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How Green Energy Patents, Energy Uncertainty, and Green Energy Quality Moves for the SDG13 in the US? A Wavelet Local Multiple Correlation Analysis

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ABSTRACT

This research aims to investigate the dynamic connectedness between green energy patents, energy uncertainty, energy quality, and climate change while considering the sample from the US economy. The study mainly focuses on an innovative approach entitled Wavelet Local Multiple Correlation (WLMC) analysis which helps to investigate the dynamic relationships between the variables. The study finds the quarterly observations from 1998Q1 to 2021Q4 by applying both the time and frequency-based empirical investigation. The findings of the WLMC reveal that green energy patents, energy uncertainty, and green energy quality significantly restrain carbon emissions in the US. This underlines their importance in meeting climate targets and supporting Sustainable Development Goal 13. Conversely, a significantly positive connection exists between green energy patents, energy uncertainty, and green energy quality, both in the short and long run. Moreover, the concerns related to the changing climate in the form of higher carbon emissions can substantially be controlled when accounted for on individual grounds. The findings reflect a few but vital policy implications for policymakers linked with the US departments, such as energy and climate change specific and generally for the rest of the similar global economies. These insights can guide strategic planning for sustainable energy transitions and effective climate action.

Keywords: Energy Patents, Energy Quality, Energy Uncertainty, Climate Change, WLMC, US
JEL Classifications: O31, P18, Q54

1. INTRODUCTION

Due to the increasing impact of climate change on societies and economies, scholars and ecological activists are showing their substantial focus on the challenges posed by carbon emissions since they are a significant contributor to environmental concerns. In 2015, 186 economies around the globe (including the United States) elicited commitments to achieve net zero carbon emissions while holding global warming below 1.5-2.0°C (Fam and Fam, 2024). Moreover, global communities have also endorsed several other agreements to promote the objective net-zero carbon emissions (Saqib and Shahzad, 2024). However, because of the political leadership change, the US became the first nation to announce its withdrawal (rejoining) from the Paris Agreement in 2017 (2021). Meanwhile, the US has set a target of reducing net greenhouse gas emissions by 50-52% by 2030 (The White House, 2021). At the recent Conference of the Parties (COP28) conference, nations gathered to boost their climate change initiatives. The most crucial decision is to transit away from the fossil fuels responsible for 89% of the carbon emissions from the energy sector (Arora, 2024). Considering such a backdrop as linked with climate change, during 1990-2020, the US economy experienced a peak during 2005 in terms of carbon emissions and then showed a decline. Moreover, by 2020, the emissions were targeted to be 17% below 2005, whereas in 2025, the emission was aimed at 26-28% below 2005 (Fam and Fam, 2024).

Among several other economic and financial factors, green energy innovations are becoming substantially significant in achieving green growth, energy transition, and eco-sustainability. More specifically, the innovative technologies would be beneficial enough to drive down the cost of clean energy while increasing energy efficiency and improving the energy storage and distribution system (Ullah et al., 2023). Investing in renewable energy innovations drives the world economy towards net zero carbon emissions (Ma et al., 2024), driving the technological revolution's imperativeness through research and development (Miremadi et al., 2019). The effectiveness and the extent of the innovative activities in the entire energy sector become vital for tackling the fundamental challenges linked with the sustainable utilization of resources and environmental sustainability (Kijek et al., 2021; Miremadi et al., 2019). Besides, green patents are not only the symbols of dedication towards improving the ecological quality, but retain the characteristics of attaining the sustainable development (Abbas et al., 2024). Therefore, the societal benefits are attributed to green energy usage and efficiency like low cost, better air quality and public health (Saqib, 2022; Saqib and Usman, 2023).

Observing the above-given debate, the US has been standing at a crucial crossroads; while recognizing the urgency to deal with climate change, several strategic environmental objectives have been settled down. In this regard, working to promote and develop renewable energy innovations tends to represent a pivotal strategy for achieving sustainable development goals. For example, a growing adoption of solar technologies for energy generation, heating, and other applications serves as a cornerstone for low-carbon and ecologically friendly landscapes (Adebayo et al., 2024). Moreover, the US Department of Energy (van den Heuvel et al.) brings a substantial amount of investment both in the people and ideas for the development of clean energy innovation, which can boost the economy and combat climate change and energy independence in the region. Among the types of renewable energy power in 2022, it states that wind and hydropower contribute 10.3% and 6% out of 20% of all US electricity. However, solar, Biomass, and geothermal tend to contribute 3.4%, 1.2%, and 0.4%, respectively (Office of Energy Efficiency and Renewable Energy, 2024). Consequently, an upward shift in the clean energy technologies in the entire energy system significantly helps achieve SDGs 7 and 13, creating a sustainable pathway.

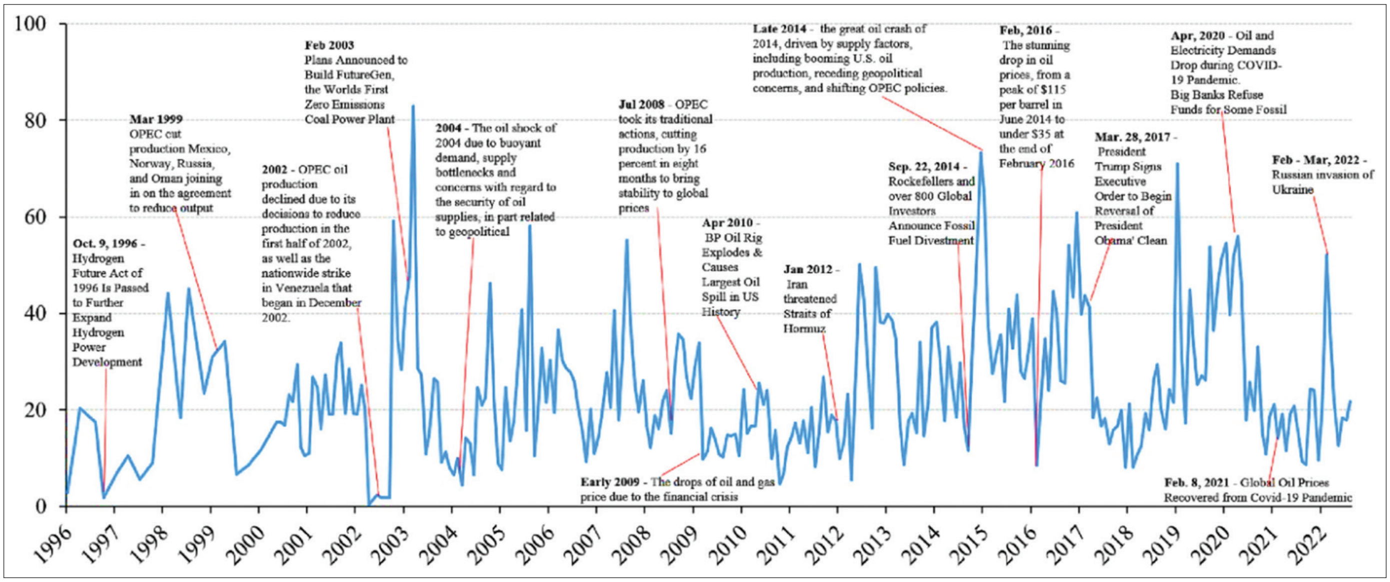
The existing literature confirms that embracing the renewable energy transition and technologies reduces carbon emissions (Kahia et al., 2020). A country typically consumes energy from coal, oil, natural gas, hydroelectricity, and renewable energy. However, sources like fossil fuels are mainly responsible for the higher carbon emissions. In contrast, renewable energy from renewable sources like hydroelectricity and nuclear has been labeled as clean or green with almost zero carbon emissions (Ji and Zhang, 2019). For this reason, one of the critical aspects of the energy transition is the decarbonization of the energy sector, whereby replacing the coal-fired power plants with solar, hydroelectric, and wind power plants would help to improve energy efficiency. Moreover, the transition towards clean energy tends to drive technological advancement, where continuous innovations drive more efficient and cost-effective solutions, hence generating more sustainable solutions by moving away from fossil fuels (Adebayo et al., 2024).

Due to economic and financial vulnerabilities, uncertainty has gained considerable attention from various stakeholders, including economists, researchers, and other macroeconomic policy formulators. In this regard, introducing several uncertainty indexes like economic policy, climate policy, geopolitical risk, and world uncertainty index has motivated the researchers to examine their influence on several economic activities (Dang et al., 2023). Since the Second World War, nine out of ten recessions in the United States have occurred following the shocks in oil prices (Hamilton, 2016). Meanwhile, such energy shocks influence not only the carbon market dynamics (Ren et al., 2022) but also the carbon emissions (Okwanya et al., 2023). However, both positive and negative changes in crude oil prices are associated with carbon emissions. Positive change causes a decline in carbon emissions, and adverse shocks boost it (Okwanya et al., 2023). However, oil prices have not been recognized as a reasonable proxy for energy prices (Cross and Nguyen, 2018); hence, a more comprehensive proxy is needed to determine the energy-related uncertainty. In this regard, Dang et al. (2023) constructed an energy-related uncertainty index using the energy components and economic uncertainty. Meanwhile, observing the US region, it is found that during 1996-2022, there was a considerable fluctuation in the EUI due to several events. For instance, Figure 1 demonstrates that the given index of the energy uncertainty in the US significantly responds to oil price shocks, the outbreak of COVID-19, and the Russian invasion of Ukraine during 2022. However, whether the energy-related uncertainty is relevant to a change in the carbon emission for the US is still a questionable debate in the available studies to date.

This research makes several distinctive contributions to the literature on green energy and climate change. First, unlike prior studies that have primarily examined the relationship between green innovations and climate change using conventional econometric or bivariate wavelet methods (Amara and Qiao, 2023; Caglar et al., 2024; Chen et al., 2024), this study is the first to apply the wavelet local multiple correlations (WLMC) technique to simultaneously explore the short-, medium-, and long-term connectedness among green energy patents, green energy quality, energy uncertainty, and carbon neutrality within the context of the United States. By extending the analysis beyond bivariate frameworks, this approach overcomes a major methodological limitation in existing literature, as WLMC (Polanco-Martínez et al., 2020) captures the dynamic interactions among multiple variables over time, revealing volatility and co-movements that standard methods overlook.

Second, the study's focus on the United States is timely and critical. As one of the world's largest energy consumers, the U.S. faces significant environmental challenges, including carbon emissions, resource depletion, and pollution (Ullah et al., 2023; Zafar et al., 2019). Notably, between 2020 and 2022, U.S. carbon emissions increased by 5.7% due to post-pandemic economic rebound effects (U. S. Environmental Protection Agency, 2024).

Figure 1: Monthly Trends in Energy Uncertainty in the US during 1996-2022



Source: Dang et al. (2023)

This underscores the urgent need to accelerate the green energy transition. By assessing how green energy patents and quality interact with energy uncertainty in driving decarbonization, the study provides empirical evidence for sustainable pathways that can reduce dependence on fossil fuels and align with both SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

Third, by bridging methodological innovation with policy relevance, this study offers actionable recommendations for fostering green technology development, improving energy quality, and mitigating the risks associated with energy market volatility. In doing so, it not only advances the methodological frontier in wavelet-based energy research but also opens a previously underexplored policy space linking green innovation, energy quality, and climate action in the U.S. context.

The remaining paper has been organized with the help of the following divisions: Section 2 debates about the literature. Sections 3 and 4 explain the research methods, empirical outcomes, and discussion. The conclusion and relevant policy suggestions have been presented in Section 5.

2. LITERATURE REVIEW

2.1. Energy Innovations and Climate Change

Achieving sustainable development goals by reducing climate change demands unprecedented changes in the energy system while reducing the fuels contribution of fossil fuels. Moreover, promoting a low-carbon economy determines a substantial need for innovation in the energy markets, for which both researchers and policymakers show keen interest. For instance, Chen et al. (2023) explore the nexus between SDG7 and 13 while adding the role of green energy patents and the transition towards the sustainability agenda of the United Nations. Using the EU economies' sample, the study determines that renewable energy patents significantly improve sustainability practices. Yu et al. (2023) consider the top-ecologically polluted economies and examine the role of energy innovations and efficiency dynamics in combating climate change. The findings through MMR estimation confirm that renewable energy innovations and efficiency factors improve the economies' sustainability practices. Ozkan et al. (2024) investigate the Chinese economy by considering wind energy innovations in determining carbon emissions. In this direction, fresh quantile-based estimations along with the Kernel-based regularized least square have been applied, for which the findings reveal that innovations in wind energy significantly lessen carbon emissions. Cao et al. (2023) investigate whether the technological innovations of clean energy are efficient enough to reduce the Chinese provinces' carbon emissions. The results reveal a significant reduction in carbon emissions by such innovations; however, such an effect is not substantial in the hydropower technological innovations. Abbas et al. (2024) focus on the Chinese region to examine the impact of energy patents, energy utilization, and research and development toward carbon neutrality while taking data from 18 cities. By employing Q-ARDL and CS-ARDL during the period of 2003-2020, the findings reveal that increasing the share of the resources towards the green technological innovations and research and development substantially improves environmental sustainability. Besides, Huang et al. (2021) focus on the energy conservation patents carried out by enterprises, higher education institutions, and scientific institutions while exploring their role in carbon emissions per capita. Overall, the results indicate that energy patents have no significant impact on carbon emissions, whereas patents from scientific institutions and enterprises significantly curb such emissions. Moreover, educational institutions tend to reduce carbon emissions by cooperating with scientific institutions and enterprises.

2.2. Energy Quality and Climate Change

Existing literature supports the argument that augmentation of the green energy transition and related technologies curb carbon emissions (Chen et al., 2023; Ozturk and Acaravci, 2013; Shahbaz et al., 2016). In this regard, the green quality of the energy mix

(GEQ) has been regarded as an innovative measure of the energy transition by considering the energy consumption from different sources. The data from the 36 OECD economies from 1970 to 2021, along with the role of institutional quality, income per capita, technology, and green energy mix, are among the key explanatory variables used to determine the trends in carbon emissions. The empirical findings indicate a negative relationship between green energy quality and carbon emissions in the long run when examined through system GMM, Feasible GLS, and panel-corrected standard error estimation strategies. Adebayo et al. (2024) consider the sample from the G7 economies while analyzing the role of energy transition (i.e., green energy quality) towards the carbon emissions through quantile regression and quantile-on-quantile regression. The study shows that energy transition promotes ecological quality by reducing carbon emissions in the G7 economies. Dong et al. (2022) explore the nexus between carbon emission efficiency and energy transition for the 32 developed economies by applying the super-efficiency slacks-based measure (SE-SBM) model. The results indicate that renewable energy development supports carbon emission efficiency; however, such a positive effect from clean energy development decreases with the energy consumption intensity. Wiredu et al. (2023) also highlight the significance of developing renewable energy sources to deal with ecological dilapidation. Besides, Chen et al. (2023) infer that promoting the energy transition is a sustainable solution for the European Union economies.

2.3. Energy Uncertainty and Climate Change

The resilience of the economies towards the shocks, specifically from the oil prices and energy, has been considered one of the most critical factors in dampening economic activities (van de Ven and Fouquet, 2017), economic development (Martin, 2012), and creating the spillover mechanism (Dang et al., 2023). Although the concept of uncertainty has widely been recognized in the available literature in terms of economic policy (Su et al., 2023), climate policy (Guesmi et al., 2023), and world uncertainty index (Guesmi et al., 2023), the focus on the uncertainty related to the energy and its linkage with the climate change has been observed with the scant literature. However, past studies majorly consider the oil price shocks as critical measures to reflect the trends in energy-related uncertainty both in developed and developing economies. For instance, Okwanya et al. (2023) consider the sample from the 30 African economies from 1987 to 2019 while exploring the role of oil price changes on carbon emissions. By applying the non-linear autoregressive distributive lag, the study findings reveal that an asymmetric association exists between oil price and CO_2 emissions. Moreover, in the long run, a positive change in the oil price is associated with the carbon emissions among the oil-importing economies. Conversely, CO_2 emissions respond more to a negative change in the oil prices among the oil-exporting economies. Zhang et al. (2014) there exists uncertainty about the company's emission reduction behavior because of the promotional impact of the rising oil prices. Besides, Barrales-Ruiz and Neudörfer (2024) produced exogenous shocks to the global economic activity and oil supply, which were subsequently utilized to compute the impulse responses for both the carbon emission and oil prices. Finally, the study investigates the shock-specific effect through a dynamic multiplier. The findings reveal that not all the oil price shocks are leading towards a reduction in carbon emissions.

3. RESEARCH METHODS

3.1. Data and Variables

In achieving the environmental sustainability objective under the present era, the mitigation of carbon emissions is the primary objective of the economies. In this connection, the present research aims to investigate the dynamic and casual association of green energy patents, green energy quality, and energy uncertainty with carbon emissions in the US, using the quarterly observations spanning from 1998Q1 to 2021Q4. The carbon emissions have been regarded as the primary outcome variable, followed by the green energy patents, energy uncertainty, and green energy quality as the main explanatory variables of the models. The description of the variables in terms of measurement and data sources has been provided in Table 1, whereas Table 2 covers the descriptive statistics. It reflects that GEP reflects the highest mean and standard deviation, followed by GEQ and EUI. Moreover, the skewness for CO_2 and GEP is negative, whereas EUI and GEQ are positive. Finally, the JB distribution reflects that all the variables confirm the presence of the non-normal distribution. The graphical presentations of the variables considering the box plots and p-norm distributions have been presented in Figure 2.

3.2. Estimation Method

As stated earlier, the present study utilizes the WLMC technique of Polanco-Martínez et al. (2020) using the software package in R. The consideration of multiple regression analysis provides some foundations for the WLMC. Consequently, the idea of Wavelet local multiple regression (WLMR) has been employed, recommended by Fernandez-Macho (2019). The general Equation for the WLMR has been presented as follows:

$$S_W = \sum_t \theta(t-s)\left[f_w(R_{-i,t}) - x_{i,t}\right]^2 \quad \text{Equation 1}$$

Where in Equation 1, the term fs(X-i) reflects {X\xi} which aims to determine the local function of S and θ(x). It also shows a predetermined moving function under average format, based upon the internals between Xs and Xt observations. In this regard, the local coefficients of the determination as supplied by s are shown in the following Equation 2:

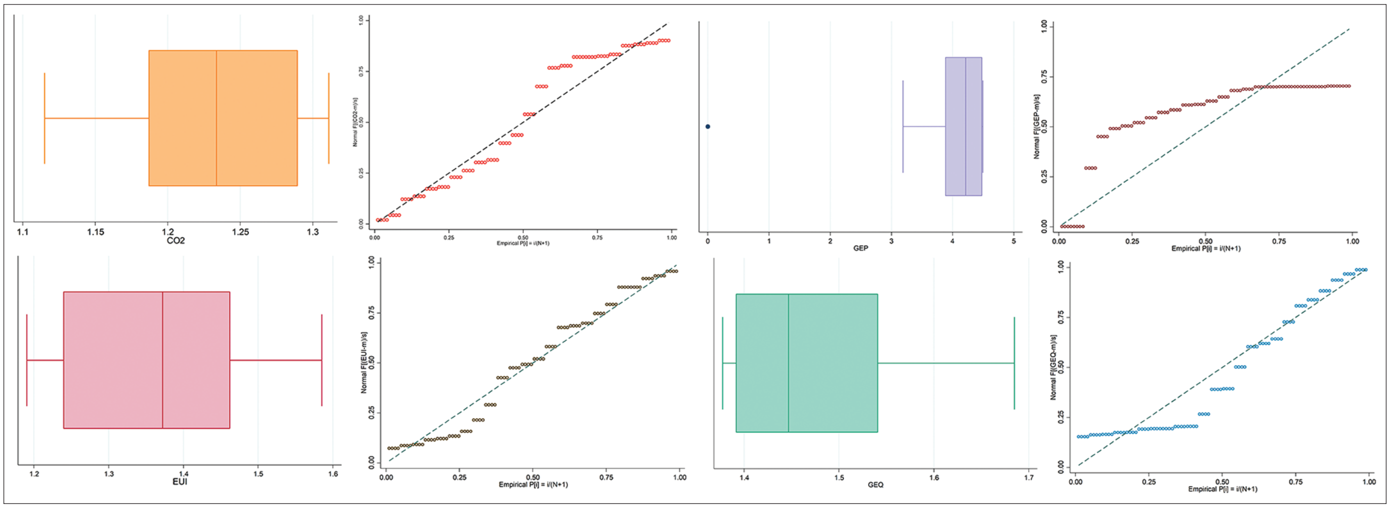
$$R_r^2 = 1 - \frac{R_W SS_s}{TWSS_s}, = s = 1\ldots T \quad \text{Equation 2}$$

In Equation 2, the residual and total weighted sum of squared has been presented through RwSSs and TWSSs, respectively. Now let the assume the W_{ij} = (w1jt..., wnjt) reflects the coefficients of the wavelet for scale entitled j collected by applying the Maximal Overlap Discrete Wavelet Transform function to the

Table 1: Description of the variables

Variable title	Measurement	Data source
Green energy patents	No. of patents during a year	IRENA.org
Carbon emissions	Metric tons per capita	WDI
Energy uncertainty index	Index	Policy uncertantiy
Green quality of the energy mix	Index	(Lau et al., 2023)

Figure 2: Box-plots and P-norm Distribution of the Variables



Source: Authors

Table 2: Descriptive statistics

Variables	Mean	Std. Dev.	Min	Max	Skew.	Kurt.	JB	Prob
CO_2	1.235	0.058	1.115	1.311	−0.323	1.89	6.612**	0.037
GEP	3.844	1.209	0	4.491	−2.664	8.742	245.4***	0.000
EUI	1.370	0.124	1.191	1.585	0.074	1.755	6.286**	0.043
GEQ	1.472	0.0927	1.377	1.684	0.750	2.383	10.53***	0.0052

CO_2: Carbon emissions, GEP: Green energy patents, EUI: Energy uncertainty index, GEQ: Green energy quality

stated variables xi∈X, i=1.,n. Considering the suggestions of the Fernández-Macho (2018) for each wavelet scale j, the ϕX, s(λj) or WLMC coefficients has been computed as regression determination coefficient for the linear combination, where the W_{ij}, i=1..., n. However, these coefficients maximize the determination.

$$\hat{\varphi} X_r(\lambda_j) = \sqrt{R^2}_{js},\ j = 1,\ldots..j\ \ s = 1,\ldots..T \quad \text{Equation 3}$$

Moreover, coefficients of $\hat{z}_i$ in aqi's Multiple local regression (MLR) on other system indicators are similar to the squared correlation between the MLR and fitted values, respectively. In this regard, the WLMC estimator can be reflected as follows:

$$\hat{\varphi} X_s(\lambda_j) = \text{corr}(\vartheta((t-r)\ )^{1/2} W_{ij}, \sqrt{Z_r^2}, \vartheta(t-s))^{1/2} W_{ij}\ \ s = 1,\ldots T \quad \text{Equation 4}$$

In Equation 4 above, the Wij reflects its selection on the ground that on the regressors of the model {Wkj, k≠i}, its local regression tailors the related determination coefficients, where Wij has demonstrated the resulted vector of the fitted values.

4. RESULTS AND DISCUSSION

4.1. Initial Estimations

The study observes the correlation between CO_2, GEP, EUI, and GEQ in the US economy, as shown in Table 3. The findings show a significant negative correlation between GEP, EUI, and GEQ with CO_2. Conversely, the linkage between GEP, EUI, and GEQ is positively significant, reflecting the fact that an increase in the value of the EUI and GEQ escorts an increase in the GEP.

Table 3: Correlation matrix

Variables	CO_2	GEP	EUI	GEQ
CO_2	1	−0.6590***	−0.3371***	−0.9228***
GEP	−0.6593***	1	0.2255**	0.5585***
EUI	−0.3371***	0.2255**	1	0.3027***
GEQ	−0.9228***	0.5585***	0.3027***	1

CO_2: Carbon emissions, GEP: Green energy patents, EUI: Energy uncertainty index, GEQ: Green energy quality

Table 4: BDS test results

Variables	CO_2	GEP	EUI	GEQ
M2	39.3551***	15.3456***	31.5048***	24.6394***
M3	41.3738***	14.7186***	30.4212***	25.2832***
M4	43.9537***	14.6543***	29.9338***	26.1570***
M5	47.8559***	15.0149***	30.0797***	27.6763***
M6	53.1941***	15.7519***	31.6501***	29.8351***

CO_2: Carbon emissions, GEP: Green energy patents, EUI: Energy uncertainty index, GEQ: Green energy quality

Correspondingly, the positive connection exists between EUI, GEP, and GEQ. Lastly, the correlation between GEQ and GEP. In the next step, this research applies the non-linearity test suggested by Broock and Dechert (1996), entitled the BDS test of non-linear trends of the data. The findings given in Table 4 confirm that variables entitled CO_2, GEP, Eui, and GEQ reflect non-normal distribution, which is consistent with the JB test outcomes under Table 2. For this reason, the implication of some linear approaches for empirical data estimation seems incorrect.

4.2. Bivariate Relationships

Considering the bivariate case for the correlation between the selected variables of interest in frequency and the time domains, the Wavelet local multiple correlation analysis (WLCM) has been utilized. The given approach has been regarded as a comprehensive technique for providing a substantial understanding of short, medium, and long-term correlation between the given variables. Figure 3a reflects the outcomes for the pairs between GEP and EUI. The figure shows a mixed correlation between GEP and EUI with positive and negative periods, indicating a fluctuating association. More specifically, it shows a significantly negative and weak correlation between GEP and EUI during 1998Q1-2002Q2 and between 2010Q1-2012Q4, where CV is less than -0.50. However, the given period between 2015Q1 and 2021Q4 reflects the presence of a significantly positive and strong correlation between both (i.e., CV > 0.50) in the long run. The findings dominate the net effect of the significantly positive but low correlation between GEP and EUI, similar to Spearman correlation outcomes (CV = 0.225). The given findings reveal that the initial period of the green energy patents reflects the entry phase of such technologies in the US market, where such innovations tend to create some uncertainties in the market regarding regulations and consumers' adjustment to such new products in the US energy system. However, over the long term, green energy patents have become widely adopted, hence causing a reduction in initial uncertainties. Considering the nexus between energy price uncertainty and green innovations, Hu et al. (2023) claim that the higher prices of energy from fossil fuels tend to make it more expensive, which subsequently derives positive pressure toward green technology innovations, leading to an increase in the green patenting activities. Such a nexus is not only attributed to environmental control but also to energy efficiency.

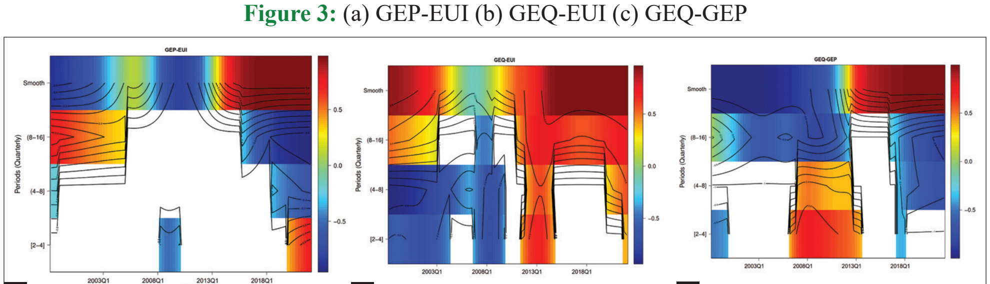
In addition, Figure 3b covers the bivariate case for the green energy quality and energy uncertainty. The findings are similar to the spearman correlation, where most of the smooth area reflects the statistically significant and positive correlation between both. More specifically, it shows that the correlation is statistically significant and positive for the recorded 1998Q1 to 2004Q4 and between 2010Q1-2021Q4, respectively. However, for a period scale of 2-4 and 4-8 quarterly, the correlation has been observed as statistically negative and significant; nevertheless, the consideration of the smooth record reveals that the nexus between GEQ-EUI is positively significant in the long run. The green quality of the energy mix reflects the utilization of green energy in a range of economic activities, which also reflects the energy transition (Lau et al., 2023). However, with the changing market dynamics, technological evolution, policy and regulatory changes, and social and environmental factors, the GEQ reflects an upward shift in energy-related uncertainty. There is clear evidence for a significantly positive correlation in Figure 3c between GEQ and GEP in the long run, starting from 2013Q1 to 2021Q4, with outcomes similar to what has been presented under the Spearman correlation matrix (Table 3; CV = 0.5585). The WLMC plot reflects that the GEQ-GEP correlation is above 0.50 in all the considered periods between 2013Q1 and 2021Q4. Moreover, the second significant outcome reveals that although the correlation in the long run is significantly positive, it fluctuates over time, reflecting that the intensity of the connectedness is inconsistent among them. For instance, the correlation between GEQ-GEP was statistically significant and negatively weak between 1998Q1 and 2012Q4. The green quality of the energy mix reflects the transition towards green Energy (Lau et al., 2023); therefore, it increasingly prioritizes sustainability practices with low reliance on fossil fuel energy, hence a growing market demand for green energy innovations. Additionally, an upward shift in the green quality of the energy mix or energy transition tends to create several economic incentives for both the business groups and investors towards ecological innovations and related technologies. Moreover, sustainable economic development tends to call for the utilization of green energy sources; therefore, a rise in the green quality of the energy mix is assumed to emit fewer polluting gases, which also derives from technological advancements in the entire energy system.

4.3. Three Variate Relationship

The three-variate instances for the given variables entitled GEP, EUI, and GEP have been presented under Figure 4a. The given approach of WLMC selects a variable automatically rather than using a predetermined one (i.e., parameter ymaxr = Null) so that for each of the wavelet scales, there exists optimize multiple correlations. This decision was made because some variables are expected to be correlated with each other; nevertheless, it remains unclear how these indicators tend to influence each other over time and at different frequencies. The three-variate case for the WLMC has been presented under Figure 4a, which reflects a considerable positive and significant correlation between the variables in all the period lengths, ranging from 0.80 to above 0.91, respectively.

The WLMC tends to reflect the significant connection between the variables of interest like GEQ and GEP; it is substantial to explain that the correlation between the other variables has also been considered (i.e., EUI-GEP, EUI, and GEQ). More specifically, the dominant indicator, which tends to explain the other variables across time intervals and periods, has been highlighted by the WLMC, which is statistically significant, as shown in Figure 4b.

Figure 3: (a) GEP-EUI (b) GEQ-EUI (c) GEQ-GEP



For example, under Figure 4b, the triplet GEP, EUI, GEQ, and GEQ have been regarded as the leading variable.

4.4. The Bi-variate Case for GEQ, GEP, and EUI vs. CO_2

The bivariate case using the WLMC approach while adding the CO_2 has been presented under Figure 5a for the GEP-CO_2. The findings reveal that from 1998Q1 to 2010Q4, the correlation between GEP-CO_2 was positively significant and above 0.50. However, the correlation between GEP- CO_2 from 2012Q1 to 2021Q4 has been statistically negative and significant. The given findings reveal that GEP negatively derives the carbon emissions in the US, hence causing an improvement in environmental sustainability. The Department of Energy reveals that the US substantially invests in the ideas and people to promote cost-effective and emerging technologies for boosting the economy while combating climate change. The given findings are consistent with He et al. (2021), who claim that renewable energy innovation tends to improve the total carbon performance index, reflectingChina'ss carbon emission efficiency. Similarly, Álvarez-Herránz and Cantos (2017) consider the sample from the OECD economies and infer that energy innovation positively contributes to reducing greenhouse gas emissions. Hence, advancement in energy technologies seems to play a substantial role in environmental quality.

The findings in Figure 5b reveal the nexus between EUI-CO_2 in the time frames entitled short, medium, and long run. The WLMC reveals a considerable negative correlation between EUI-CO_2, specifically between 1998Q1-2006Q4 and 2014Q1-2021Q4. Predominantly, the blue part in the smooth region reflects the significantly negative correlation between EUI- CO_2, confirming the findings under Spearman correlation. This would reflect that a higher level of energy-related uncertainty has been reflected in low carbon emissions. In this regard, several associated channels can be highlighted. For instance, during higher levels of energy uncertainty, economic slowdowns, and reduced industrial activities have been experienced, leading to a lower level of fossil fuel consumption and subsequent low carbon emissions.

Figure 5c covers the nexus between GEQ- CO_2 through WLMC. As per the given outcomes under short-term entitled as 2-4, medium-term entitled as 4-8, and long-term entitled as 8-16, the connection between green energy quality and carbon emission in the US has been observed as significantly negative. This means that the GEQ negatively and significantly determines the carbon emissions during the US study period. More specifically, the given findings reflect that most of the time duration demonstrates a a significantly negative connection between GEQ and CO_2, confirming favorable environmental outcomes. The same has been reported under the Spearman correlation matrix, where the CV is −0.9228, which is significant at 1%. As observed in the present research, the GEQ promotes environmental sustainability through low carbon emissions, consistent with Lau et al. (2023) for the OECD economies. In contrast, Adebayo et al. (2024) affirm that GEQ reduces greenhouse gas emissions in G7 economies.

4.5. The 3-Variate Cases for GEP, EUI, and GEQ vs. CO_2

The 3-variate cases for the variables entitled GEP, EUI, and GEQ towards CO_2 have been covered under Figure 6a-c, where the carbon emissions have been considered the primary outcome variable. The key objective of examining such tri-variate wavelet correlation is to explore under which frequencies and variables are mostly connected with the carbon emissions in the US. The heatmap of WLMC for the GEQ and EUI Vs. CO_2 has been presented in Figure 6a. It reflects a significantly positive correlation between GEQ and EUI Vs. Carbon emissions are more frequent, as depicted in the high-color map.

Figure 4: (a and b) GEP, EUI, GEQ

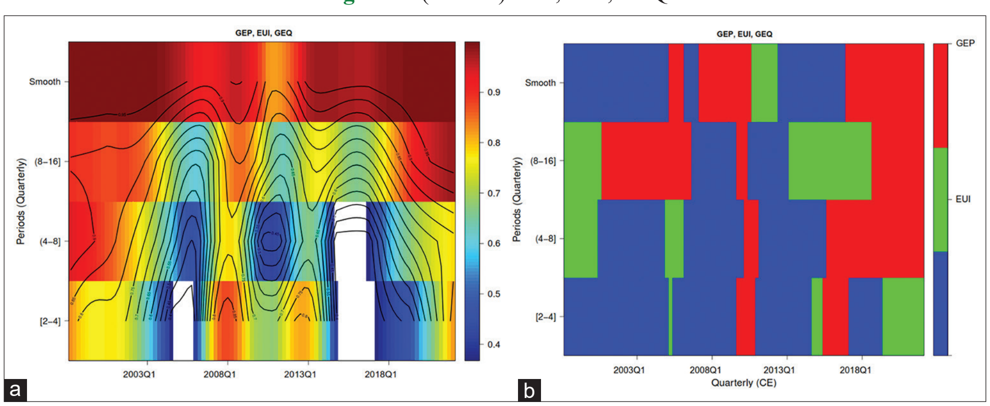


Figure 5: (a) GEP vs. CO_2 (b) EUI-CO_2 (c) GEQ-CO_2

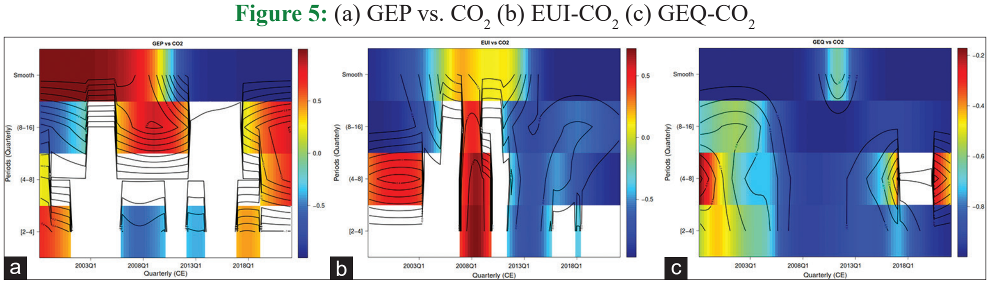
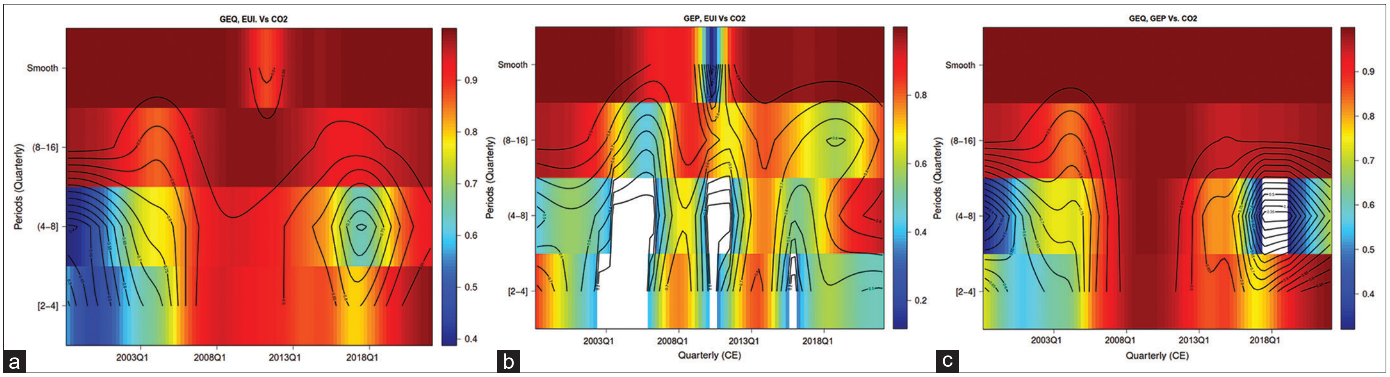


Figure 6: (a) GEQ and EUI Vs. CO_2 (b) GEP and EUI vs. CO_2 (c) GEQ, GEP vs. CO_2



Similarly, the effect of GEP and EUI on CO_2 (Figure 6b) has been positive, ranging from 2 to 16 frequency distributions. The given findings reveal that under a multivariate correlation, comparable findings exist, which are not consistent when analyzed independently, specifically from the context of CO_2. More specifically, the bivariate WLMC heatmap reflects that the individual effect of the GEP, EUI, and GEQ towards carbon emission is significantly negative, reflecting an improvement in environmental quality. However, the same effect has not been reflected in the multivariate scenario. Besides, the effect of the GEQ and GEP towards CO_2 (Figure 6c) has also been observed as positively significant, inferring that their combined effect is not playing its role as a panacea towards environmental degradation in the case of the US.

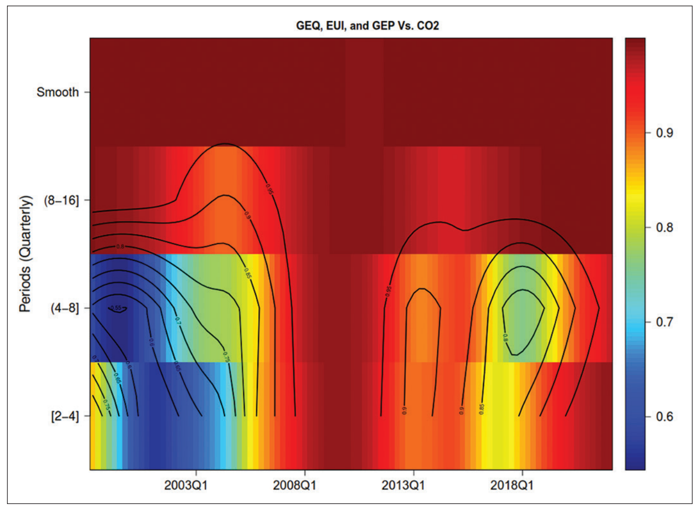
4.6. The Four-variate Case

Finally, the four-variate case for the GEQ, EUI, and GEP Vs CO_2 has been presented using Figure 7. The findings reconfirm the significance of the GEQ, EUI, and GEP towards CO_2, hence consistent outcomes regarding bivariate Vs multivariate investigation. It reflects a long-term connection between the given variables; nevertheless, the observed correlation is weak under low frequencies. However, the long-term trends confirm the presence of a significantly positive connection (CV > 0.90) between the given variables.

4.7. Discussion of the Findings

The empirical outcomes reveal that GEQ significantly contributes towards controlling the ecological damages in the form of higher carbon emissions in the US across different time domains. More specifically, it reflects that the sustainability paradigm in the US needs to be protected by a greener energy mix as such energy transition is attributed to low pollution because of minimal hydrocarbon contents (Lau et al., 2023). In this regard, deploying green energy quality among different economic sectors would help achieve sustainable environmental quality. Additionally, encouraging the green energy mix through subsidizing and facilitating green energy production would be of substantial attention to policymakers and ecological activists. No doubt, energy fuels the economy, and the US has enjoyed remarkable economic growth based upon the green energy mix as it serves the dual interests of environmental protection and green economic progression. The implementation of the green quality of the energy mix would also be reflected in the form of achieving SDG7 (i.e., affordable and clean energy) with SDG13(i.e., climate change). Therefore, the complementary green energy mix in the economy would productively impact the nation's capability to secure the ecosystem from increasing ecological threats.

Figure 7: GEQ, EUI, and GEP vs. CO_2



Additionally, the GEP reflects their significantly negative connection with the CO_2 emissions across different time frequencies. According to such findings, the US CO_2 emissions may be reduced by increasing the share of clean and green innovations, specifically in the energy sector, for which support through research and development and climate finance would be highly recommended. The given nexus between GEP and CO_2 further implies that technological progression is a powerful instrument for sustainable economic development but inducing the In this regard, the US has been witnessing with focus on adopting green energy sources, which accounts for all 24% of electricity production in 2022, comparatively to 10% proportion during 2010 (Adebayo et al., 2024). Meanwhile, it also has discounted the utilization of coal-fired plants, which account for a significant source of greenhouse gas emissions (Adebayo et al., 2024). The presented findings of Chen et al. (2023) and Kamran et al. (2023) confirm that green energy patents help achieve the sustainability agenda of the European Union member states and G7 economies. Besides, IRENA confirms that clean energy technologies are the most effective approach in achieving over 90% decline in the value of carbon emissions.

5. CONCLUSION AND POLICY IMPLICATIONS

With an increasing ecological threat from traditional energy utilization, it has become evident that fossil energy should be transformed into more efficient and green sources. In this regard, a clean and ecological environment can substantially aid the achievement of sustainable development goals, specifically those for the 7th and 13th. To revitalize both the sociétés and the economies, economies like the US must accelerate their efforts and pace towards searching for better solutions for the loss of biodiversity, changing climate, and environmental pollution. Considering the given thoughts, this research examines the dynamic relationship between the green energy quality, green energy patents, energy-related uncertainty, and carbon emissions for the United States from 1998Q1 to 2021Q4, for which the implications of both multivariate and bivariate connection between the given variables has been regarded as a significant contribution. More specifically, compared to the conventional wavelet approaches, the present study applies the WLMC, reflecting its first contribution in the available literature for examining the influence of green energy quality, patents, and energy-related uncertainty on carbon emissions. The study findings conclude that green energy quality, patents, energy-related uncertainty, and carbon emissions have a significant negative connection. The outcomes indicate that an energy transition towards clean and green sources is substantially required to address the SDGs, specifically regarding affordable and clean energy and climate change. Moreover, a higher level of green energy patents and related innovations reflects a significant reduction in the environmental damages for the US. In contrast, energy-related uncertainty determines a significantly low correlation with carbon emissions. Besides, the multivariate findings reflect the long-term connection between the stated variables; nevertheless, a weak correlation exists under lower frequencies. Based on the findings mentioned above, the policy implications are as follows.

Firstly, on overall empirical grounds, this research serves its role as a comprehensive roadmap for a range of stakeholders, including the key officials at the US Department of Energy, the Environmental Protection Agency, and the Department of Climate and Environment, while offering valuable insight regarding the management and mitigation of the carbon emissions. For this purpose, the suggested strategies include formulating policies that would be further beneficial for adopting green energy eco-friendly innovations. The relevant authorities are recommended to promote energy transitions regarding sustainable production and consumption patterns, carbon capture and storage, and global collaboration on climate action. In this regard, encouraging the global economies to collaborate by sharing resources and technologies seems to be the best practice in tackling climate change as a team. Moreover, another possible solution is to stimulate community awareness towards green energy utilization while moving away from fossil energy sources.

Secondly, under short-, medium-, and long-term frequencies, the findings reveal that GEQ significantly reduces the carbon emissions in the US, reflecting the significance of all three-time domains while developing policies related to the promotion of green energy and climate change. The US government must establish targeted measures since the proposed green energy transition and related projects frequently pose substantial financial risks. Meanwhile, the implications of an intelligent energy management system would also be beneficial enough for allocating energy on a real-time demand-supply mechanism while reducing energy requirements and carbon footprints. Another possible solution to promote green energy in the US economy is to exclude firms and business enterprises from the taxes for installing, purchasing, and selling machinery and equipment. Such an act will also promote green economic growth, with the outcome being low ecological damage.

Lastly, the present research observes limitations that should be addressed in future studies. For instance, this work is limited to the geographical location of the US, so the researchers can consider both the time series and panel data estimations for some different regions to compare the findings. Moreover, this research only considers the role of green energy quality, green energy patents, and energy uncertainty towards carbon emissions while neglecting other variables entitled energy efficiency, clean energy consumption, environmental taxes, digital financial inclusion, and green growth towards some other climate change measures like ecological footprints and resource efficiency. Besides, future studies can also consider the quantile Vector Autoregressive (QVAR) approach and other possible estimation techniques for examining the nexus between the proposed variables.

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