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Technological innovation and energy transition in G7 economies: Country-specific evidence from quantile and wavelet approaches

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HIGHLIGHTS

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ABSTRACT

The aim of this study is to examine the impact of technological innovation on renewable energy consumption in the G7 countries. Annual data covering the period 1985-2021 are used, and the analysis focuses on the G7 countries, including Canada, Germany, France, Italy, Japan, the United Kingdom, and the United States. Renewable energy consumption is considered the dependent variable, while technological innovation is represented by patent applications. In order to analyse the relationship between the variables across different distribution levels and time scales more comprehensively, the Modified Cross Quantile Regression (MCQR), Quantile-on-Quantile Kernel Regularized Least Squares (QQKRLS), and Wavelet Quantile Granger Causality (WQGC) methods are employed. The empirical findings reveal the existence of a nonlinear and quantile-dependent relationship between technological innovation and renewable energy consumption. The results also indicate that the impact of technological innovation on renewable energy consumption exhibits a heterogeneous structure across countries and varies across different quantiles. In addition, the findings identify the presence of time- and quantile-dependent causal relationships running from technological innovation to renewable energy consumption. The findings of this study provide important implications for policymakers, energy sector stakeholders, and researchers by improving the understanding of the role of technological innovation in shaping energy transition policies.

1. Introduction

The increasing global energy demand, environmental degradation, and climate change have made the transformation of energy systems toward a more sustainable structure inevitable (Sarigul and Cetin 2025; Jalal 2025). In this context, increasing the share of clean and renewable energy sources within energy production systems has become a critical policy objective for both environmental sustainability and long-term energy security. However, the expansion of clean energy use is not solely dependent on natural resource potential; it is also closely related to technological progress and innovation capacity. Technological innovation is therefore considered a key driving force in the development of renewable energy technologies, the reduction of their production costs, and their effective integration into energy systems (Geng and Ji 2016; Solarin et al. 2022; Ozkan 2026).

Technological innovation influences the growth of clean energy consumption through several channels. First, innovation activities improve the production efficiency of renewable energy technologies such as solar, wind, and

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biomass, while simultaneously reducing the costs of energy generation. This makes renewable energy sources more competitive compared to fossil fuels and encourages a structural shift in energy consumption patterns. In addition, technological advancements support the development of infrastructure technologies such as energy storage systems and smart energy grids, which facilitate the integration of renewable energy sources into existing energy systems. For this reason, technological innovation is widely recognized as one of the key determinants of the transition toward low-carbon energy systems (Khan et al. 2022; Khan and Su 2023).

Studies in the literature examining the relationship between technological innovation and clean or renewable energy consumption generally suggest that innovation activities play a positive role in promoting renewable energy use. For instance, economies with stronger innovation capacity tend to experience faster growth in renewable energy production and consumption, which accelerates the overall energy transition process (Solarin et al. 2022). Similarly, technological progress has been shown to facilitate the diffusion of renewable energy technologies and support the expansion of clean energy use within energy systems (Khan et al. 2021). Nevertheless, the impact of technological innovation on clean energy consumption may vary depending on factors such as national energy policies, institutional structures, and technological infrastructure (Li et al. 2023).

Recent studies further indicate that technological innovation not only increases renewable energy production but also strengthens the sustainability of the energy transition process. Green technological innovation improves the environmental performance of energy systems while simultaneously contributing to the wider adoption of clean energy (Li et al. 2022). In addition, several studies suggest that innovation in renewable energy technologies may help alleviate energy poverty and improve access to modern energy services (Lee et al. 2022; Wang et al. 2022). Furthermore, technological innovation may generate spillover effects across energy markets and economic cycles, thereby reinforcing the broader transition toward clean energy systems (Wang et al. 2024). In this context, technological innovation is considered a critical factor in expanding clean energy consumption and facilitating the transition toward sustainable energy systems. Technological progress contributes to the development and diffusion of renewable energy technologies and supports their integration into energy systems, thereby promoting the expansion of clean energy consumption. However, the relationship between technological innovation and clean energy consumption may differ across countries, and the dynamics of the energy transition process may exhibit a heterogeneous structure. Therefore, examining the relationship between technological innovation and clean energy consumption across different countries and development levels represents an important research area for designing more effective energy transition policies.

This study aims to comprehensively examine the impact of technological innovation on clean energy consumption in the G7 countries. In this context, annual data covering the period from 1985 to 2021 for Canada, Germany, France, Italy, Japan, the United Kingdom, and the United States are utilized in the analysis. To more clearly capture how the impact of technological innovation on clean energy consumption varies across different levels of energy consumption and over different time horizons, the study employs the Modified Cross-Quantile Regression (MCQR), Quantile-on-Quantile Kernel Regularized Least Squares (QQKRLS), and Wavelet Quantile Granger Causality (WQGC) approaches. These methods make it possible to investigate not only the average effect of technological innovation on clean energy consumption but also the extent to which this relationship differs across quantiles and time frequencies. Accordingly, the study seeks to provide a deeper understanding of whether the effects of technological innovation on clean energy consumption differ across G7 countries and how this relationship evolves across both the quantile and time dimensions.

The relationship between technological innovation and renewable energy consumption has attracted increasing attention in recent years; however, the number of empirical studies examining this relationship remains relatively limited. A significant portion of the existing literature focuses on the effects of technological innovation on energy efficiency, energy intensity, or renewable energy production, while its impact on renewable energy consumption has been examined to a lesser extent. Moreover, most previous studies analyse the relationship between technological innovation and energy indicators using linear models, and therefore the variation of this relationship across different parts of the distribution has not been sufficiently explored. In addition, many of these studies rely on panel data analyses or focus on a single country sample. In this context, this study aims to fill this gap in the literature by examining the relationship between technological innovation and renewable energy consumption for the G7 countries on a country-specific basis. In doing so, the study provides new empirical evidence by revealing whether the impact of technological innovation on renewable energy consumption differs across countries. Another important contribution of this study is the use of recent and advanced econometric methods to uncover the nonlinear structure of the relationship between technological innovation and renewable energy consumption. In this study, MCQR, QQKRLS, and WQGC methods are employed to conduct analyses across both quantile dimensions and time-frequency domains. Through these methods, it becomes possible to investigate not only the average effect of the relationship between the variables but also how this relationship varies across different quantiles and time scales, while the robustness of the findings can be tested using multiple methodological approaches. In this respect, the study

contributes to the literature methodologically by revealing the nonlinear and country-specific dynamics between technological innovation and renewable energy consumption. Furthermore, the findings provide important policy implications by highlighting the critical role of technological innovation in accelerating the energy transition. The results may assist policymakers in promoting renewable energy investments, strengthening innovation-based energy strategies, and developing more effective and sustainable energy transition policies.

This study consists of seven sections. Following the introduction, the second section presents the theoretical framework on the relationship between technological innovation and renewable energy consumption. The third section introduces the data set, sample, and methods used in the study. The fourth section presents the empirical findings. In the fifth section, the results are discussed and compared with the existing literature. The sixth section provides policy implications. Finally, the seventh section discusses the limitations of the study and offers suggestions for future research.

2. Literature review

The impact of technological innovation on energy, clean energy, and renewable energy has become a central focus of a rapidly expanding body of literature. The general trend in this literature suggests that technological advancements play a critical role in improving energy efficiency, optimizing resource utilization, and promoting lower-carbon production structures within energy systems. One of the earlier studies by Herring and Roy (2007) provides an important conceptual framework by emphasizing that technological innovation supports energy-efficient design, although it may also generate complex outcomes such as the rebound effect. Subsequent research has further demonstrated that technological innovation is not only a factor that enhances energy efficiency but also a strategic driver shaping the transformation of energy production and consumption structures.

A significant portion of empirical studies has focused on the effects of technological innovation on energy efficiency and energy intensity. Research conducted on China indicates that technological innovation enhances energy efficiency and contributes to the transformation of energy consumption structures (Wang and Wang 2020; Zhang and Fu 2022). Similarly, studies examining strategic emerging industries reveal that technological innovation increases energy utilization efficiency and supports sustainable production processes (Miao et al. 2018). Within the context of Industry 4.0, technological innovation has also been found to positively influence energy efficiency, although this effect may be moderated by structural factors such as the shadow economy (Chen et al. 2021). Evidence from Indonesia and Bangladesh suggests that technological innovation can reduce energy intensity; however, this relationship should be considered alongside macroeconomic factors such as financial development and trade openness (Saudi et al. 2019; Pan et al. 2019). Findings from the agricultural sector in South Asia also support the view that technological innovation significantly improves technically derived energy efficiency (Khan et al. 2023). In addition, spatial analyses conducted across three continents show that the impact of technological innovation on energy efficiency is not limited to domestic effects but also generates cross-border spillover effects (Zafar et al. 2021). Taken together, these findings indicate that the influence of technological innovation on energy systems is multidimensional and operates through various channels, including efficiency improvements, reductions in energy intensity, and sectoral transformation.

Another important strand of the literature focuses on the relationship between technological innovation and renewable or clean energy development. Early studies using patent counts demonstrate that innovation capacity is closely associated with renewable energy development (Geng and Ji 2016). Subsequent research expands this evidence by showing that technological innovation increases renewable energy production and that this relationship becomes stronger when combined with economic and environmental factors (Solarin et al. 2022). Studies conducted in Belt and Road Initiative countries reveal that technological innovation influences not only renewable energy use but also non-renewable energy consumption and environmental outcomes (Khan et al. 2021). Similarly, empirical evidence confirms that technological innovation acts as a complementary factor supporting the renewable energy transition (Khan and Su 2023). In the case of Tunisia, technological innovation, together with electricity prices and biomass energy, has been shown to dynamically influence the energy transition process (Li et al. 2023). Research on the diffusion of solar photovoltaic systems in Ethiopia indicates that technological innovation systems play a decisive role in the adoption and dissemination of renewable energy technologies by shaping institutional structures and diffusion capacity (Kebede and Mitsufuji 2017). Overall, these studies suggest that technological innovation not only facilitates technical progress in renewable energy technologies but also accelerates institutional, market-based, and structural transformations associated with the energy transition.

More recent literature has further broadened the scope by demonstrating that technological innovation affects not only energy efficiency and renewable energy development but also wider outcomes such as energy security, energy poverty, energy resilience, and green growth. For example, research conducted in China shows that technological

innovation, together with financial development, contributes to improvements in energy security (Lee and Wang 2022). Other studies reveal that renewable energy technology innovation can alleviate energy poverty and that this relationship is influenced by climate risk and market conditions (Lee et al. 2022; Wang et al. 2022). Recent work also indicates that artificial intelligence–based technological innovation, supported by green finance, can enhance energy resilience (Nepal et al. 2025). The complementary relationship between green energy and green technological innovation has been identified as a new determinant of green growth (Li et al. 2022). Similarly, new energy policies have been found to stimulate green technology innovation in energy enterprises, thereby accelerating the energy transition process (Zhang et al. 2024). In addition, green technology innovation has been shown to generate spillover effects in energy markets and economic cycles (Wang et al. 2024). In this context, the role of technological innovation in the energy sector is no longer limited to improvements in production technologies; it also encompasses broader dimensions such as social welfare, energy access, system resilience, and macroeconomic stability.

Studies focusing on the relationship between green technological innovation and sustainability have further expanded the literature. Evidence from China indicates that green technological innovation improves energy total factor productivity (Wang et al. 2021). More broadly, research demonstrates that green technological innovation and energy efficiency jointly contribute to sustainable transformation and play complementary roles in shaping a greener future (Song et al. 2024). Studies mapping knowledge development and technological change in energy management also highlight that innovation processes transform institutional learning and managerial capacity in the energy sector (Al-Awamleh et al. 2026). Therefore, the literature increasingly views technological innovation not merely through the lens of patents, efficiency improvements, or renewable capacity expansion, but as a multidimensional driver of transformation within the broader framework of sustainable development.

Overall, three main conclusions emerge from the existing literature. First, although technological innovation generally contributes positively to energy systems, its effects differ considerably across countries, sectors, market structures, and institutional settings. Second, the influence of technological innovation is neither linear nor one-dimensional; rather, it operates through multiple channels, including energy efficiency, energy intensity, renewable energy deployment, energy security, and energy poverty. Third, while the existing literature predominantly relies on country- or region-level linear analyses, the heterogeneous and regime-dependent nature of energy transition processes suggests that the effects of technological innovation may vary substantially across different quantiles and time horizons. Therefore, studies employing advanced nonlinear approaches and providing country-specific evidence can offer deeper insights into the technological innovation-energy transition nexus and make valuable contributions to the literature.

3. Data and theoretical framework

3.1. Data

The aim of this study is to investigate the effect of technological innovation on renewable energy consumption and to examine how this relationship evolves across different time horizons. Within this framework, the study analyses the nexus between technological innovation and renewable energy consumption by accounting for both short- and long-run dynamics. Furthermore, to capture potential heterogeneity across different distribution levels, the impact of technological innovation on renewable energy consumption is examined separately for each G7 country. In the study, annual data covering the period 1985-2021 are used. The analysis includes the G7 countries: Canada, Japan, Germany, France, Italy, the United Kingdom, and the United States. The main reason for selecting these countries is that the G7 economies play an important role globally in terms of both technological development and energy consumption structures. In particular, these countries are among the key actors shaping global innovation processes due to their high R&D expenditures, strong innovation capacities, and advanced technological infrastructures. Moreover, G7 countries occupy a critical position in the transition toward renewable energy, as they account for a significant share of global energy consumption and carbon emissions. In these countries, technological innovation has a substantial potential to transform energy production and consumption structures. Therefore, examining the effect of technological innovation on renewable energy consumption in these countries provides important insights for both the academic literature and energy policy discussions. Furthermore, G7 countries play a leading role globally in the development and implementation of sustainable energy policies. For this reason, analysing the relationship between technological innovation and renewable energy consumption in these countries is expected to contribute to the development of important policy implications for sustainable development goals and energy transition policies.

Table 1 presents the variables used in the study, their descriptions, and data sources. Renewable energy consumption (RE) represents the share of renewable energy in total final energy consumption (%) and the data are obtained from the database of the World Bank. The technological innovation (TI) variable is measured by patent applications to represent the technological development level of countries, and these data are also obtained from the World Bank database. The variables used in this study are calculated and analysed separately for the G7 countries. This approach makes it possible to examine in more detail whether the impact of technological innovation on renewable energy consumption differs across countries and how this relationship evolves for each country individually. Therefore, Table 1 summarizes the measurement of the variables used in the study, their data sources, and the basic data structure of the analysis conducted specifically for the G7 countries.

Table 1. Variables, descriptions, and data sources

Variable	Abbreviation	Unit of the variable	Source
Renewable Energy Consumption	RE	Renewable Energy Consumption (% of total final energy consumption)	World Bank
Technological Innovation	TI	Patent Applications	World Bank

3.2. Theoretical framework

In this study, the Cross-Quantile Regression (CQR) approach developed by Li (2024) is employed following the implementation of linearity and stability tests. Extending the traditional Quantile-on-Quantile Regression (QQR) framework proposed by Sim and Zhou (2015), the CQR approach facilitates an examination of how different quantiles of one variable affect the corresponding quantiles of another variable while explicitly accounting for dynamic interactions across the entire joint distribution (Athari et al. 2025). A key advantage of the Modified Cross-Quantile Regression (MCQR) method is its ability to address the bandwidth-related limitations of the conventional QQR approach, which may fail to adequately capture distributional dependence structures under varying market conditions. Consequently, MCQR provides a more accurate and computationally efficient framework for identifying quantile-dependent spillover effects. The procedure begins by estimating the quantile series of the dependent variable (Y) and the independent variable (X) through the Quantile Series (QSER) method introduced by Li (2024). Subsequently, regressions are estimated across all quantile combinations, allowing the full distributional dependence structure between the variables to be identified. In this context, the cross-quantile effect of X on X is modeled as in Equation (1):

$$Q_\tau(Y) = \Upsilon_0(\tau,\theta) + \Upsilon_1(\tau,\theta)\, Q_\theta(X) + \varepsilon(\tau,\theta) \tag{1}$$

where $Q_\tau(Y)$ represents the conditional τ-th quantile of Y, $Q_\theta(X)$ denotes the conditional θ-th quantile of X; $\Upsilon_0(\tau,\theta)$ indicates the intercept, $\Upsilon_1(\tau,\theta)$ demostrates the slope coefficient measuring the cross-quantile impact of X on Y, and $\varepsilon(\tau,\theta)$ the error term.

Then, we used the Quantile-on-Quantile Kernel-Based Regularized Least Squares (QQKRLS) suggested by Adebayo et al. (2024a) as a robustness check. The Kernel-Based Regularized Least Squares (KRLS) method, developed as a machine learning approach by Hainmueller and Hazlett (2014), is capable of learning the optimal functional form using Gaussian kernels without imposing restrictive specifications or assumptions, thereby mitigating model misspecification bias. KRLS examines the magnitude, direction, and statistical significance of the predictor's marginal effects at each observation of the predicted variable, and uses the distribution of these marginal effects to reveal heterogeneous (nonlinear) relationships (Hainmueller and Hazlett 2014; Ferwerda et al. 2017; Ozkan et al. 2025). Specifically, the KRLS method analysis the effect of a predictor variable X on the predicted variable Y using the following average point marginal effect Equation (2):

$$E_N\left[\frac{\widehat{\beta Y}}{\beta X_k}\right] = \frac{-2}{\sigma^2 N}\sum_k\sum_i j_i e^{\frac{\|x_i - x_k\|^2}{\sigma^2}}(X_i - X_k) \tag{2}$$

wherein $E_N\left[\frac{\widehat{\beta Y}}{\beta X_k}\right]$ denotes the estimated average pointwise marginal effect of the predictor variable X on the predicted variable Y, k represents a single observation, and N shows the sample size. To this point, KRLS has been understood to primarily characterize the distributional behaviour of the dependent variable, without explicitly modelling the distribution of the explanatory variable. Moreover, while the nonlinear effects are illustrated at each observation of the dependent variable, statistical significance is summarized by a single measure—the average

pointwise marginal effect. To include all distributions of the predictor variable in the analysis and examine statistical significance for all distributions of the predictor and predicted variables, the QQKRLS method proposed by Adebayo et al. (2024b) was preferred in this study. The impact of X on Y can be analysed by the QQKRLS as below as shown in Equation (3):

$$E_N\left[\frac{\widehat{\beta QY_\tau}}{\beta QX_{\theta k}}\right] = \frac{-2}{\sigma^2 N}\sum_k \sum_i j_i e^{\frac{\|X_{\theta i}-X_{\theta k}\|^2}{\sigma^2}}(X_{\theta i} - X_{\theta k}) \quad (3)$$

where, $E_N\left[\frac{\widehat{\beta QY_\tau}}{\beta QX_{\theta k}}\right]$ denotes the estimated average pointwise marginal effect of θ-th conditional quantile of X on the τ-th conditional quantile of Y. Compared to KRLS approaches, the QQKRLS method offers distinct methodological advantages (Adeboya et al. 2024b). First, QQKRLS captures complex and nonlinear relationships among variables that conventional linear approaches, such as KRLS, may fail to detect. Second, it incorporates a regularization mechanism to mitigate overfitting, thereby enhancing generalizability and improving predictive accuracy, particularly in the presence of nonlinear relationships or non-normal data distributions. Third, QQKRLS exhibits strong versatility across diverse data types and application domains, such as finance, economics. Its ability to estimate effects at different quantiles provides a more comprehensive understanding of data heterogeneity and conditional distributions, which standard KRLS cannot offer.

In this study, the Wavelet Quantile Granger Causality (WQGC) approach proposed by Saint Akadiri et al. (2025) is employed as the final method in order to test the robustness of the results. This method integrates the traditional Granger causality framework, the Maximal Overlapping Discrete Wavelet Transform (MODWT), and quantile-based estimation techniques to provide a more comprehensive causality analysis. Through this integrated structure, causal relationships between variables can be examined simultaneously across both time and quantile dimensions. Unlike conventional quantile causality approaches, the WQGC method allows the causal relationship to be evaluated not only across quantiles but also within a time-frequency framework. In this way, it becomes possible to analyse how a potential Granger causal variable influences the conditional quantiles of a dependent variable over time (Saint Akadiri et al. 2025). Consequently, this approach enables a deeper assessment of causal relationships by revealing how they vary both across different time periods and across different levels of the distribution. The stages of the empirical analysis followed in this study are summarized in Figure 1.

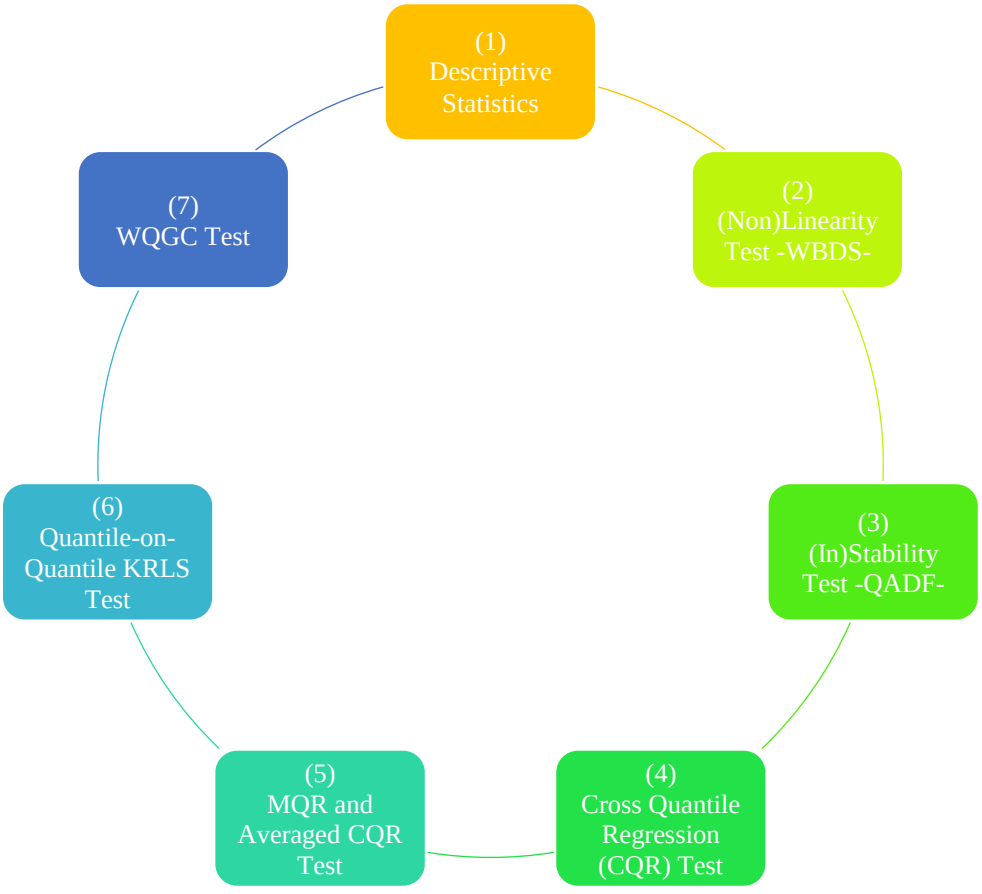


Figure 1. Empirical analysis phases

4. Empirical findings

In this section of the study, empirical findings on the nonlinear effects of technological innovation on renewable energy consumption in the G7 countries are presented.

Table 2. Descriptive statistics of variables

	Mean	Median	Max.	Min.	Std. Dev.	Skewness	Kurtosis	Jarque-Bera	Prob.	Sum	Obs
CN_RE	62.27	61.69	66.74	58.11	2.46	0.35	2.2	1.76	0.42	2304.12	37
CN_TI	3851	4061	5522	2092	1003.96	-0.33	1.91	2.53	0.28	142487	37
DE_RE	14.32	7.75	44.37	3.17	12.58	1	2.69	6.29	0.04	529.85	37
DE_TI	42997.08	46632	51736	30724	6892.9	-0.73	1.89	5.16	0.08	1590892	37
FR_RE	14.99	14.02	23.71	9.66	3.42	0.68	2.73	2.98	0.23	554.74	37
FR_TI	13557.24	13519	14748	12050	886.19	-0.16	1.53	3.48	0.18	501618	37
IT_RE	25.02	20.84	43.64	15.59	9.13	0.9	2.21	5.95	0.05	925.63	37
IT_TI	7361.35	8247	10281	2000	2274.58	-1.32	3.66	11.49	0	272370	37
JP_RE	11.64	10.26	20.12	7.92	3.07	1.1	3.43	7.68	0.02	430.65	37
JP_TI	313007.4	319938	387364	222452	45158.35	-0.25	2.05	1.8	0.41	11581274	37
UK_RE	9.73	2.87	43.06	1.33	12.36	1.51	3.89	15.28	0.00	360.13	37
UK_TI	17455.76	18184	22050	11592	2896.16	-0.48	2.18	2.47	0.29	645863	37
US_RE	11.72	10.6	20.74	7.51	3.33	1.36	4.02	13.03	0.00	433.58	37
US_TI	184069.6	188941	295327	63673	80857.13	-0.07	1.51	3.44	0.18	6810576	37

Table 2 presents the descriptive statistics of the renewable energy consumption and technological innovation variables for the G7 countries. When renewable energy consumption is evaluated, it is observed that there are notable differences among the countries. In some countries, the share of renewable energy in total energy consumption appears relatively high, whereas in others this share remains comparatively lower. This situation can be explained by differences in national energy policies, natural resource endowments, and investments in renewable energy. When technological innovation, represented by patent applications, is considered, it becomes clear that innovation capacity is not evenly distributed across the G7 countries. Some countries demonstrate a stronger position in terms of technological development and patent activities, while others show relatively more limited innovation capacity. In addition, the distribution statistics indicate that some variables may deviate from a normal distribution. Overall, the findings reported in Table 2 suggest that the G7 countries exhibit a heterogeneous structure in terms of both technological innovation and renewable energy consumption, implying that the dynamics of the energy transition differ across countries.

The Figure 2 presents the Wavelet BDS (WBDS) test results for the technological innovation (TI) and renewable energy consumption (RE) variables for the G7 countries. The findings show that the Z statistics calculated at different dimensions exceed the critical values, particularly in the medium- and long-term scales. This indicates that the variables deviate from a linear structure and suggests the presence of nonlinear dynamics in the data set. In addition, the higher test statistics observed in the long-term frequencies for some countries imply that the relationships between technological innovation and renewable energy consumption may behave differently across time scales. Overall, the results of the Wavelet BDS test reveal that the examined variables exhibit a nonlinear structure for the G7 countries, supporting the appropriateness of using nonlinear methods in the analysis.

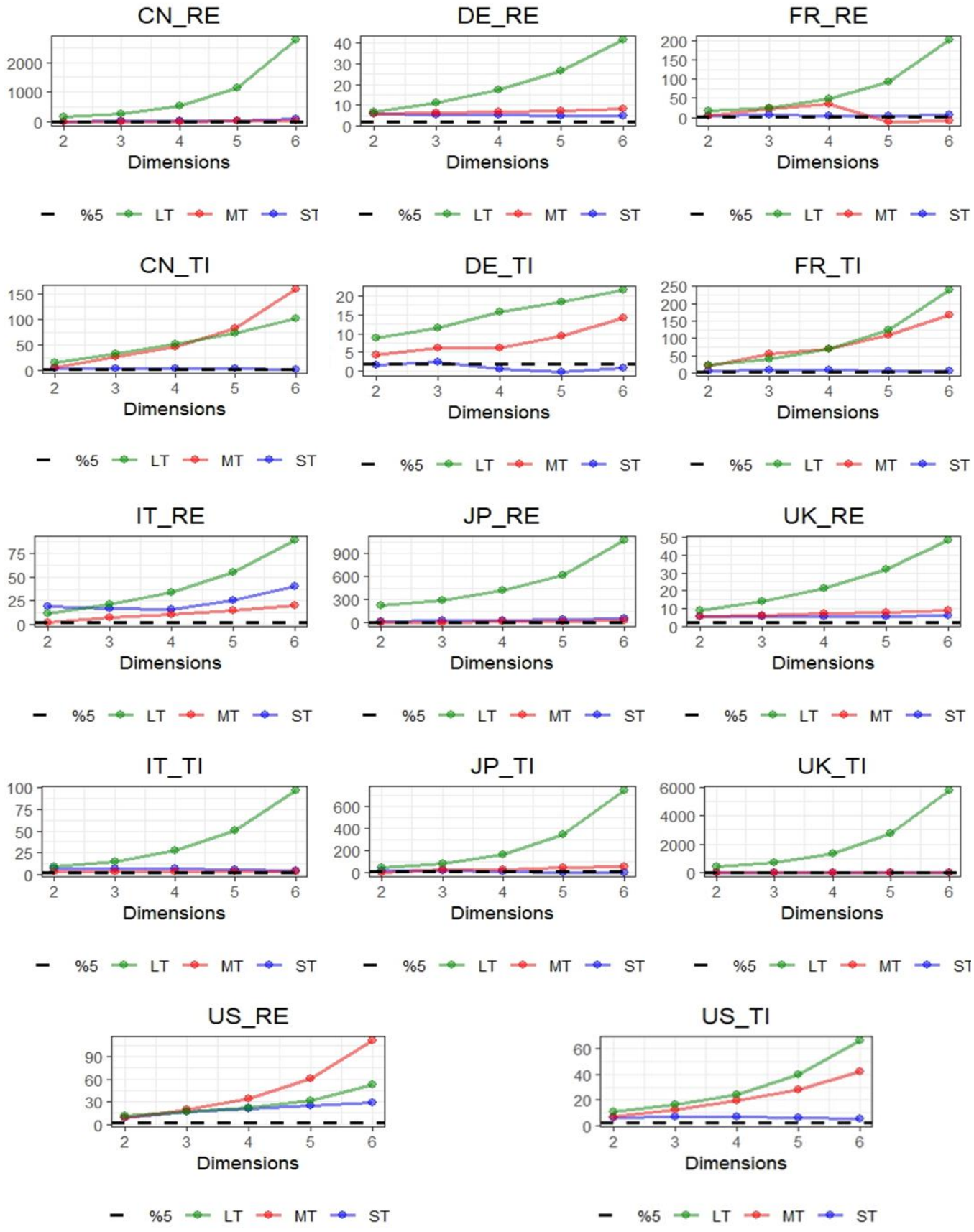


Figure 2. Wavelet BDS test results

The Quantile ADF (QADF) test was used to examine the stationarity attributes of the data across various quantiles. The QADF test, implemented to avoid spurious regression, by examining multiple quantiles, takes into account heterogeneity and nonlinearity that mean-based tests may miss. According to Figure 3, all variables are non-stationary (possess a unit root) across various quantiles of the distribution at the level. Accordingly, to achieve stationarity, all

variables were transformed into their first differences, and the subsequent empirical analyses were performed on the differenced series.

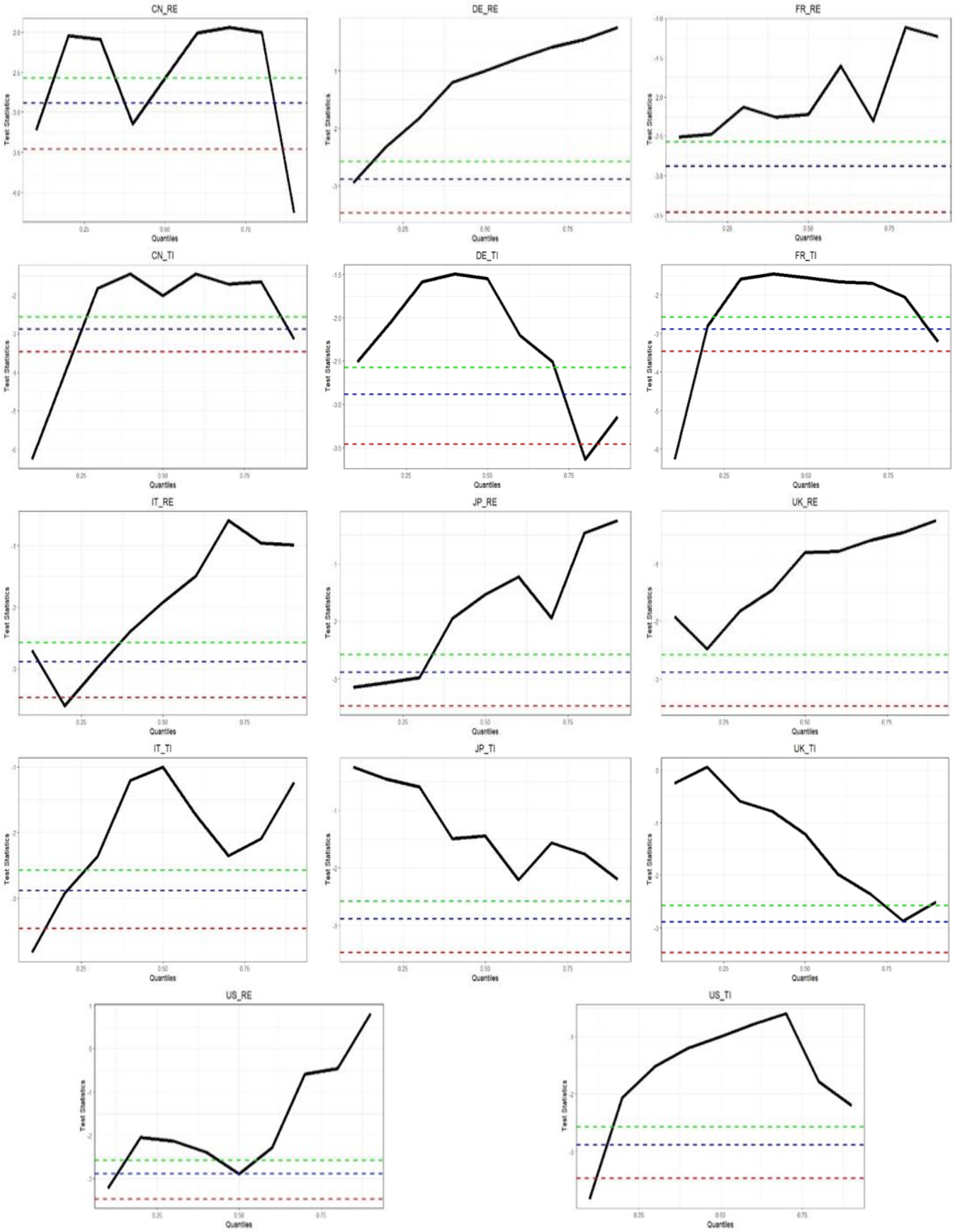


Figure 3. Quantile ADF unit root test results

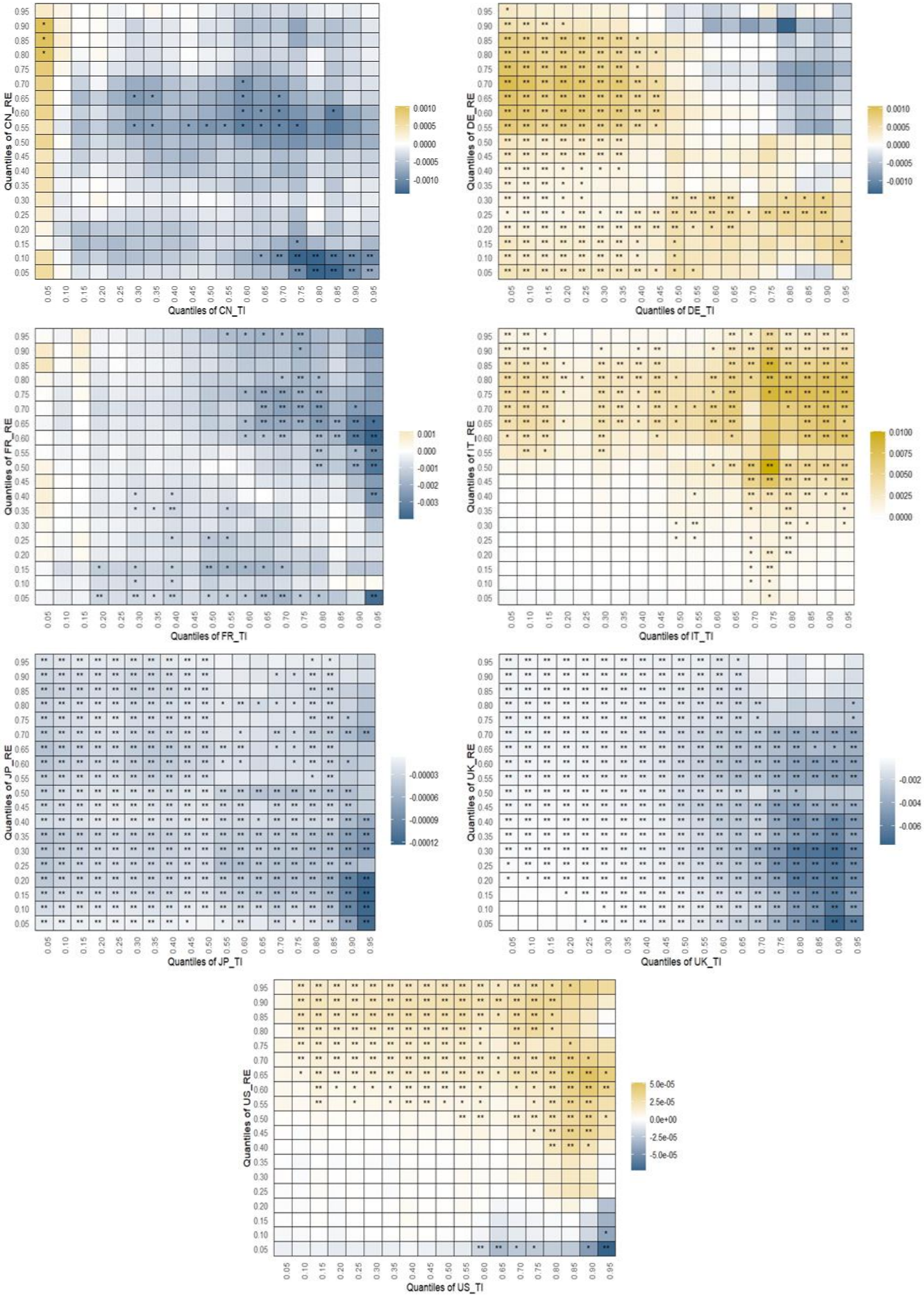


Figure 4. Cross Quantile Regression results

The Cross Quantile Regression (CQR) results presented in Figure 4 reveal that the effect of technological innovation on renewable energy consumption varies across different quantiles in the G7 countries. When Canada and France are considered, it is observed that the impact of technological innovation on renewable energy consumption becomes more pronounced particularly in the middle and upper quantiles. This suggests that technological progress in these countries can play a supportive role in renewable energy investments and the overall energy transition. In contrast, the relationship appears to be weaker or more limited in some lower quantiles. This finding indicates that when renewable energy consumption is at lower levels, the influence of technological innovation may remain relatively limited.

For Germany and Italy, the results show a stronger relationship between technological innovation and renewable energy consumption, particularly in the middle and upper quantiles. In these countries, technological advancements appear to contribute significantly to the development of energy technologies, the strengthening of renewable energy infrastructure, and improvements in energy efficiency. Similarly, in Japan, the effect of technological innovation varies across different points of the distribution, with the relationship becoming more pronounced in certain quantiles. However, in some quantiles the relationship appears relatively weak or limited. This may indicate that the country's energy policies and energy supply structure interact with technological development in different ways.

When the results for the United Kingdom and the United States are evaluated, it can be seen that the impact of technological innovation on renewable energy consumption differs across quantiles. In particular, technological innovation appears to support renewable energy consumption in the higher quantiles, while the relationship may be weaker or even negative in some lower quantiles. Overall, the findings suggest that the effect of technological innovation on renewable energy consumption in the G7 countries exhibits a nonlinear and country-specific structure. These results indicate that energy transition processes should not only be evaluated in terms of technological innovation but also in relation to countries' energy policies, institutional structures, and investment strategies.

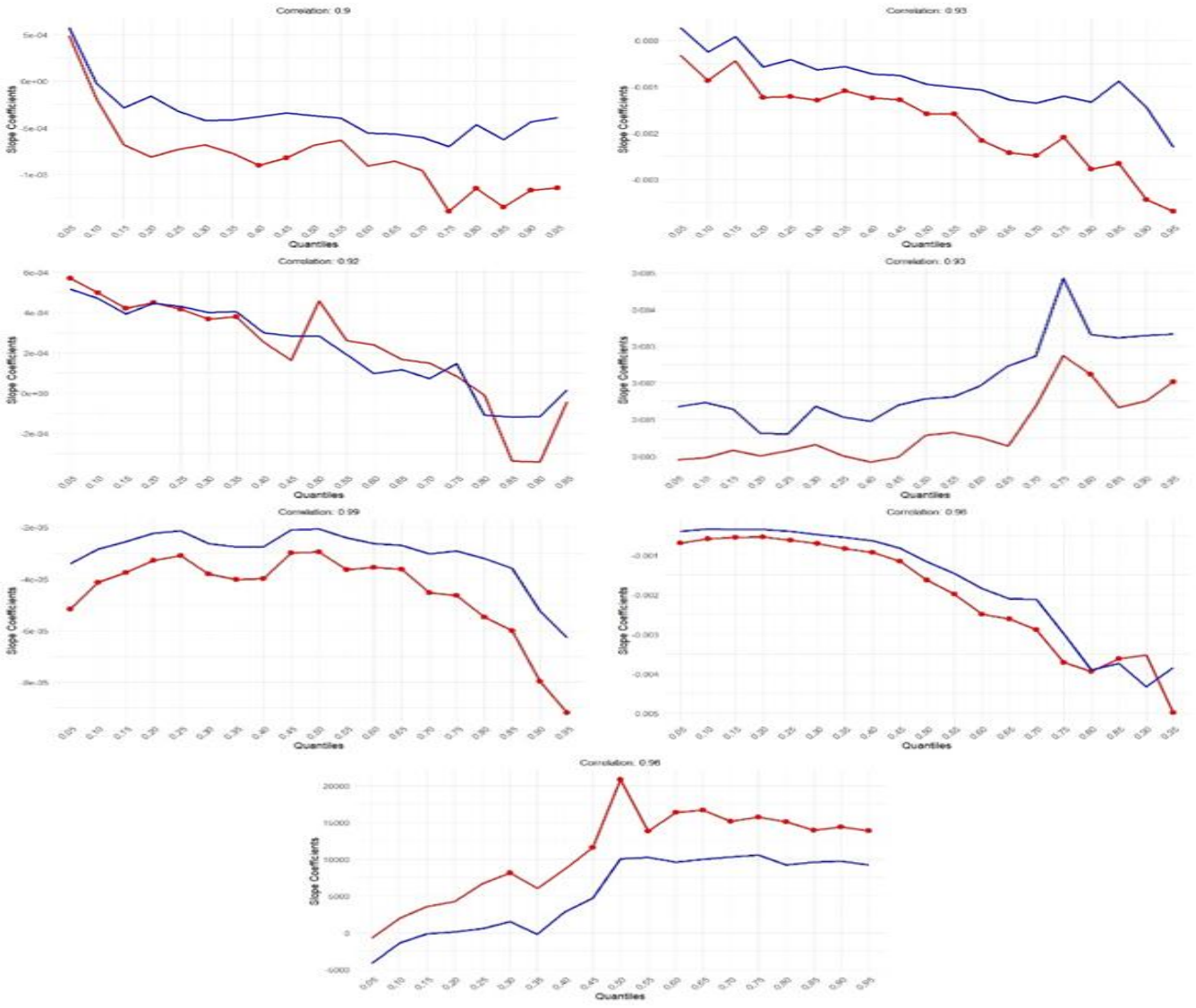
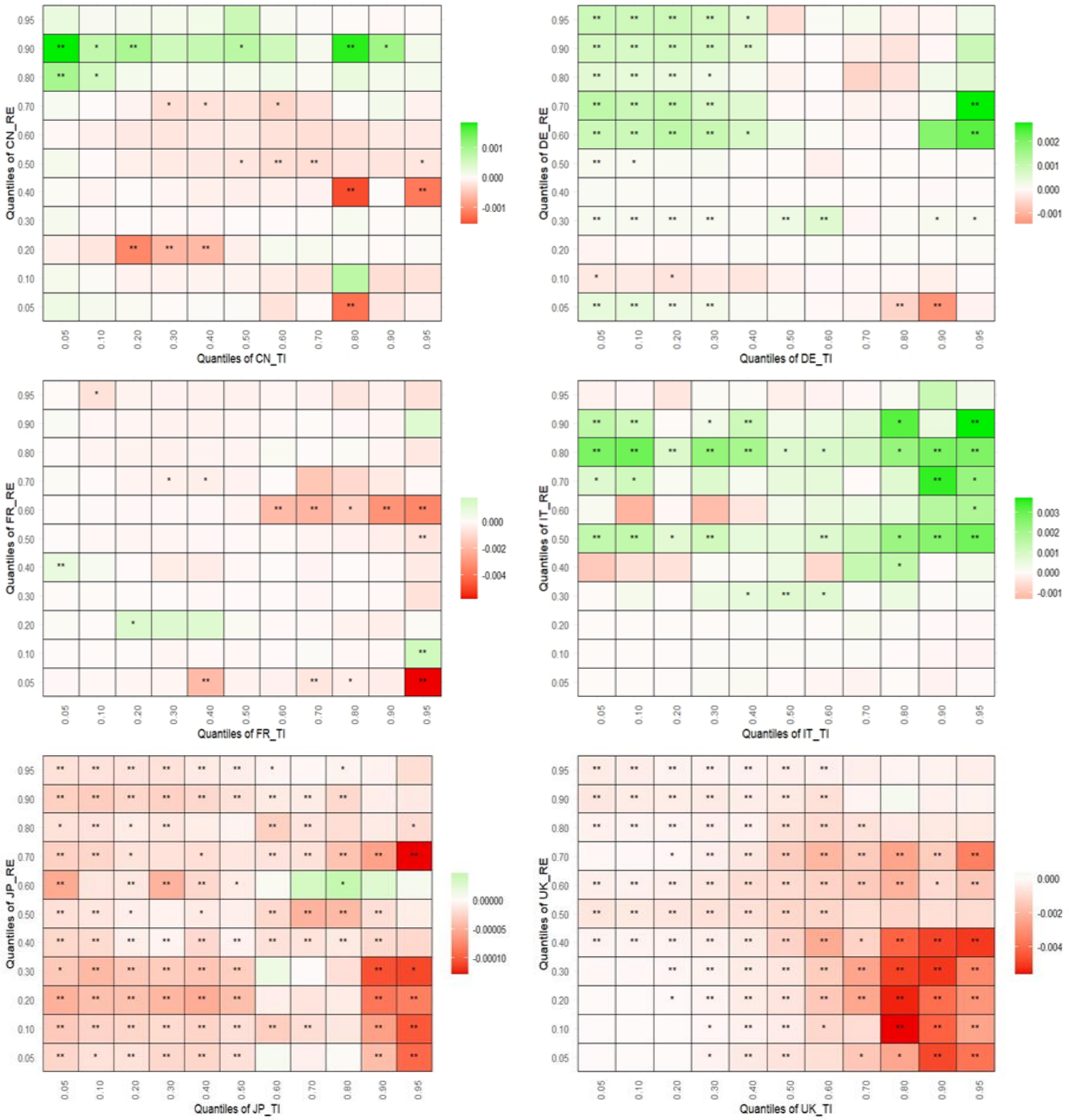


Figure 5. MQR (red) and Averaged CQR (blue) estimates results

The MQR (red) and Averaged CQR (blue) estimation results presented in Figure 5 indicate that the relationship between technological innovation and renewable energy consumption exhibits a nonlinear structure that varies across quantiles. It is observed that both estimation methods follow largely similar patterns across the quantiles, and the high correlation values (approximately between 0.78 and 0.96) demonstrate that the obtained results are methodologically consistent and robust. The relationship appears relatively weaker at lower quantiles, while the effect becomes more pronounced toward the middle quantiles and, in some cases, shows a stronger impact. However, toward the upper quantiles, the coefficients tend to weaken in some cases. This suggests that the marginal effect of technological innovation may decrease in economies where renewable energy consumption has already reached higher levels. Overall, the findings indicate that the impact of technological innovation on renewable energy consumption is quantile-dependent and varies across different development levels. In addition, the high correlation values between the MQR and Averaged CQR estimations support the reliability of the results and the consistency between the estimation methods.



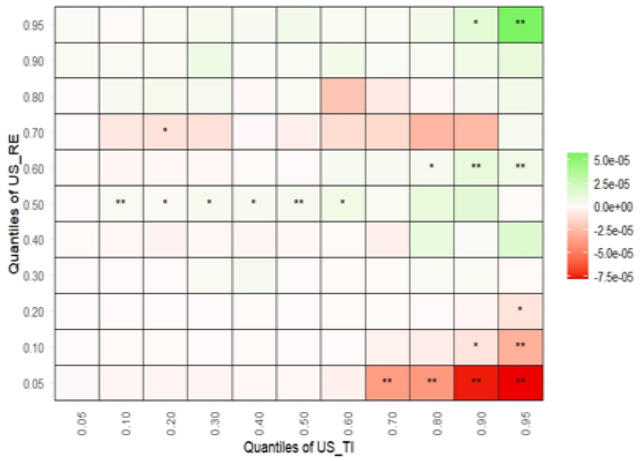
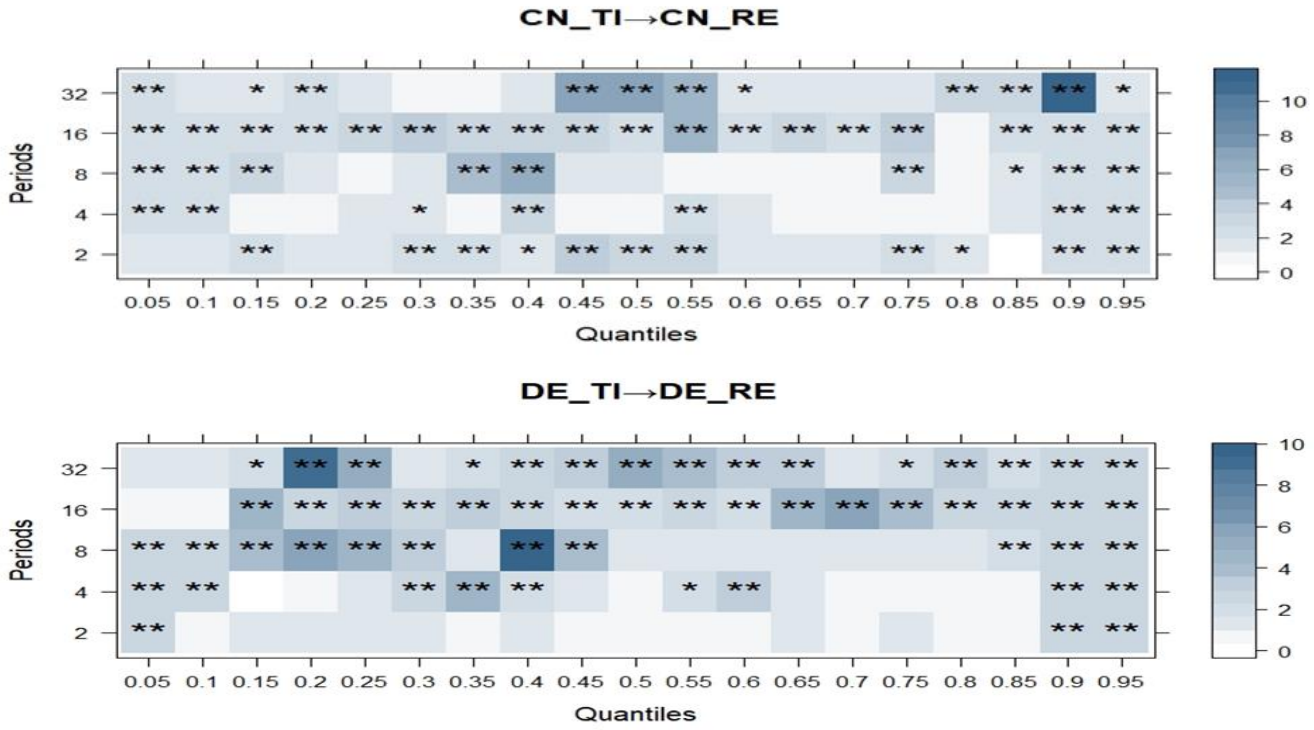


Figure 6. Quantile-on-Quantile KRLS results

The QQKRLS results presented in Figure 6 indicate that the impact of technological innovation on renewable energy consumption exhibits a nonlinear structure that varies across quantiles for the G7 countries. The findings for Canada and Germany show that technological innovation can generate positive effects on renewable energy consumption, particularly in the middle and upper quantiles. For France and Italy, the relationship appears more stable across quantiles and is mostly positive. This suggests that technological progress in these countries may contribute to the diffusion of renewable energy technologies and support the energy transition process. These results also show patterns largely consistent with the findings obtained from the previously applied Cross Quantile Regression (CQR) analysis, confirming that technological innovation tends to have stronger effects particularly in the middle and upper quantiles.

In contrast, the results for Japan, the United Kingdom, and the United States reveal a more heterogeneous pattern. In Japan, the relationship appears weak or negative in some lower and middle quantiles, while the effect becomes more pronounced in higher quantiles. For the United Kingdom and the United States, negative effects are more visible in some lower quantiles, whereas in several middle and upper quantiles the relationship weakens and becomes more balanced. Overall, the QQKRLS results demonstrate that the relationship between technological innovation and renewable energy consumption in the G7 countries follows a country-specific, nonlinear, and quantile-dependent structure. Moreover, the similarity of these findings with the results obtained from the earlier CQR analysis supports the robustness of the empirical findings.



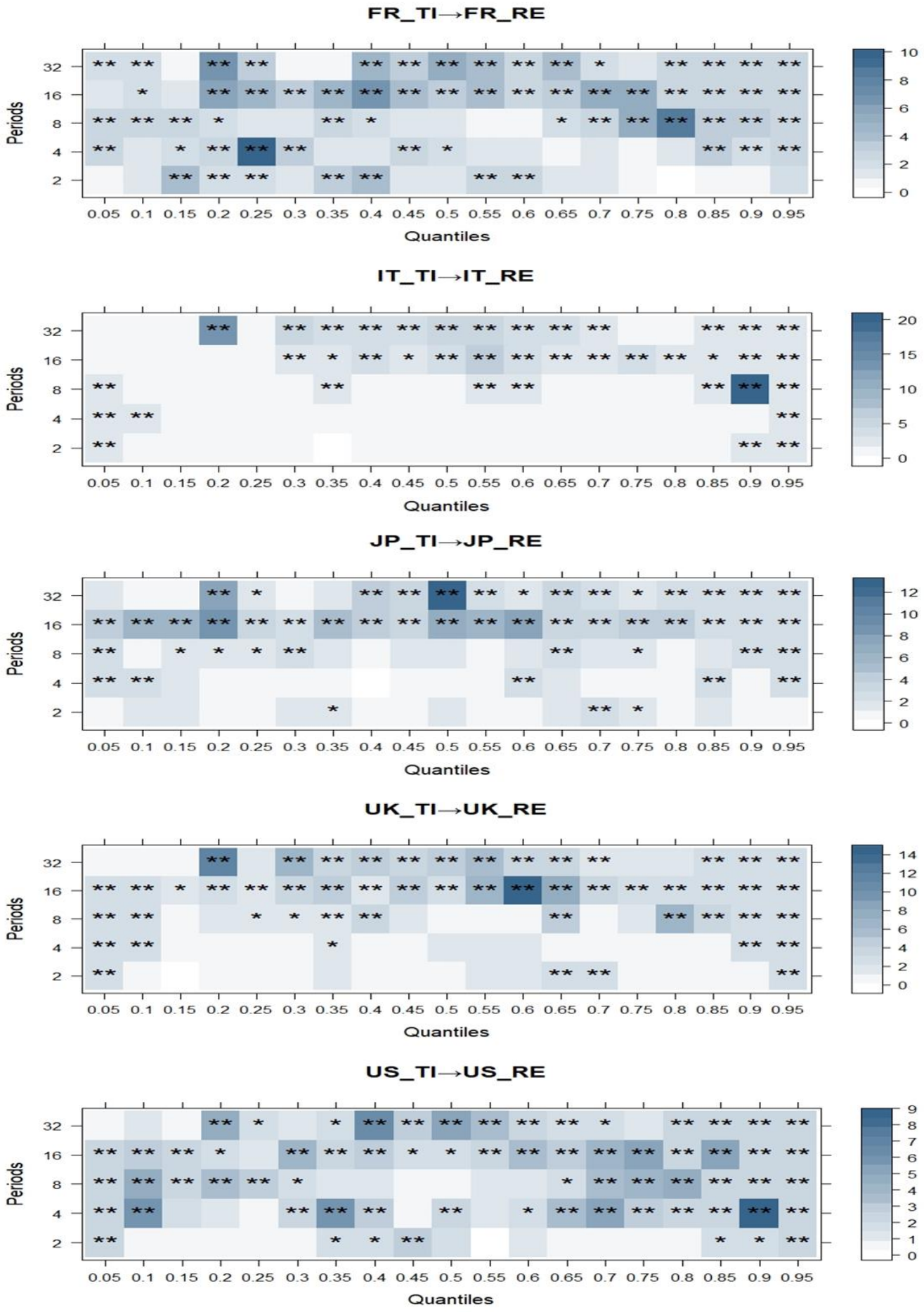


Figure 7. Wavelet Quantile Granger Causality results

The Wavelet Quantile Granger Causality (WQGC) results presented in Figure 7 reveal that the causal relationship from technological innovation to renewable energy consumption in the G7 countries varies across both time and quantile dimensions. When the findings for Canada, France, and Germany are examined, it can be observed that there is a significant causal relationship from technological innovation to renewable energy consumption particularly in the middle and upper quantiles and in the medium- to long-term frequencies. This suggests that technological progress and increases in innovation capacity in these countries may support the development and diffusion of renewable energy technologies.

For Italy and Japan, the results indicate that the causal relationship from technological innovation to renewable energy consumption becomes more evident in certain quantiles and specific time scales. In contrast, the findings for the United Kingdom and the United States reveal a more heterogeneous structure. In these countries, strong causal relationships are observed in some quantiles and time horizons, while the relationship appears weaker in other regions. Overall, the WQGC findings reported in Figure 7 demonstrate the existence of a time- and quantile-dependent causal relationship running from technological innovation to renewable energy consumption in the G7 countries. These results also support the nonlinear relationship patterns identified in the earlier quantile-based analyses.

5. Discussion

The empirical findings of this study reveal that the relationship between technological innovation and renewable energy consumption exhibits a nonlinear and country-specific structure. In particular, the quantile-based analysis results indicate that the impact of technological innovation on renewable energy consumption varies depending on the level of energy consumption. The stronger effects of technological innovation observed in the middle and upper quantiles for countries such as Canada, Germany, France, and Italy suggest that technological progress can support the diffusion of renewable energy technologies. These findings are largely consistent with the existing literature demonstrating that technological innovation contributes to the development of renewable energy. For instance, studies based on patent data show that innovation capacity is an important determinant of renewable energy development (Geng and Ji 2016). Similarly, several empirical studies have reported that technological innovation increases renewable energy production and supports the energy transition process (Solarin et al. 2022; Khan et al. 2021).

The results further indicate that the impact of technological innovation on renewable energy consumption is heterogeneous across countries. In particular, the relatively weaker and more variable relationships observed across certain quantiles in Japan, the United Kingdom, and the United States suggest that the effectiveness of technological innovation in promoting renewable energy consumption is closely associated with country-specific energy policies, technological capabilities, and institutional frameworks. This finding is consistent with the existing literature, which emphasizes that the contribution of technological innovation to energy transitions should be evaluated within the broader context of economic structures and institutional conditions (Li et al. 2023; Wang et al. 2024). Moreover, previous studies have shown that technological innovation functions as a complementary driver of renewable energy adoption by facilitating the transition toward cleaner energy systems and enhancing the long-term sustainability of energy development (Khan and Su 2023).

Another important finding of the study is the presence of time- and quantile-dependent causal relationships running from technological innovation to renewable energy consumption. The Wavelet Quantile Granger Causality results particularly show that technological innovation supports renewable energy consumption in the medium- and long-term frequencies. This suggests that technological innovation can generate long-term structural effects in the transformation of energy systems. The literature also emphasizes that technological innovation supports energy transition through several channels, including improvements in energy efficiency, advancements in energy technologies, and increases in clean energy investments (Lee et al. 2022; Wang et al. 2022). Furthermore, green technological innovation has been shown to generate positive impacts on energy markets and sustainable development processes (Song et al. 2024; Li et al. 2022).

6. Policy implications and practical recommendations

The empirical analysis results indicate that technological innovation has a significant but distribution-dependent impact on renewable energy consumption in the G7 countries. In particular, the findings obtained from quantile-based analyses suggest that technological innovation generates stronger effects at certain levels of renewable energy development. This result highlights that technological capacity and innovation activities are key drivers of the energy

transition, especially during the development stages of renewable energy systems. In this context, increasing research and development investments in renewable energy technologies and maintaining innovation-oriented energy policies in the G7 countries may enhance the effectiveness of the energy transition process. In particular, supporting innovation activities related to energy storage technologies, smart energy grids, energy efficiency applications, and low-carbon production technologies may contribute to the broader diffusion of renewable energy systems.

The findings of the study also reveal that the relationship between technological innovation and renewable energy consumption is not homogeneous across countries and may generate different outcomes in economies with different energy systems. The more pronounced positive effects of technological innovation on renewable energy consumption in countries such as Canada, Germany, France, and Italy indicate that the energy transition in these economies is closely linked to their innovation capacity. In contrast, the more heterogeneous and sometimes weaker relationship observed in countries such as Japan, the United Kingdom, and the United States suggests that the energy transition cannot be explained solely by technological developments. These results imply that energy policies should be designed by considering countries' existing energy production structures, energy security concerns, technological infrastructure, and institutional characteristics of energy markets. In this regard, a stronger integration between technology policies and energy policies may facilitate a more balanced and sustainable energy transition.

The results further reveal that the impact of technological innovation on renewable energy consumption follows a nonlinear pattern, indicating that the effectiveness of policy interventions may vary across different stages of the energy transition process. In the early phases, when renewable energy consumption remains relatively limited, policies aimed at stimulating technological innovation and accelerating the development of new energy technologies appear to be particularly important. As renewable energy systems become more advanced and widely adopted, however, greater emphasis should be placed on complementary policies supporting energy storage technologies, smart grid infrastructure, and energy efficiency improvements. Accordingly, policy frameworks designed to facilitate the energy transition should extend beyond innovation-oriented strategies and incorporate a broader set of instruments. These include financial incentives that promote renewable energy investments, carbon mitigation policies that encourage cleaner production and consumption patterns, and institutional arrangements that enhance the efficiency and stability of energy markets. The integration of these policy measures can amplify the contribution of technological innovation to the decarbonization of the energy sector, strengthen the resilience of renewable energy systems, and foster a more sustainable and inclusive energy transition.

7. Limitations and future research

This study has several limitations. First, the analysis is conducted using data covering the 1985-2021 period and focuses only on the G7 countries. This may limit the generalizability of the findings to other country groups, particularly developing economies with different energy structures and technological capacities. Since G7 countries represent highly developed economies in terms of technological capability, energy policies, and renewable energy investments, the results obtained in this study may differ in countries that are at earlier stages of energy transition or have different economic and institutional structures.

Another important limitation of the study is that technological innovation is represented by a single indicator. In this research, technological innovation is measured using a limited proxy such as patent applications. However, innovation is a multidimensional concept, and factors such as research and development expenditures, high-technology exports, digital infrastructure, human capital, and technological investments may also play a significant role in explaining innovation capacity. Therefore, the selected indicator may not fully capture the complex structure of technological innovation.

Future studies may address these limitations by employing broader datasets that include different country groups and by measuring technological innovation using multiple indicators. In addition, incorporating variables such as carbon emissions, energy efficiency, energy investments, and environmental policy indicators could provide a more comprehensive understanding of the energy transition process. Furthermore, the use of alternative econometric techniques and additional nonlinear analytical approaches may offer deeper insights into the relationship between technological innovation and renewable energy consumption.

Declaration of competing interest

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

Ethical approval

This study which does not require ethics committee approval and/or legal/specific permission complies with the Research and Publication Ethics.

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CRediT authorship contribution statement

The entire research is written by the author.

References

Adebayo, T. S., Özkan, O., & Eweade, B. S. (2024a). Do energy efficiency R&D investments and information and communication technologies promote environmental sustainability in Sweden? A quantile-on-quantile KRLS investigation. *Journal of Cleaner Production, 440*, 140832. https://doi.org/10.1016/j.jclepro.2024.140832

Adebayo, T. S., Meo, M. S., Eweade, B. S., & Özkan, O. (2024b). Examining the effects of solar energy innovations, information and communication technology and financial globalization on environmental quality in the United States via quantile-on-quantile KRLS analysis. *Solar Energy, 272*, 112450. https://doi.org/10.1016/j.solener.2024.112450

Al-Awamleh, H. K., Omoush, M. M., Ahmed, R. T., Assaf, N., Alqudah, M. Z., & Samara, H. (2026). Innovation in energy management: Mapping knowledge development and technological change. *International Journal of Energy Sector Management*, *20*(3), 734-758. https://doi.org/10.1108/IJESM-03-2025-0016

Athari, S. A., Kirikkaleli, D., Saliba, C., & Olanrewaju, V. O. (2025). Unlocking the investment nexus between artificial intelligence and Bitcoin: Modified cross-quantile regression insights. *Social Sciences & Humanities Open, 12*, 102131. https://dx.doi.org/10.2139/ssrn.5628793

Chen, M., Sinha, A., Hu, K., & Shah, M. I. (2021). Impact of technological innovation on energy efficiency in industry 4.0 era: Moderation of shadow economy in sustainable development. *Technological Forecasting and Social Change*, *164*, 120521. https://doi.org/10.1016/j.techfore.2020.120521

Ferwerda, J., Hainmueller, J., & Hazlett, C. J. (2017). Kernel-based regularized least squares in R (KRLS) and Stata (KRLS). *Journal of Statistical Software*, *79*, 1-26. https://doi.org/10.18637/jss.v079.i03

Geng, J. B., & Ji, Q. (2016). Technological innovation and renewable energy development: Evidence based on patent counts. *International Journal of Global Environmental Issues*, *15*(3), 217-234. https://doi.org/10.1504/IJGENVI.2016.076945

Hainmueller, J., & Hazlett, C. (2014). Kernel regularized least squares: Reducing misspecification bias with a flexible and interpretable machine learning approach. *Political Analysis*, *22*(2), 143-168. https://doi.org/10.1093/pan/mpt019

Herring, H., & Roy, R. (2007). Technological innovation, energy efficient design and the rebound effect. *Technovation*, *27*(4), 194-203. https://doi.org/10.1016/j.technovation.2006.11.004

Jalal, M. M. (2025). Energy demand, financial access, and urbanization as determinants of the load capacity factor: Fresh evidence from the United States. *International Journal of Business and Economic Studies*, *7*(4), 272-285. https://doi.org/10.54821/uiecd.1830333

Kebede, K. Y., & Mitsufuji, T. (2017). Technological innovation system building for diffusion of renewable energy technology: A case of solar PV systems in Ethiopia. *Technological Forecasting and Social Change*, *114*, 242-253. https://doi.org/10.1016/j.techfore.2016.08.018

Khan, A., Chenggang, Y., Hussain, J., & Kui, Z. (2021). Impact of technological innovation, financial development and foreign direct investment on renewable energy, non-renewable energy and the environment in Belt & Road Initiative countries. *Renewable Energy*, *171*, 479-491. https://doi.org/10.1016/j.renene.2021.02.075

Khan, K., Su, C. W., Rehman, A. U., & Ullah, R. (2022). Is technological innovation a driver of renewable energy?. *Technology in Society*, *70*, 102044. https://doi.org/10.1016/j.techsoc.2022.102044

Khan, D., Nouman, M., & Ullah, A. (2023). Assessing the impact of technological innovation on technically derived energy efficiency: A multivariate co-integration analysis of the agricultural sector in South Asia. *Environment, Development and Sustainability*, *25*(4), 3723-3745. https://doi.org/10.1007/s10668-022-02194-w

Khan, K., & Su, C. W. (2023). Does technology innovation complement the renewable energy transition?. *Environmental Science and Pollution Research*, *30*(11), 30144-30154. https://doi.org/10.1007/s11356-022-24336-3

Lee, C. C., & Wang, C. S. (2022). Financial development, technological innovation and energy security: Evidence from Chinese provincial experience. *Energy Economics*, *112*, 106161. https://doi.org/10.1016/j.eneco.2022.106161

Lee, C. C., Yuan, Z., Lee, C. C., & Chang, Y. F. (2022). The impact of renewable energy technology innovation on energy poverty: Does climate risk matter?. *Energy Economics*, *116*, 106427. https://doi.org/10.1016/j.eneco.2022.106427

Li, J., Dong, K., & Dong, X. (2022). Green energy as a new determinant of green growth in China: The role of green technological innovation. *Energy Economics*, *114*, 106260. https://doi.org/10.1016/j.eneco.2022.106260

Li, S., Cifuentes-Faura, J., Talbi, B., Sadiq, M., Mohammed, K. S., & Bashir, M. F. (2023). Dynamic correlated effects of electricity prices, biomass energy, and technological innovation in Tunisia's energy transition. *Utilities Policy*, *82*, 101521. https://doi.org/10.1016/j.eneco.2022.106260

Li, T. H. (2024). Spline autoregression method for estimation of quantile spectrum. (arXiv:2412.17163). https://doi.org/10.48550/arXiv.2412.17163

Miao, C., Fang, D., Sun, L., Luo, Q., & Yu, Q. (2018). Driving effect of technology innovation on energy utilization efficiency in strategic emerging industries. *Journal of Cleaner Production*, *170*, 1177-1184. https://doi.org/10.1016/j.jclepro.2017.09.225

Nepal, R., Zhao, X., Dong, K., Wang, J., & Sharif, A. (2025). Can artificial intelligence technology innovation boost energy resilience? The role of green finance. *Energy Economics*, *142*, 108159. https://doi.org/10.1016/j.eneco.2024.108159

Ozkan, A. (2026). Exploring the drivers of renewable energy consumption: The roles of innovation, financial globalization, and uncertainty in Next-11 countries. *Journal of Research in Economics, Politics & Finance*, *11*(1), 120-139. https://doi.org/10.30784/epfad.1820631

Ozkan, O., Obekpa, H. O., & Alola, A. A. (2025). Examining the nexus of energy intensity, renewables, natural resources, and carbon intensity in India. *Energy & Environment*, *36*(1), 168-186. https://doi.org/10.1177/0958305X231169706

Pan, X., Uddin, M. K., Han, C., & Pan, X. (2019). Dynamics of financial development, trade openness, technological innovation and energy intensity: Evidence from Bangladesh. *Energy*, *171*, 456-464. https://doi.org/10.1016/j.energy.2018.12.200

Saint Akadiri, S., Ozkan, O., & Alola, A. A. (2025). Investigating the determinants of load capacity factor in Nigeria: An asymmetric quantile approach on urbanization, economic growth, FDI, and resource dependency. *Resources Policy*, *104*, 105586. https://doi.org/10.1016/j.resourpol.2025.105586

Sarigul, S. S., & Cetin, M. (2025). Renewable energy, fossil fuels, and globalization: Policy lessons from Japan for a sustainable future. *Journal of Sustainable Digital Futures*, *1*(1), 36-45. http://dx.doi.org/10.29228/jsdf.82693

Saudi, M. H. M., Sinaga, O., Roespinoedji, D., & Ghani, E. K. (2019). The impact of technological innovation on energy intensity: Evidence from Indonesia. *International Journal of Energy Economics and Policy*, *9*(3), 11. https://doi.org/10.32479/ijeep.7731

Sim, N., & Zhou, H. (2015). Oil prices, US stock return, and the dependence between their quantiles. *Journal of Banking & Finance*, *55*, 1-8. https://doi.org/10.1016/j.jbankfin.2015.01.013

Solarin, S. A., Bello, M. O., & Tiwari, A. K. (2022). The impact of technological innovation on renewable energy production: Accounting for the roles of economic and environmental factors using a method of moments quantile regression. *Heliyon*, *8*(7). https://doi.org/10.1016/j.heliyon.2022.e09913

Song, A., Rasool, Z., Nazar, R., & Anser, M. K. (2024). Towards a greener future: How green technology innovation and energy efficiency are transforming sustainability. *Energy*, *290*, 129891. https://doi.org/10.1016/j.energy.2023.129891

Wang, H., & Wang, M. (2020). Effects of technological innovation on energy efficiency in China: Evidence from dynamic panel of 284 cities. *Science of the Total Environment*, *709*, 136172. https://doi.org/10.1016/j.scitotenv.2019.136172

Wang, M., Li, Y., & Liao, G. (2021). Research on the impact of green technology innovation on energy total factor productivity, based on provincial data of China. *Frontiers in Environmental Science*, *9*, 710931. https://doi.org/10.3389/fenvs.2021.710931

Wang, W., Xiao, W., & Bai, C. (2022). Can renewable energy technology innovation alleviate energy poverty? Perspective from the marketization level. *Technology in Society*, *68*, 101933. https://doi.org/10.1016/j.techsoc.2022.101933

Wang, K. H., Wen, C. P., Long, H., & Moldovan, N. C. (2024). Towards sustainable development: Exploring the spillover effects of green technology innovation on energy markets and economic cycles. *Technological Forecasting and Social Change*, *203*, 123368. https://doi.org/10.1016/j.techfore.2024.123368

Zafar, S. Z., Zhilin, Q., Malik, H., Abu-Rumman, A., Al Shraah, A., Al-Madi, F., & Alfalah, T. F. (2021). Spatial spillover effects of technological innovation on total factor energy efficiency: Taking government environment regulations into account for three continents. *Business Process Management Journal*, *27*(6), 1874-1891. https://doi.org/10.1108/BPMJ-12-2020-0550

Zhang, R., & Fu, Y. (2022). Technological progress effects on energy efficiency from the perspective of technological innovation and technology introduction: An empirical study of Guangdong, China. *Energy Reports*, *8*, 425-437. https://doi.org/10.1016/j.egyr.2021.11.282

Zhang, Z., Luo, C., Zhang, G., Shu, Y., & Shao, S. (2024). New energy policy and green technology innovation of new energy enterprises: Evidence from China. *Energy Economics*, *136*, 107743. https://doi.org/10.1016/j.eneco.2024.107743