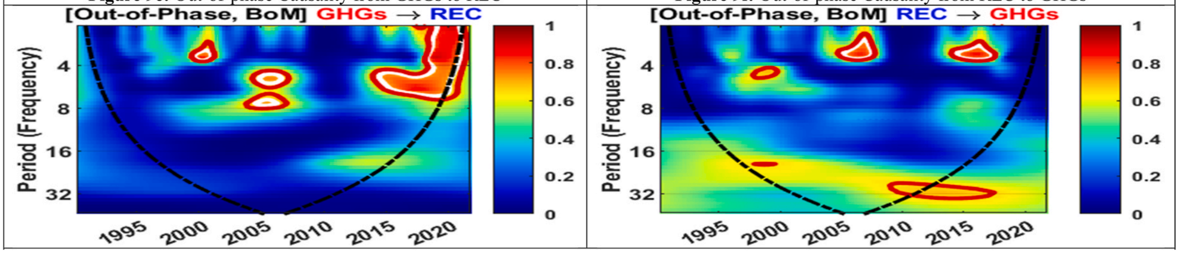


Figure 9e: Out-of-phase Causality from GHGs to REC

Figure 9f: Out-of-phase Causality from REC to GHGs

Fig. 9. Causality between GHGs and REC

quality (Etokakpan et al., 2021; Adebayo and Ullah, 2023).

Regarding coal energy efficiency, the impacts across the periods also reflect the wavelet correlation and the WBOLS evidence. With a negative impact on GHG emissions, an improvement in coal energy efficiency by 1 percent reduces the emission of GHG in the short, medium-, and long-term by ~0.23 percent, ~0.19 percent, and ~0.91 percent respectively. Although the use of coal energy is largely established to be environmentally hazardous, in this case, the result implies that efficient utilization of coal energy source benefits the environment. Besides improving the competitiveness and quality of coal energy sources, coal energy utilization can be deployed in an environmentally efficient manner through the use of energy efficient appliances, thus justifying the environmental desirability of OCOEF in the current study. This evidence clearly contradicts the revelation that Clean coal technology policies in China reduce air quality by 18.82 percent (Zhang et al., 2022).

Lastly, the results also provide more understanding of the role of innovation in environmental sustainability. As indicated in the result, a percent surge or improvement in innovation through environmental-related technologies causes a reduction in GHG emissions in the short-, medium-, and long-term respectively by ~0.56 percent, ~0.10 percent, and ~0.02 percent. This evidence is expectedly desirable considering the current global attention to harnessed resources toward mitigating climate change-related challenges through environmental initiatives. However, this result shows that the desirable effect of INNO on GHG emissions is weakening over time, attesting to the possibility of inadequate adherence to environmental-related standards from innovative approaches that are inspired domestically and internationally. In spite of this observation, studies have largely reported about the positive role of innovation or environmental-related technologies in GHG emissions. For instance, especially in the Nordic and advanced economies, environmental-related technologies and innovations are fast contributing to environmental sustainability (Alola and Adebayo, 2022; Lasisi et al., 2022; Alola and Adebayo, 2023).

5.5. *Wavelet-based causality results*

The research goes beyond assessing the causal relationships between GHGs emissions and its determinants, specifically renewable energy, gas efficiency, coal efficiency, and innovation. To achieve this, we utilized the Time-Frequency Causality (CWT) method introduced by Olayeni (2016). The advantage of employing CWT causality, which falls under the category of time-frequency causality analysis, lies in its ability to illuminate how causal connections evolve over time and across different frequency components. Time-frequency causality analysis enables us to observe the fluctuations of causality across various frequency ranges and time intervals. This stands in contrast to conventional causality analysis, which focuses solely on interactions within a single time domain.

In Figs. 6–9, the vertical and horizontal axes show the frequency and time respectively. Fig. 6 illustrates the causal relationship between coal efficiency (COEF) and GHG emissions (GHGs) in Denmark. The aggregate causality is evident (depicted in Fig. 6a and b), indicating a feedback causality between coal efficiency and GHGs across all frequencies in Denmark. This suggests that both coal efficiency and GHGs can mutually influence each other on an aggregate level. Further examination of the in-phase causality (shown in Fig. 6c and d) between coal efficiency and GHGs reveals no significant causal connection between the two series, indicating the absence of a positive causal association between coal efficiency and GHGs. Moreover, analyzing the out-of-phase causality (displayed in Fig. 6e and f) between coal efficiency and GHGs demonstrates a significant causal connection between the two across all frequencies.

The results showcased a negative bidirectional causal interrelationship between GHGs and coal efficiency. This implies that changes in coal efficiency leads to opposite changes in GHGs. In simpler terms, improvements in coal efficiency leads to a mitigation in GHG emissions, while declines in coal efficiency leads to an upsurge in GHG emissions. This negative bidirectional causal connection highlights that as efforts are directed towards enhancing coal efficiency, potentially via the adoption of more eco-friendly technologies, the resulting mitigation in GHGs contributes to environmental well-being by mitigating the impacts of climate change. Furthermore, this causality aids in achieving ecological goals by launching an equilibrium where gains in one aspect counterbalance negative effects in another aspect. The study of Liu et al. (2023) reported similar result by highlighting feedback causality between coal efficiency and GHGs across all frequencies.

Furthermore, Fig. 7 present the causal interaction between gas efficiency and GHGs emissions. The aggregate causality as showcased in Fig. 7a and b disclosed the emergence of bidirectional causality between gas efficiency and GHGs emissions in Denmark. Interesting results were observed in the results of the In-phase causality (see Fig. 7c and d) as no evidence of causality is observed across all periods and timeframes. This demonstrates that both series i.e., gas efficiency and GHGs emissions can forecast each other. Also, the out-of-phase causality result uncovered that in the short and long-term, gas efficiency has predictive power over GHGs emissions (see Fig. 7e) while in the short and medium-term, GHGs can be forecasted by gas efficiency (see Fig. 7f).

The outcomes of this investigation mark a substantial development in the field of environmental and energy literature. The intricate causal pathway, which has often been ignored in past investigation endeavors, has now been illuminated by the current analysis. The findings underscore the robust causal link between GHGs and gas efficiency. This revelation not only closes a gap in prior investigation but also imparts irreplaceable fresh viewpoints into the GHGs-gas efficiency causal association.

The results also buttress the results from the wavelet-based OLS which highlights the role of gas efficiency in curbing GHGs; thus, improving ecological excellence. This outcome aligns with expectations, considering that the significance of gas efficiency expands across various sectors, optimizing resource use and emission mitigation. As a result, the study's findings reaffirm the vital role of improving gas efficiency as a crucial element in progressing economic effectiveness and ecological conservation.

Higher gas efficiency can synergistically align with efforts to transition towards alternative fuels and renewable energy sources. These advancements in technology and regulatory frameworks give rise to a constructive feedback loop, wherein heightened gas efficiency not only leads to decreased GHGs but also serves as a catalyst, inspiring further innovation aimed at achieving even more pronounced efficiency enhancements. The result obtained from this study is similar to the study of Adebayo and Ullah (2023) who documented that across all frequencies, feedback causality emerged between GHGs emissions and gas efficiency for the case of Sweden.

Furthermore, Fig. 8 presents the causal interaction between innovation and GHGs emissions. The results of the aggregate causality between innovation and GHGs emissions (see Figs. 7a and 8b) showcased that in the short-term, innovation and GHGs emissions can predict each other. Surprisingly, no evidence of a causal connection between innovation and GHGs emissions in the medium and long-term; thus, shifts in both innovation and GHGs emissions do not affect each other. . Fig. 8c showcases no causality across all frequencies from GHGs to INNO while in the short-run, specifically from 2015 to 2020, there is causality from positive causal linkage from INNO to GHGs emissions (see Fig. 8d). This infers that INNO exerts positive predictive power over GHGs. The results of the Out-of-phase causality are shown in Fig. 8e and f respectively. Specifically, from 2005 to 2007 and in the short-run, innovation has a predictive power over GHGSs with negative causality emerging (see Fig. 8e). In addition, in the short-run, particularly, from 1995 to 1997, 2005–2007, and 2019–2020, negative causality emerged from innovation to GHGs (see Fig. 8f).

The concept of out-of-phase feedback causality between GHGs and renewable energy occurs when changes in green energy result in opposite effects on GHGs. This means that an intensification in green energy usage leads to a lessening in GHGs, while a decline in green energy adoption results in an upsurge in GHGs. Within the realm of sustainability and confronting climate change, this concept emphasizes that actions to lessen GHGs can incentivize the uptake of renewable energy sources. Conversely, an augmented dependence on clean energy can play a role in mitigating GHGs.

The outcomes observed in our study closely parallel the findings presented in the research conducted by Alola and Adebayo (2022) concerning the Nordic nations. Similarly, the investigation carried out by Liu et al. (2023) for the United States and Alola and Adebayo (2023) for Finland also documented the presence of feedback causality arising between clean energy adoption and GHG emissions. However, our study distinguishes itself by not only confirming the existence of this feedback causality but also by delineating the precise trajectory it follows. This exclusive characteristic of our investigation holds substantial implications for policy makers as it enables them with priceless intuitions for fashioning effective and comprehensive sustainable development policies.

Fig. 9 presents the causality result at different frequencies and timeframes between GHGs and REC in Denmark. The causality is divided into three sub-categories: aggregate, in-phase and out-of-phase. Fig. 9a and b presents aggregate causality between REC and GHGs. The results from the aggregate causality uncovered bidirectional causality in the short-term; however, in the long-term specifically, we fail to dismiss the null hypothesis of “no causality”. Thus, feedback causality only exists in the short-run. Fig. 9c and d presents the In-phase causality (positive causality) between REC and GHGs emissions in Denmark with interesting results surfacing. We observed no significant evidence substantiating causality between REC and GHGs; thus, we fail to refute the null hypothesis of “no causality” between REC and GHGs. In addition, no proof of positive causality between REC and GHGs.

Fig. 9e and f illustrate the occurrence of out-of-phase causality (negative causality) between GHGs and REC in Denmark. In Fig. 9e, the display of causality from GHGs to REC is evident in the short and medium-term, effectively refuting the null hypothesis of “no causality.” However, over the long term, our findings fail to provide evidence of such causality, thereby retaining the null hypothesis of “no causality.” Conversely, as depicted in Fig. 9f, a causal relationship is observed in the short and medium-term, originating from REC to GHGs, leading to the rejection of the null hypothesis. However, this causal connection from REC to GHGs does not persist in the long term. These observations collectively showcase the existence of feedback causality, albeit at different frequencies, between GHGs and REC.

To sum up, the feedback interrelationship between GHGs and REC demonstrates a circular interconnection, wherein efforts to alleviate GHGs can expedite the embracement of REC on a broader scale. Subsequently, this enhanced acceptance of REC contributes to GHGs mitigation. This interdependence holds crucial consequences for accomplishing SDGs and solving the climate change challenges. The result complies with the opinion of Usman et al. (2022) who highlighted that clean energy sources increasingly substitute fossil fuels in the generation of energy, dropping direct GHGs from combustion. The results are also similar to the results obtained from the studies of Adebayo and Ullah (2023) for Sweden and Liu et al. (2023) for the United States. Similarly, Saidi and Ben Mbarek (2016) found evidence of feedback causality between REC and GHGs.

6. Conclusion and policy recommendation

In the literature, and specifically for the case of Denmark, there is a rare documentation of the determinants of environmental quality from the perspective of environmental-related technologies and energy efficiency. Therefore, the current attempt explored the role of coal energy efficiency, natural gas efficiency, renewable energy use, and innovations in driving Denmark’s environmental sustainability. By using the dataset that covers the period 1990 to 2021, the investigation mainly relied on wavelet-based approaches for the preliminary and main estimations. After deploying the Broock et al. (1996) to establish the non-linearity evidence, evidence of correlation was significantly substantiated through the ordinary wavelet correlation, wavelet coherence, and wavelet cohesion approaches. Meanwhile, a combination of CWT and wavelet-based OLS provided Granger causality and coefficient estimates.

Indicatively, with the CWT approach, there is a significant and strong Granger causality evidence running from COED to GHG emissions in the short-, medium-, and long-term and mostly over the examined period (1990–2021). From natural gas efficiency and renewable energy consumption to GHG emission, evidence of Granger causality is also supported but only observable in selected years periods. In comparison, Granger causality from innovation to GHG emissions is the weakest over the examined period. Meanwhile, the results of the wavelet-based OLS estimation indicate that all the indicators (coal energy efficiency, natural gas efficiency, renewable energy use, and innovations) promote environmental sustainability by mitigating emissions from GHGs. Notably, the environmental desirability of coal energy efficiency is the highest across the periods followed by that of natural gas efficiency.

6.1. Policy recommendations

Acknowledging a potential limitation, it is worth noting that the aforementioned observation may exhibit variations across different sectors, such as household, commercial, and industrial. This variation stems from the fact that energy sector utilization hinges on factors like compatibility, security, and the efficiency of energy sources. Thus, this aspect presents an avenue for exploration in future investigations. Nonetheless, the outcomes of the present study hold significant policy implications. Particularly, we advocate for a shift in the approach to designing and implementing environmental-related technologies and innovations. This shift should be geared towards prioritizing traits like long-term reliability, durability, and adaptability. While this approach might entail higher initial costs, the enduring value of these technologies and innovations is likely to yield cost-effective benefits in the long run. Regarding the utilization of energy sources, especially coal, natural gas, and renewable energy, further strides in energy efficiency can be accomplished by advancing energy standards, promoting energy-efficient appliances, and similar measures. This can be achieved by scaling up energy financing and offering incentives for research and development efforts.

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Credit author statement

Tomiwa Sunday Adebayo: Data; Methodology; Conceptualization; Formal analysis. Andrew Adewale ALOLA: Discussion of result; Writing of the introduction and literature; Corresponding.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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