Journal of Environmental Management 359 (2024) 120971

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Role of energy transition in easing energy security risk and decreasing CO_2 emissions: Disaggregated level evidence from the USA by quantile-based models

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A R T I C L E I N F O

Keywords:
Energy transition
Energy security
CO_2 emissions
USA
Quantile-based models

A B S T R A C T

Consistent with the increasing environmental interest, the clean energy transition is highly critical to achieving decarbonization targets. Also, energy security has become an important topic under the shadow of the energy crisis,. Accordingly, countries have been trying to stimulate clean energy use to preserve the environment and ensure energy security. So, considering the leading role of economic size and volume of energy use, the study examines the USA to define whether energy transition helps decrease energy security risk (ESR) and curb CO_2 emissions. So, the study applies a disaggregated level analysis by performing quantile-based models for the period from 2001/Q1 through 2022/Q4. The results demonstrate that (i) the energy transition index decreases environmental ESR at higher quantiles and reliability ESR at lower and middle quantiles, whereas it is not beneficial in declining economic and geopolitical ESR; (ii) energy transition curbs CO_2 emissions in building and transport sectors at lower quantiles, whereas it does not help decrease CO_2 emissions in industrial and power sectors; (iii) energy transition is mostly ineffective on ESR, whereas it is highly effective in curbing CO_2 emissions in all sectors except for transport across various quantiles as time passes; (iv) the results differ according to the aggregated and disaggregated levels; (v) the results are consistent across main and alternative models. Hence, the study highlights the dominant effect of energy transition in curbing sectoral CO_2 emissions rather than easing ESR. Accordingly, the study discusses various policy implications for the USA.

1. Introduction

The world has been witnessing an escalated and continuous increase in energy over the past decades, which is driven by industrialization, increasing population, and economic growth pressures (Mujtaba et al., 2022; Adedoyin et al., 2023; Kartal et al., 2023a; Bekun, 2024). As the world economies continue to grow, the energy need increases in many industries, such as power, transportation, building, industrial, and households, and intensifies the strain on existing energy resources (Adekoya et al., 2021). The increasing reliance on energy creates higher consumption of electricity, fossil fuels, and other energy sources to feed industrial growth. However, the increasing energy demand comes with significant challenges, such as environmental degradation, CO_2 emissions, resource depletion, and energy security issues (Magazzino et al., 2020; Taşkın et al., 2022). Fossil fuels stand as the major responsible for CO_2 emissions (Alharthi et al., 2021; Ulussever et al., 2023). Moreover, fossil fuel reserves remain finite, and geopolitical tensions over these finite sources highlight the necessity of shifting to sustainable clean

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https://doi.org/10.1016/j.jenvman.2024.120971
Received 29 March 2024; Received in revised form 14 April 2024; Accepted 20 April 2024

energy sources to obtain the necessary energy to meet the booming energy demand while mitigating environmental deterioration (Doğan et al., 2020).

The limits of fossil fuel resources, alongside increasing tensions all around the world, pose threats to countries to meet the energy demands and create ESR. The ESR may stem from various sources as geopolitical risks, natural and climate disasters, changes in energy market dynamics, and technological disruptions (Iyke, 2024). The recent developments, such as the Russia-Ukraine conflict, have placed disruptions to the supply of energy as well as intensified the uncertainty in energy markets, and these developments have almost doubled household energy costs (Christopoulos et al., 2021; Inacio et al., 2023). The increasing concerns over reaching net-zero emissions and ensuring energy security have accelerated the search for energy transition in many countries (Rabbi et al., 2022). Energy transition is crucial to meet net-zero targets through shifting from fossil fuel usage to clean energy adaptation because such a transition brings a trigger for achieving carbon neutrality (Balcılar et al., 2019; Pata et al., 2024). There are several challenges inherent in energy transition, such as technological, economic, and social matters (Papadis and Tsatsaronis, 2020) and the paces of energy transition differ across countries. Irrespective of the speed of transition, many countries put energy security and economic concerns over environmental goals (Komendantova, 2021) and it can be expected that these motivations might hustle the progress on energy transition.

Among all countries, the USA has enjoyed remarkable growth as well as has been the biggest economy in the world (World Bank, 2024). The USA is a major country that makes high CO_2 emissions as the second largest emitter and has been known for its role in extensive usage of resources as of 2022-year end (Energy Institute, 2024). The extensive usage of natural resources and lower commitments to environmental agreements ended up with high levels of CO_2 emissions, environmental pollution, and significant levels of resource depletion (Zafar et al., 2019). There are significant obstacles that the USA has been facing in achieving energy transition including political, economic, and technological matters. Even though the clean energy transition has the potential for new opportunities in economies, it is also expected to reduce employment and tax revenues in carbon-intensive industries (Mayfield and Jenkins, 2021). Hence, several industry groups and political lobbies resist keeping the current energy structure that is dependent on fossil fuels and act contradictory to energy transition (Raimi et al., 2022). Yet, the USA has performed significant attempts to reduce energy intensity by about almost 20% until the beginning of 2020s, without cutting down on economic growth (Yang et al., 2021). Despite the reluctance of the government of the USA in most climate agreements, it is still seen that coal power plants with 100 GW capacity were halted between 2002 and 2021 and 59 GW will be retired by 2035 (Energy Information Administration, 2021). Shifting from coal power plants has caused the CO_2 emission growth to decline, but, this decline is caused by market forces instead of specifically designed policies.

Fig. 1 depicts the development of CO_2 emissions in the USA, by decomposing the emissions into significant sectors, such as building, industrial, power, transport, and total.

As seen from Fig. 1, CO_2 emissions tend to decline, but with minimal trend, where there is a significant disruption in emissions in the pandemic period, with returning to its track. Power generation and transportation sectors have the most significant role in CO_2 emissions (Yang et al., 2021), followed by building and industrial sectors, which analyze sectors of importance given their diverse effects.

When the energy prices are considered, crude oil prices display high volatilities and they are inclined to follow key macroeconomic and social issues despite their significant role as inputs of production (Alola et al., 2023). Various events have created climbs in energy prices, such as the Russia-Ukraine conflict, and created low regimes during the pandemic, reducing the crude oil prices below zero dollars. Thus, ESR is not only affected by political tensions but also by various factors that might create disruptions in the supply of energy sources and affect the availability of these energy sources at an reasonable price (IEA, 2022).

To ensure that global net zero targets are met, ESR factors, particularly those arising from imbalances between demand and supply should be investigated thoroughly. Given the "globally traded commodity" feature of petroleum and natural gas, with the high concentration of reserves in the Middle East, the supply of oil and gas is subject to high political instability. Thus, the geopolitical risk is a concern in energy security, that might create a shortage of energy sources following any dispute. ESR also has an economic risk component, given the fact that a significant part of national income for net oil-exporting countries is spent on energy. Thus, volatility in energy prices or upsurges in energy prices creates exposure in economic terms. ESR also carries a reliability issue in that any disruption to energy supplies creates high costs. Natural or deliberate attempts to energy supplies can create shortages, thus reliability issues can have economic or geopolitical effects. Lastly, energy security inherits environmental risks regarding the effects of energy to environmental effects as well as to the economic effects through the actions to reduce emissions. Given the divergence, yet interconnected nature of the constituents of the ESR, it is imperative to delve into the assessment of energy security determinants. Fig. 2 exhibits the evolution

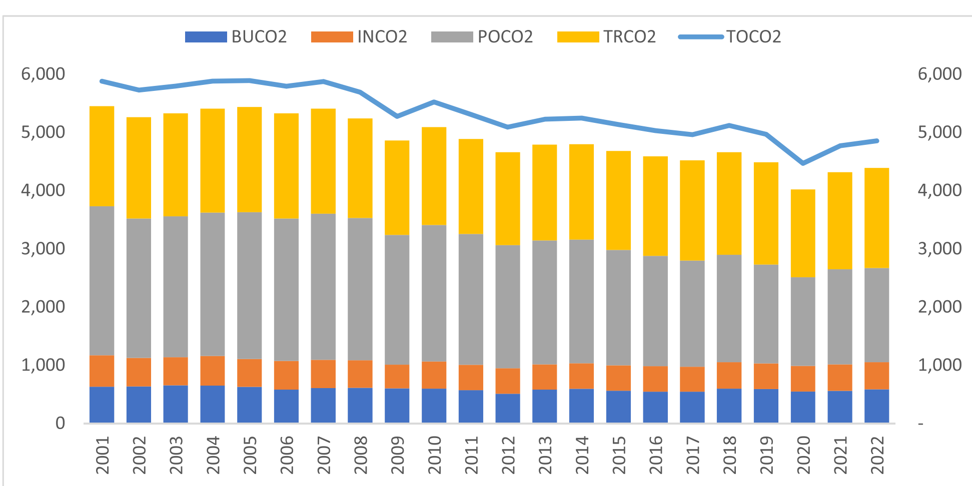


Fig. 1. Progress of CO_2 Emissions in the USA.
Note: The unit is a million tons. $BUCO_2$, $INCO_2$, $POCO_2$, $TRCO_2$, and $TOCO_2$ denote building, industrial, power, transport, and total CO_2 emissions, in order.
Source: EDGAR (2024).

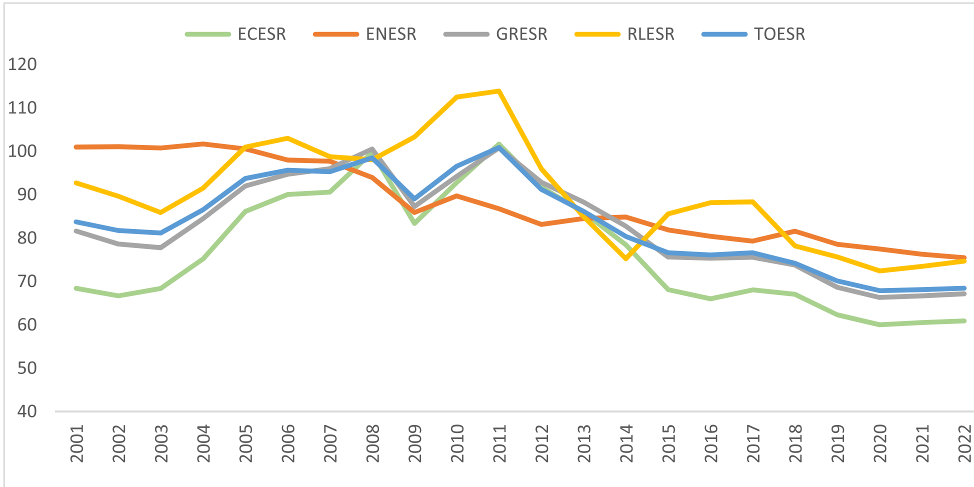


Fig. 2. Progress of ESR in the USA.
Note: ECESR, ENESR, GRESR, RLESR, and TOESR denote the economic, environmental, geopolitical, reliability, and total ESR, in order.
Source: USC (2024).

of these four pillars and the total ESR for the USA.

The graph shows a smooth decline in environmental ESR, whereas all other remaining ESRs have a varying nature with increases until the global financial crisis and there is a declining trend at large following it. Overall, the environmental and reliability factors seem to dominate all other types of ESR.

Given the necessity of curbing CO_2 emissions, alongside the disruptions to energy supplies due to geopolitical tensions and the recent energy crisis, the USA aims to decline fossil fuel consumption and shift to clean energy sources. Given the intricate nature of these variables, the study uncovers the effect of energy transition to mitigate ESR and CO_2 emissions by allowing for a disaggregated level analysis by focusing on the sub-components of ESR and CO_2 emissions at the sectoral level. So, the study adopts novel quantile-based models to investigate the time frame between 2001/Q1 and 2022/Q4. In this way, the study mainly reveals the dominant effect of energy transition in curbing sectoral CO_2 emissions rather than easing ESR.

The study provides some benefits to the literature. Firstly, despite the vast number of research focusing on the factors affecting CO_2 emissions, this is the sole study analyzing the effects of the energy transition on both ESR and CO_2 emissions simultaneously. Secondly, through the examination of sub-components of ESR and CO_2 emissions at the sectoral level, the study sheds light on the varying effects of energy transition within different segments of the economy. By doing so, the study allows researchers for a better understanding of the nexus between energy transition policies and their effects. Third, by using the most recent available data for the period 2001/Q1-2022/Q4 and performing quantile-based models, the study focuses on the temporal effects of energy transition effects, which enables a better explanation of the effects of evolving transition policies.

The remaining parts of the study is structured that Section 2 constructs the theoretical framework and reviews the literature; Section 3 presents the methods; Section 4 demonstrates the results; and Section 5 concludes.

2. Theoretical framework and literature review

2.1. Theoretical framework

As a major contributor to climate change, CO_2 emissions have far-reaching environmental effects including changes in precipitation patterns and extremely increasing temperatures (Li et al., 2023). To achieve decarbonization targets, it is highly important to transition from fossil energy sources to clean energy sources. In addition, energy security has gained importance with the effect of the current energy crisis.

Some countries, such as the USA, have begun to transition to renewable energy since the 1970s, and an energy transition program has been proposed to increase energy security while reducing fossil fuel dependence and curbing CO_2 emissions (Pata et al., 2024). In energy transitions, fossil fuels are replaced with clean energy sources to reduce emissions (Ahmad et al., 2024).

In the last few decades, the nexus between CO_2 emissions and clean energy sources has been comprehensively explored. Studies, such as Chen et al. (2021), underline that increasing CO_2 emissions is associated with the development of renewable energy, but Polcyn et al. (2021) argue that energy production from renewable sources does not depend heavily on CO_2 emissions. On one side, some studies have underlined the importance of renewable energy on CO_2 emissions (Cai and Wei, 2023). On the other side, some other studies, such as Rehman et al. (2023), have concluded that CO_2 emissions cannot be affected by renewable energy.

At the COP26 meeting, it was unanimously agreed that the energy sector must be aligned to combat climate change (Chu et al., 2023). It is urgently necessary to transform energy in a way that addresses both sustainable economic development and environmental sustainability. To reduce fossil fuel dependence and the associated risks, countries have been seeking cleaner and more sustainable (i.e., renewable or nuclear) energy sources as well as reducing CO_2 emissions and accelerating the transition to a sustainable future (Borozan, 2024). ESR pushes countries into more clean energy sources. Thus, fossil fuel use must be mitigated to reduce its negative effect on the environment without hindering economic growth. An energy shift may be necessary in these circumstances to maintain environmental sustainability. As a result of switching to clean energy sources, the development of eco-friendly products is encouraged, pollution is reduced, and ecosystem stress is eased. Using renewable energy can reduce dependence on nonrenewable energy markets, diversify energy supplies, and mitigate the effects of climate change (Seriño, 2022). To sum up, with renewable energy resources, the energy transition significantly lowers ESR.

Based on the aforementioned theoretical framework, the expected effect of energy transition can be shown in Fig. 3.

2.2. Empirical literature

This research aims mainly to uncover the effect of the energy transition on ESR and CO_2 emissions. Hence, the study examines the empirical literature under two sub-sections (i) the literature on energy

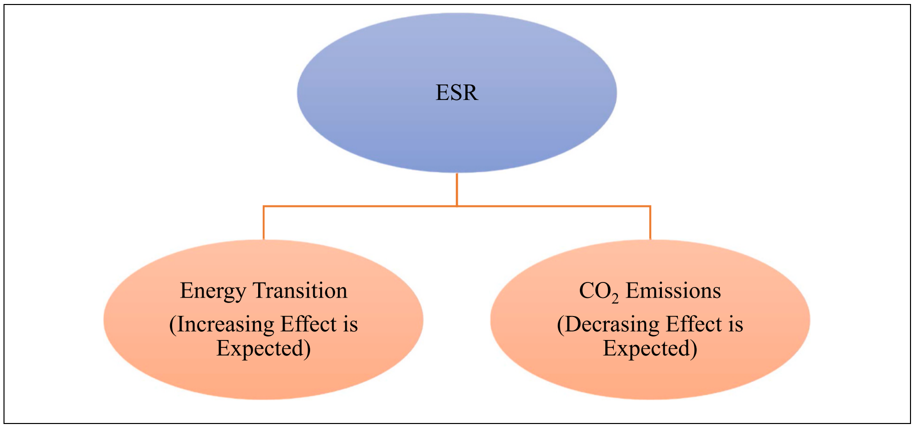


Fig. 3. Expected effect of energy security risk on ESR and CO_2 emissions.

transitions and energy security nexus, and (ii) the literature on energy transitions and environment nexus.

2.2.1. Literature on energy transition and energy security nexus

Research on the environment has been conducted in many different ways, particularly concerning CO_2 emissions and the EF (Adebayo and Kartal, 2023; Kartal et al., 2023b; Jahanger et al., 2023; Pata et al., 2023; Dam et al., 2024; Gyamfi et al., 2024). However, a limited number of studies have concentrated the effect of energy transition on ESR.

The study of Garg and Shukla (2009) concludes that carbon capture and storage has a declining effect on CO_2 emissions from large coal-based point sources and mitigates ESR for India. Oda et al. (2013) explore the link between energy security and CO_2 emissions in the USA and Western Europe and conclude the reducing effect on CO_2 emissions while maintaining energy security. Also, they reveal that Asian countries face a trade-off between energy security and CO_2 emissions. Selvakkumaran and Limmeechokchai (2013) focus on the energy efficiency perspective in Sri Lanka and define that it increases energy security, reduces conventional primary energy usage, which implies energy independence from fossil sources by enabling energy transition, and mitigates CO_2 emissions.

In recent times, using panel-based approaches for Asian economies, Shittu et al. (2021) aim to capture the link between the EF and ESR. They conclude that there is an adverse linkage between energy security and environmental quality, implying that the Asian economies must be energy-secure to prevent environmental degradation. Cergibozan (2022) concludes that ESR for OECD countries is reduced by hydro, wind, and total renewable electricity. Focusing on 41 BRI countries by applying panel data approaches, Aslam et al. (2024) find that ESR is significantly decreased by increasing renewable resources. Moreover, renewable energy resources significantly reduce ESR as a result of energy transition.

2.2.2. Literature on energy transition and environment nexus

In the literature, few studies have explored the negative effects of energy transition on the environment. However, the effects of an energy transition can play a significant role in climate governance and sustainable development on a national and global scale. To prevent future energy security crises, governments can use this document to develop and plan energy transition programs. Therefore, investigating the energy transition effect on energy security and the environment is an important issue.

Murshed (2020) examines the nonlinear effects of ICT-trade openness on the prospects for undergoing renewable energy transition, improving energy efficiency, and mitigating CO_2 emissions across selected South Asian economies. By boosting renewable energy use and improving energy efficiency, ICT-trade indirectly mitigates CO_2 emissions. According to Shi et al. (2020), energy transition projects improve air quality indices by curbing various air pollutants. Murshed et al. (2021) aim to explore the importance of clean energy transition on the environment and they argue that clean energy transition is very important in Bangladesh case.

For the OECD countries, an analysis of the effect of energy transitions by considering also clean energy consumption on the EF is realized by Khan et al. (2022a) from 1990 to 2015. They conclude that the quality of the environment is improved by energy transitions and renewable energy consumption. A similar model is conducted for the case of Switzerland, Sweden, and Denmark by Khan et al. (2022b) to identify the importance of energy transitions on the environment and determine the improving effect of energy transition in making the environment more sustainable.

In recent times, using panel approaches for top-ten manufacturing countries from 1995 to 2019, Bashir et al., 2023a,b conclude that environmental degradation can be mitigated through energy transitions. A similar argument is presented for the USA by Pata et al. (2024). Also, European Union countries have been investigated in terms of the effect of climate technologies and energy transition on CO_2 emissions by Ahmad et al. (2024) by using second-generation panel approaches. They define that European Union countries can mitigate CO_2 emissions by using the use of climate technologies and energy transitions.

2.2.3. Overall evaluation

The effect of renewable energy on the environment has been examined by many researchers, and the results mainly underlined that rising clean energy use is associated with a better environment (Dong et al., 2020; Usman, 2023). Moreover, some other studies (e.g., Shi et al., 2020; Ahmad et al., 2024; Kartal et al., 2024), underlined the importance of energy transition on the environment. According to Borozan (2024) and Iyke (2024), countries are seeking cleaner, more sustainable energy sources globally because of ESR. It is widely accepted that fossil fuel use must be mitigated to reduce its negative effect on the environment. However, the importance of renewable energy and energy transition on ESR is emphasized by the study of Cergibozan (2022), Aslam et al. (2024), and Tugcu and Menegaki (2024). However, any of this research has considered the role of energy transition on ESR and CO_2 emissions simultaneously. Therefore, the present research fills in the literature gap by focusing on the USA case.

3. Methods

3.1. Data and variables

To analyze the effect of energy transition on sub-components of ESR and sectoral CO_2 emissions, the study focuses on the USA. To do so, the study collects the data of energy transition, ESR, and sectoral CO_2 emissions from UNCTAD (2024), USC (2024), and EDGAR (2024), in order. Considering these factors, the yearly data for this study is gathered from 2001 to 2022.

Following the data collection, the annual data is converted into quarterly data by using a quadratic-sum approach consistent with the contemporary literature (e.g., Shahbaz et al., 2023; Kartal, 2024a). Also, by considering the contemporary literature (e.g., Kartal, 2024b), this research uses logarithmic differences series in running the novel quantile-based models. So, the study examines quarterly data between 2001/Q1 and 2022/Q4, which is the most up-to-date accessible dataset. Table 1 reports the properties of the variables.

3.2. Empirical methodology

To uncover the energy transition effect on sub-components of ESR and sectoral CO_2 emissions, the study follows up a comprehensive methodological process that consists of a total of eight steps as indicated in Fig. 4.

In the pioneering four steps, the study examines the main statistics. In doing this, descriptive statistics as well as correlations are analyzed first. Also, the nonlinearity structure of the variables is tested by applying the BDS test (Broock et al., 1996). Later, the stationarity characteristics of the variables are investigated by performing the PP test (Phillips and Perron, 1988). Hence, the empirical background of the model selection is constructed.

Considering the data characteristics, in the fifth step, the study uses the QQ model (Sim and Zhou, 2015) to make a quantile-based effect analysis. Hence, the effect can be investigated across quantiles of the variables. In the sixth step, the GQ model (Troster, 2018) is used to investigate quantile-based causality analysis. Hence, the causality effect can be uncovered across quantiles of the variables. In the seventh step, the CQ model (Han et al., 2016) is run to research the effects and whether they can differ across various time lags. Finally, the QR model (Koenker and Bassett, 1978) is used for the check the robustness check.

3.3. Quantile-based models

3.3.1. The QQ model

The QQ model is calculated by using Eq. (1):

$$Y_t = \beta^\theta(X_t) + u_t^\theta \tag{1}$$

where Y_t presents the dependent variable (i.e., ESR types and sectoral CO_2 emissions), X_t denotes the independent variables (i.e., ENTRI), θ refers to the θ^{th} quantile of the dependent variable, and u_t^θ is the error term. To examine the nexus between the θ^{th} quantile of Y_t and the τ^{th} quantile of X_t, $\beta^\theta(.)$ can be estimated via first-order Taylor expansion as follows:

$$\beta^\theta(X_t) \approx \beta^\theta(X^\tau) + \beta^{\theta'}(X^\tau)(X_t - X^\tau) \tag{2}$$

Table 1
Variables.

Symbol	Definition	Unit	Source
ECESR	Economic ESR	Index	USC (2024)
ENESR	Environmental ESR		
GRESR	Geopolitical ESR		
RLESR	Reliability ESR		
TOESR	Total ESR		
$BUCO_2$	Building Sector CO_2	Million Ton	EDGAR (2024)
$INCO_2$	Industrial Sector CO_2		
$POCO_2$	Power Sector CO_2		
$TRCO_2$	Transport Sector CO_2		
$TOCO_2$	Total CO_2		
ENTRI	Energy Transition Index	Index	UNCTAD (2024)

$$\beta^\theta(X_t) \approx \beta_0(\theta,\tau) + \beta_1(\theta,\tau)(X_t - X^\tau) \tag{3}$$

Overall, if Eq. (3) is replaced with Eq. (1), the QQ model can be rewritten as follows (Sim and Zhou, 2015):

$$Y_t = \beta_0(\theta,\tau) + \beta_1(\theta,\tau)(X_t - X^\tau) + u_t^\theta \tag{4}$$

3.3.2. The GQ model

Consideration of the causal nexus between the variables is crucial after examining the structure of dynamic correlation (Troster, 2018). Applying the VAR framework, the GQ model is beneficial for time series data analysis since it can identify causal linkages in different quantiles of both dependent and independent variables' distribution. Also, it is more useful than traditional causality tests because it can detect nonlinear causality and time-varying interactions (Zhang et al., 2024). Across the τ quantiles of the conditional distribution, this method is specified as:

$$H_0^{Z\nRightarrow Y} : Q_\tau^{Y,Z}\left(y \setminus I_t^Y, I_t^Z\right) = Q_t^Y\left(y \setminus I_t^Y\right) \text{ as for all } \tau \in \Gamma \tag{5}$$

where $Q_\tau^{Y,Z}(y \setminus I_t^Y, I_t^Z)$ represents the τ quantile of $F_Y(.\setminus I_t^Y, I_t^Z)$ (Troster, 2018).

3.3.3. The CQ model

The CQ model provides an estimate of bivariate directional spillover between two series in an asymmetrical and heavy-tail distribution as well as in outlier observations. Let $x_{i,t}$ $(t \in Z_i, i = 1,2)$ are two stationary time series, whose probability density and cumulative functions are denoted by $f_i(.)$ and $F_i(.)$, respectively. The quantile function is defined as:

$$q_i(\alpha_i) = \inf\{v : F_i(v) \geq \alpha_i \quad \text{for } \alpha_i \in (0,1)\} \tag{6}$$

$\Psi_\alpha(\mu) \equiv 1\ [\mu < 0] - \alpha$ represents the serial correlation between two series at different quantiles. The CQ for α quantile with k lags is given as:

$$\rho_\alpha(k) = \frac{E\left[\Psi_{\alpha_1}\left(x_{1,t} - q_1(\alpha_1)\right)\Psi_{\alpha_2}\left(x_{2,t-k} - q_2(\alpha_2)\right)\right]}{\sqrt{E\left[\Psi_{\alpha_1}^2\left(x_{1,t} - q_1(\alpha_1)\right)\right]}\sqrt{E\left[\Psi_{\alpha_2}^2\left(x_{2,t} - q_2(\alpha_2)\right)\right]}} \tag{7}$$

where $(x_{i,t-}q_i(\alpha_i))$ denotes quantile-hit procedure and $\rho_\alpha(k)$ displays the cross-correlation estimator of quantile-based (Han et al., 2016).

3.3.4. The QR model

The QR model is a nonparametric approach, which is more flexible than OLS, which has some assumptions (normality, homoscedasticity, etc.). The QR model can be modeled as follows:

$$Qy_{i,t}\left(\tau | x_{i,t}\right) = x_{i,t}^\tau\beta(\tau) + \alpha_i \tag{8}$$

Eq. (8) demonstrates that the effects of independent variables rely on the τ quantile level. α_i is a pure location shift effect on the conditional quantiles of the dependent variable. To estimate Eq. (8) for each quantile level, the minimization problem can be solved by using Eq. (9) (Koenker, 2004):

$$\min_{\alpha,\beta} \sum_{k=1}^{Q} \sum_{i=1}^{N} \sum_{t=1}^{T} w_k \rho_{\tau_k}\left(y_{i,t} - \alpha_i - x_{i,t}^T\beta(\tau_k)\right) \quad \rho_\tau(u) = u(\tau - I(u < 0)) \tag{9}$$

where w_k are the weights that control the relative effect of the quantiles on the estimation of independent variables. $\rho_\tau(u)$ defines the piecewise linear quantile loss function (Koenker and Bassett, 1978).

4. Results

4.1. Preliminary statistics

First of all, fundamental statistics of the variables are examined. In this context, Table 2 demonstrates the descriptive statistics.

Accordingly, The TOESR values range from 16.90 to 25.41 with an

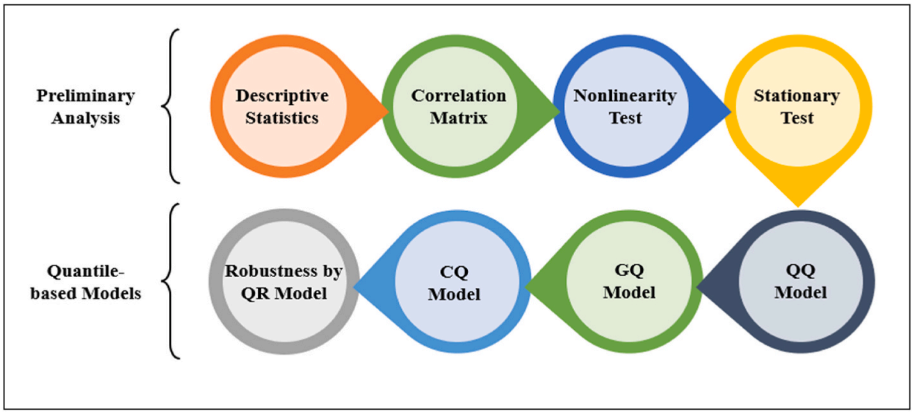


Fig. 4. Methodological processes.

Table 2
Descriptive statistics.

Variable	Mean	Max.	Min.	SD	Skewness	Kurtosis	JB	JB Prob.
ECESR	19.23	25.58	14.94	3.33	0.38	1.76	7.75	0.0208
ENESR	22.05	25.44	18.82	2.30	0.28	1.54	8.92	0.0115
GRESR	20.70	25.41	16.51	2.74	0.07	1.81	5.27	0.0717
RLESR	22.53	29.10	18.04	3.05	0.26	2.19	3.42	0.1808
TOESR	20.90	25.41	16.90	2.60	0.03	1.79	5.39	0.0674
$BUCO_2$	147.15	163.15	125.48	9.13	−0.21	2.54	1.43	0.4888
$INCO_2$	115.17	138.41	100.77	7.89	0.72	3.11	7.56	0.0228
$POCO_2$	533.87	645.51	378.17	81.98	−0.41	1.83	7.53	0.0232
$TRCO_2$	426.34	455.40	372.39	19.02	−0.65	3.17	6.30	0.0429
$TOCO_2$	1334.98	1478.21	1107.32	104.48	−0.15	1.97	4.19	0.1231
ENTRI	19.43	20.11	19.10	0.21	1.14	5.21	36.93	0.0000

Notes: Min: Minimum; Max: Maximum; SD: Standard Deviation; JB: Jarque-Bera. The unit for all sectoral GHG emissions is million tons.

average of 20.90. Meanwhile, $TOCO_2$ values vary between 1107.32 and 1478.21, averaging at 1334.98. Once the sub-components of ESR and sectoral CO_2 emissions are examined, the coefficient of variation remains consistently low across all variables, indicating minimal variability. According to the skewness, kurtosis, and Jarque-Bera test statistics, the null hypothesis, which assumes that the variable is statistically normally distributed, cannot be accepted for RLESR, $BUCO_2$, and $TOCO_2$, which indicates that all variables are nonnormally distributed (probability <0.10).

Also, the pairwise associations of the variables through the correlation matrix are presented in Table 3.

There is a significantly high correlation between ECESR versus GRESR and TOESR, GRESR versus TOESR, $POCO_2$ versus $TOCO_2$, and $TRCO_2$ versus $TOCO_2$. The coefficients of the aforementioned nexus are 0.98, 0.95, 0.97, 0.92, and 0.87, in order. In addition, there is a moderate correlation between ECERS versus ENESR, ENESR versus GRESR, and TOESR, $BUCO_2$ versus $POCO_2$ and $TOCO_2$, $INCO_2$ versus $POCO_2$ and $TOCO_2$, and $POCO_2$ and $TRCO_2$. The remaining pairwise correlations have a low effect.

Besides, the nonlinearity test results obtained by the BDS test are given in Table 4.

It is seen that all sub-components of ESR and all sectoral CO_2 emissions have either a nonlinear or mixed structure, except $POCO_2$, which has a linear structure. This result underscores the necessity of applying empirical models that capture the nonlinear nexus between variables. Moreover, the stationarity test results of the variables by using the PP test are presented in Table 5.

In the PP test, the unit root of the time series indicates non-

Table 3
Correlation matrix.

Variable	ECESR	ENESR	GRESR	RLESR	TOESR	ENTRI
ECESR	1.00					
ENESR	0.52	1.00				
GRESR	0.98	0.56	1.00			
RLESR	0.25	−0.15	0.29	1.00		
TOESR	0.95	0.52	0.97	0.49	1.00	
ENTRI	0.27	0.39	0.28	−0.16	0.22	1.00
	$BUCO_2$	**$INCO_2$**	**$POCO_2$**	**$TRCO_2$**	**$TOCO_2$**	**ENTRI**
$BUCO_2$	1.00					
$INCO_2$	0.05	1.00				
$POCO_2$	0.52	0.53	1.00			
$TRCO_2$	0.41	0.28	0.68	1.00		
$TOCO_2$	0.59	0.56	0.92	0.87	1.00	
ENTRI	0.17	0.45	0.39	−0.12	0.21	1.00

Notes: Values indicate correlation coefficients.

Table 4
Nonlinearity test results.

Variable	D2	D3	D4	D5	D6	Result
ECESR	0.0000	0.0000	0.0000	0.0000	0.0000	NL
ENESR	0.0081	0.1219	0.3366	0.0869	0.0479	M
GRESR	0.0000	0.0000	0.0000	0.0000	0.0000	NL
RLESR	0.0000	0.0000	0.0000	0.0000	0.0000	NL
TOESR	0.0000	0.0000	0.0000	0.0000	0.0000	NL
$BUCO_2$	0.0000	0.0001	0.0011	0.0013	0.0033	NL
$INCO_2$	0.0270	0.2688	0.6592	0.1689	0.0581	M
$POCO_2$	0.2151	0.9851	0.4762	0.9942	0.7487	L
$TRCO_2$	0.0000	0.0001	0.0009	0.0000	0.0000	NL
$TOCO_2$	0.0001	0.0069	0.0427	0.0139	0.0082	NL
ENTRI	0.0460	0.2192	0.3355	0.0271	0.0042	M

Notes: Values indicate probability values. D, L, NL, and M denote the dimension, linear, nonlinear, and mixed, in order.

Table 5
Stationarity test results.

Variable	Level	1st Differences	Decision
ECESR	0.0002	–	S
ENESR	0.0000	–	S
GRESR	0.0002	–	S
RLESR	0.0022	–	S
TOESR	0.0003	–	S
$BUCO_2$	0.0001	–	S
$INCO_2$	0.0000	–	S
$POCO_2$	0.0000	–	S
$TRCO_2$	0.0000	–	S
$TOCO_2$	0.0000	–	S
ENTRI	0.0000	–	S

Notes: Bartlett Kernel is used in the PP test. S denotes the stationarity.

stationarity, which is the null hypothesis. An alternative hypothesis for the time series' absence of a unit root is that it is stationary. Based on this information, it can be said that the null hypothesis can be rejected for each variable, which means that all variables are stationary.

To sum up, the fundamental statistics mainly present that the variables have mostly nonnormal distribution, there is a low correlation of ENTRI with ESR types and sectoral CO_2 emissions, and the variables highly follow either a nonlinear or a mixed structure. This requires to use of nonlinear models instead of linear methods to capture such data characteristics in empirical analysis. Accordingly, the study relies on novel quantile-based models for comprehensive empirical investigation in line with the data specialties.

4.2. QQ results

4.2.1. ENTRI effect on ESR

In the fifth step, to analyze the effect of ENTRI on ESR across quantiles, the QQ model is performed. In all QQ graphs, the x-axis represents ENTRI while the y-axis represents the respective ESR types. The effect of ENTRI on ESR types across quantiles is illustrated in Fig. 5.

The effect of ENTRI on ECESR, GRESR, and TOESR at different quantiles follow a similar structure. However, the effect of ENTRI on ENESR and RLESR is differentiated from other types of ESR. In general, the effect of ENTRI on ECESR, GRESR, and TOESR is relatively at a high level in the lowest and highest quantiles of ENTRI while this effect is close to zero around the middle quantiles of ENTRI. Contrarily, the effect of ENTRI on ENESR is relatively at a high level in the lowest quantiles of ENTRI. However, the effect of ENTRI on ENESR is getting weaker from the lowest quantiles to the highest quantiles of ENTRI. Finally, the effect of ENTRI on RLESR is significantly negative in the lower and middle quantiles of ENTRI while this effect gets stronger from the middle quantiles to the upper or lower quantiles of ENTRI.

4.2.2. ENTRI effect on CO_2 emissions

The QQ results for ENTRI effect on sectoral CO_2 emissions across quantiles are presented in Fig. 6.

The effect of ENTRI on $BUCO_2$ is highly negative in the lowest quantiles. However, the effect of ENTRI on $BUCO_2$ is getting weaker from the lowest quantiles to the middle quantiles. In addition, its effect turns to positive from negative after the middle quantiles and this positive effect is getting stronger at the highest quantiles. The nexus between ENTRI and $INCO_2$ is completely positive but differentiated from quantile to quantile. Similarly, the effect of ENTRI on $POCO_2$ is mainly positive. Moreover, the effect of ENTRI on $TRCO_2$ is around zero in all quantile combinations, except in the quantiles lower than 0.20. Finally, the effect of ENTRI on $TOCO_2$ is relatively at a high level in the lowest and highest quantiles of ENTRI while this effect is close to 0.50 around the middle quantiles of ENTRI.

4.3. GQ results

In the sixth step, the GQ analysis is used to measure the causality at different quantiles of variables. The GQ analysis results, which are reported in Table 6, show that there is, in general, a causality from ENTRI to sub-types ESR and sectoral CO_2 emissions. However, this causality is not statistically significant in some quantiles.

In the causality results obtained from ENTRI to ESR, there are two or three areas, where the aforementioned causality is statistically significant. In the causality from ENTRI to ECESR, the effect is statistically significant in all quantiles except for 0.45 and 0.85. Also, the causality from ENTRI to ENESR, GRESR, RLESR, and TOESR is significant in the quantiles from 0.10 to 0.35, but it is not significant around the middle quantile. Moreover, generally, it is significant between the middle and the upper quantiles except for the effect from ENTRI to ENESR. In the causality from ENTRI to ENESR, it can be said that there are three significant areas, where this effect is significant. These areas are the quantiles from 0.10 to 0.35, from 0.50 to 0.55, and from 0.85 to 0.90.

Once the causality from ENTRI to CO_2 emissions is examined, there are two distinct areas, where the causality effect is statistically significant. These areas are between the quantiles from 0.10 to 0.40 and from 0.60 to 0.90, except for ENTRI⇨$POCO_2$. In the causality from ENTRI to $POCO_2$, it can be said that there are three significant areas, where this effect is significant. These areas are the quantiles from 0.20 to 0.35 and from 0.65 to 0.90.

4.4. CQ results

4.4.1. ENTRI effect on ESR

The CQ model, which helps to determine the mutual quantile dependence of ENTRI with ESR types and sectoral CO_2 emissions, is performed for three different lags (i.e., 1, 2, & 4). The Box-Ljung test serves to assess the statistical significance of predictable directionality, with any insignificant correlations set to zero (Han et al., 2016).

Fig. 7 displays the quantile-based mutual significance between ECESR, ENESR, GRESR, RLESR, TOESR, and ENTRI for three different lags (3, 6, and 12 months).

According to Fig. 7, it can be said that the effects of ENTRI on ESR-related sub-components are highly positive. Nonetheless, even if the critical regions vary based on the lag sequence, they often become less strong in the second and third lags.

In the case of lag 1 for ECESR and ENTRI, the effect is relatively at a high level in the areas where the lowest and highest quantiles of both ECESR and ENTRI. However, this effect gets weaker in lag 2 and, in lag 4 case, it can be said that in the area, where the quantiles are higher than 0.75 in both ECESR and ENTRI, the effect is relatively high. In the case of lag 1 for ENESR and ENTRI, the effect of ENTRI on ENESR is statistically significant in the upper and lower triangles but not significant in the diagonal line. On the contrary, in the lag 4 case, it can be said that this effect is significant in the diagonal line.

In the effect of ENTRI on GRESR and RLESR in all three lag cases, there is no clear pattern but there are many significant effects in different quantile combinations. However, in the lag 1 case, the effect of ENTRI on TOESR is significant for almost all quantile combinations except in the area, where the quantiles are higher than 0.50 for ENTRI and lower than 0.50 for TOESR. The number of significant areas composed of quantile combinations declines from lag 1 to lag 4.

4.4.2. ENTRI effect on CO_2

The quantile-based mutual significance for $BUCO_2$, $INCO_2$, $POCO_2$, $TRCO_2$, $TOCO_2$, and ENTRI at three distinct lags (i.e., 3, 6, & 12 months) is displayed in Fig. 8.

There is a positive correlation between CO_2 emissions and ENTRI. Furthermore, the effect of key regions varies with lag order; it is less pronounced at lags two and four. When considering lag 1 for $BUCO_2$, the region, where the quantiles of $BUCO_2$ are greater than 0.75 and the

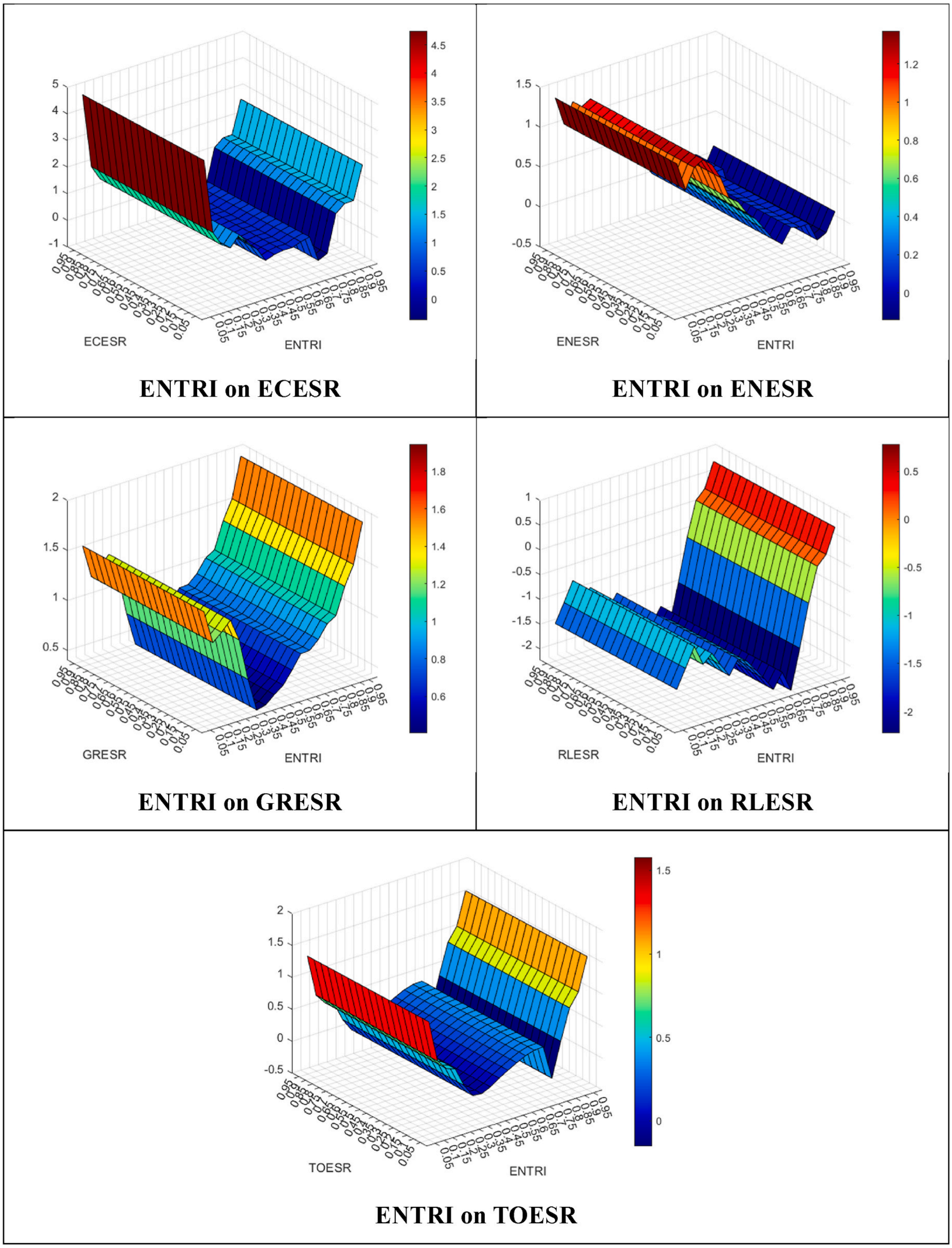


Fig. 5. QQ results for ENTRI effect on ESR types.

quantiles of ENTRI are between 0.45 and 0.65 is comparatively high for the effect of ENTRI on $BUCO_2$. Also, in the situations of lag 2 and 4, the effect is notably strong in the region, where the ENTRI and $BUCO_2$ quantiles fall between 0.35 and 0.45 and 0.35 and 0.65, respectively. Conversely, in lag 1, the effect of ENTRI on $INCO_2$ is generally significant across all quantile combinations except for the region, where the quantiles of $INCO_2$ and ENTRI are both between 0.45 and 0.75. Furthermore, this effect becomes less pronounced at lags 2 and 4.

The effect of ENTRI on $POCO_2$ is statistically significant in the lag 1 and 2 cases when the quantiles of ENTRI fall between 0.45 and 0.55. It can also be stated that this effect is significant in the lag 4 scenario in the region, where the ENTRI and $POCO_2$ quantiles are, respectively, between 0.65 and 0.95 and 0.25 and 0.35.

There are numerous significant effects in various quantile

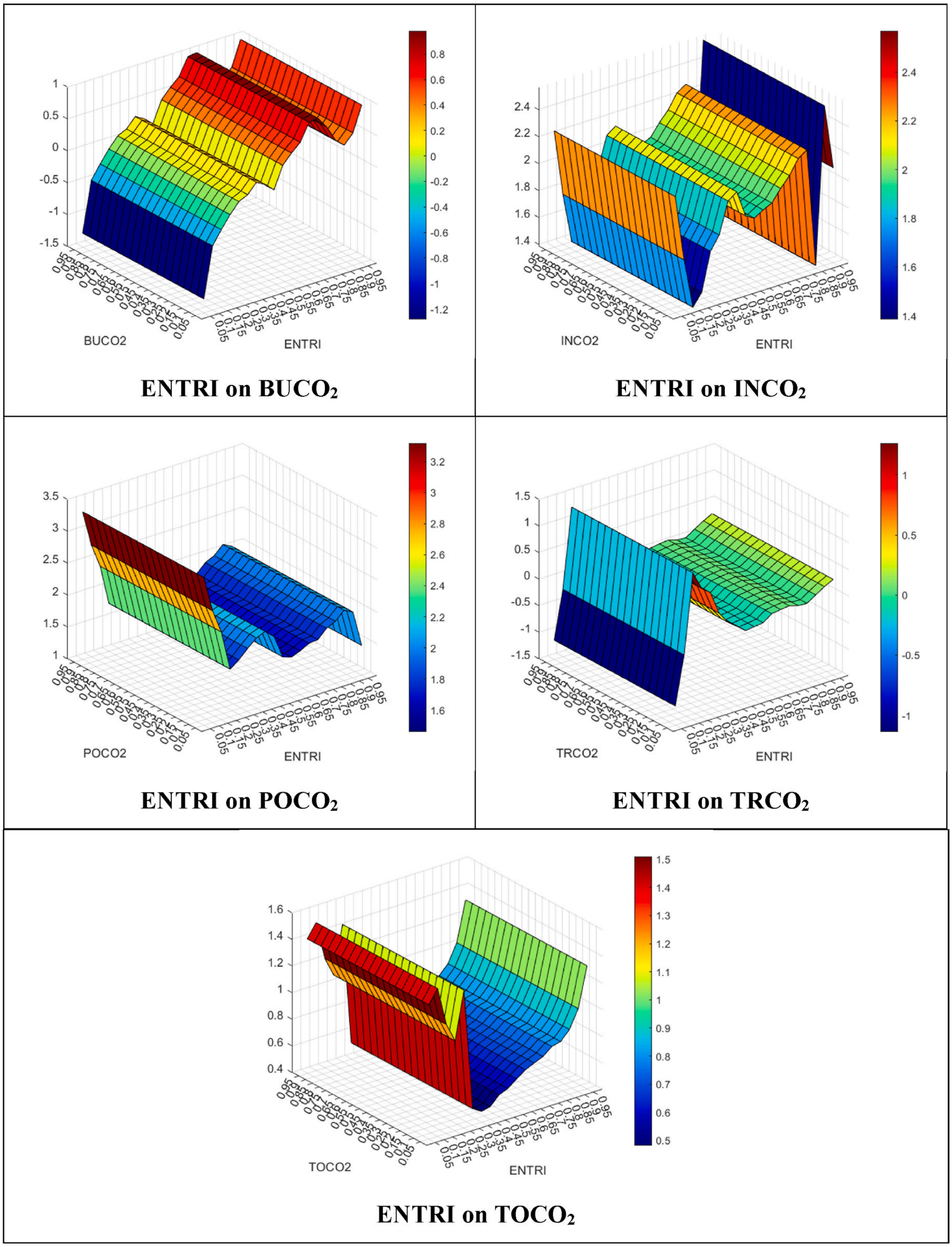


Fig. 6. QQ results for ENTRI effect on CO_2.

combinations, but there is no discernible pattern in the effect of ENTRI on $TRCO_2$ and $TOCO_2$ in the lag 1 instance. However, for lag 2, the region, where the quantiles of ENTRI and associated CO_2 variables lie between 0.45 and 0.50 and 0.15 and 0.50, respectively, is comparatively high for the influence of ENTRI on $TRCO_2$ and $TOCO_2$. Furthermore, the effect of ENTRI on $TRCO_2$ and $TOCO_2$ is noteworthy in a few key regions in the lag 4 instance.

4.5. *Robustness check*

Lastly, the QR model is performed to check the robustness of the QQ results. Annex 1 1 and 2 present the effect of ENTRI on ESR and CO_2 emissions obtained from both QQ and QR models comparatively. In all graphs, blue and orange lines represent the QQ and the QR coefficients, respectively. If these two lines are close to each other, it can be said that

Table 6
GQ results.

Causality Way	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95
ENTRI⇒ECESR	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.55	0.02	0.02	0.02	0.02	0.02	0.02	0.02	1.00	0.02	0.02
ENTRI⇒ENESR	0.21	0.02	0.02	0.02	0.02	0.02	0.02	0.43	0.64	0.04	0.05	0.30	0.46	0.57	0.73	0.21	0.05	0.02	0.45
ENTRI⇒GRESR	0.02	0.02	0.02	0.02	0.02	0.04	0.04	0.25	0.36	0.64	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.02	1.00
ENTRI⇒RLESR	1.00	0.02	0.04	0.02	0.02	0.07	0.07	0.02	0.13	0.02	0.04	0.09	0.05	0.04	0.07	0.04	0.11	0.02	0.07
ENTRI⇒TOESR	0.13	0.02	0.02	0.02	0.02	0.02	0.07	0.21	1.00	0.50	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.07	0.21
ENTRI⇒$BUCO_2$	0.05	0.02	0.02	0.02	0.02	0.02	0.04	0.04	0.18	0.38	0.32	0.05	0.02	0.02	0.02	0.02	0.02	0.02	1.00
ENTRI⇒$INCO_2$	1.00	0.02	0.02	0.02	0.02	0.02	0.02	0.04	0.02	0.39	0.64	0.04	0.02	0.02	0.02	0.02	0.02	0.02	1.00
ENTRI⇒$POCO_2$	0.09	0.30	0.16	0.04	0.02	0.02	0.04	0.29	1.00	0.91	0.48	0.52	0.02	0.02	0.02	0.02	0.02	0.02	1.00
ENTRI⇒$TRCO_2$	0.02	0.02	0.21	0.09	0.02	0.02	0.02	0.02	0.13	0.20	0.05	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.27
ENTRI⇒$TOCO_2$	0.05	0.02	0.02	0.02	0.02	0.09	0.04	0.04	0.02	0.91	0.52	0.02	0.02	0.02	0.02	0.02	0.02	0.07	1.00

Note: Values indicate probability values.

the robustness of the model used is relatively high. Besides, the correlations between QQ and the QR results obtained from different pairs are shown in Table 7.

As Table 7 presents, the correlation between QQ and QR results is quite high. In other words, there is a high similarity between the results of QQ and QR methods reaching 99%, which implies robustness. Hence, the results obtained from novel quantile-based models can be used to discuss various policy implications for the USA case.

5. Conclusion, policy implications, and future research

5.1. Conclusion and discussion

The whole world has been facing an ongoing energy crisis resulting from geopolitical tensions. In this context, energy transition has come to the force to curb ESR and ensure decarbonization of economics that is consistent with increasing environmental awareness of the societies. Accordingly, the recent focus point of policymakers has directed to the point whether countries can benefit from energy transition, which implies much more than phasing out fossil fuel energy use, to ease ESR and decrease CO_2 emissions. In uncovering answers to this research question, the study examines the USA case as the leading country in the world from the perspectives of economic size, high amount of energy use, higher CO_2 emissions, and low ESR. In doing this, the study uses disaggregated level ESR and CO_2 emissions by performing quantile-based models and using data for the period 2001/Q1-2022/Q4.

By following up on comprehensive theoretical and econometric approaches, the study determines that ENTRI decreases environmental ESR at higher quantiles and reliability ESR at lower and middle quantiles. However, ENTRI is not beneficial in declining economic and geopolitical ESR. Also, ENTRI curbs CO_2 emissions in building and transport sectors at lower quantiles. However, ENTRI does not help decrease CO_2 emissions in industrial and power sector CO_2 emissions. Besides, ENTRI is mostly ineffective on ESR, but, highly effective in curbing CO_2 emissions in all sectors except for transport across various quantiles as time passes. Moreover, the results vary based on aggregated and disaggregated level analyses. Furthermore, the results obtained in the study are consistent across base and alternative models. Hence, the study highlights the dominant effect of energy transition in curbing sectoral CO_2 emissions rather than easing ESR.

The results collected are mainly similar to the current literature. For example, ENTRI is generally ineffective in decreasing ESR similar to the studies of Oda et al. (2013) for the USA, Selvakkumaran and Limmeechokchai (2013) for Sri Lanka, Shittu et al. (2021) for Asian countries, and Cergibozan (2022) for OECD countries. Also, ENTRI is highly effective in curbing CO_2 emissions consistent with the studies of Shi et al. (2020) for China, Khan et al. (2022a) for OECD countries, and Pata et al. (2024) for the USA. While the study presents consistent results with the literature, it extends the current body of knowledge by applying disaggregated level analysis for both ESR and CO_2 emissions across different quantiles.

Focusing on the USA case, the study finds an answer (to the research question of whether countries can benefit from energy transition) that this is possible for curbing sectoral CO_2 emissions, but not valid for decreasing sub-types of ESR for the USA case. Overall, the study provides fresh insights into the effect of energy transition on both ESR and CO_2 emissions as well as makes some contributions to the literature in various ways, such as analyzing both ESR and CO_2 energy transition perspectives simultaneously, examining the issue by disaggregated level (i.e., sub-components) with a comprehensive point of view, making a nonlinear analysis to uncover the nexus across different quantiles.

5.2. Policy implications

Based on the novel robust insights obtained by following up a comprehensive approach, a variety of policy implications can be

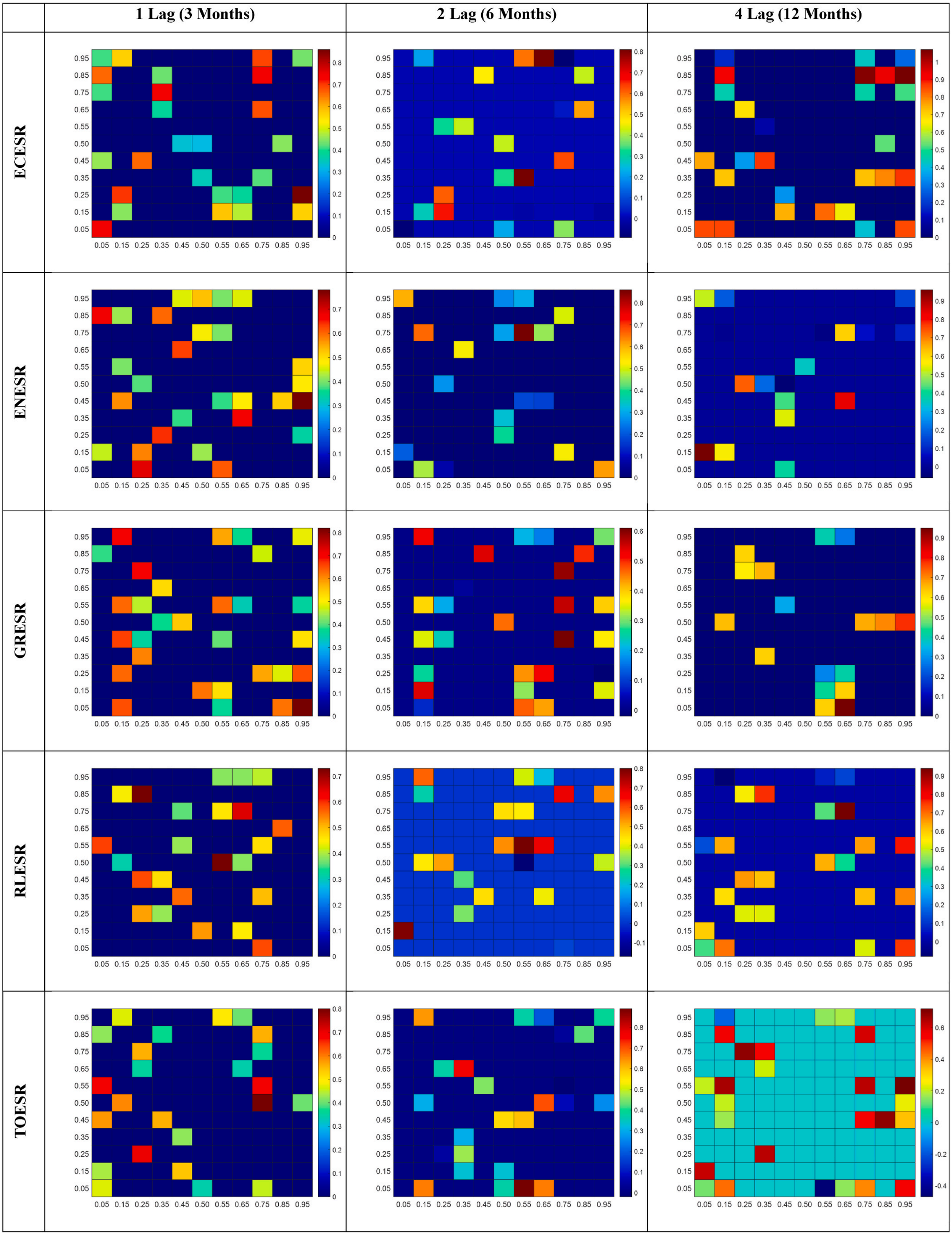


Fig. 7. CQ Results for ENTRI Effect on ESR
Note: y and x axes denote ESR and ENTRI, respectively.

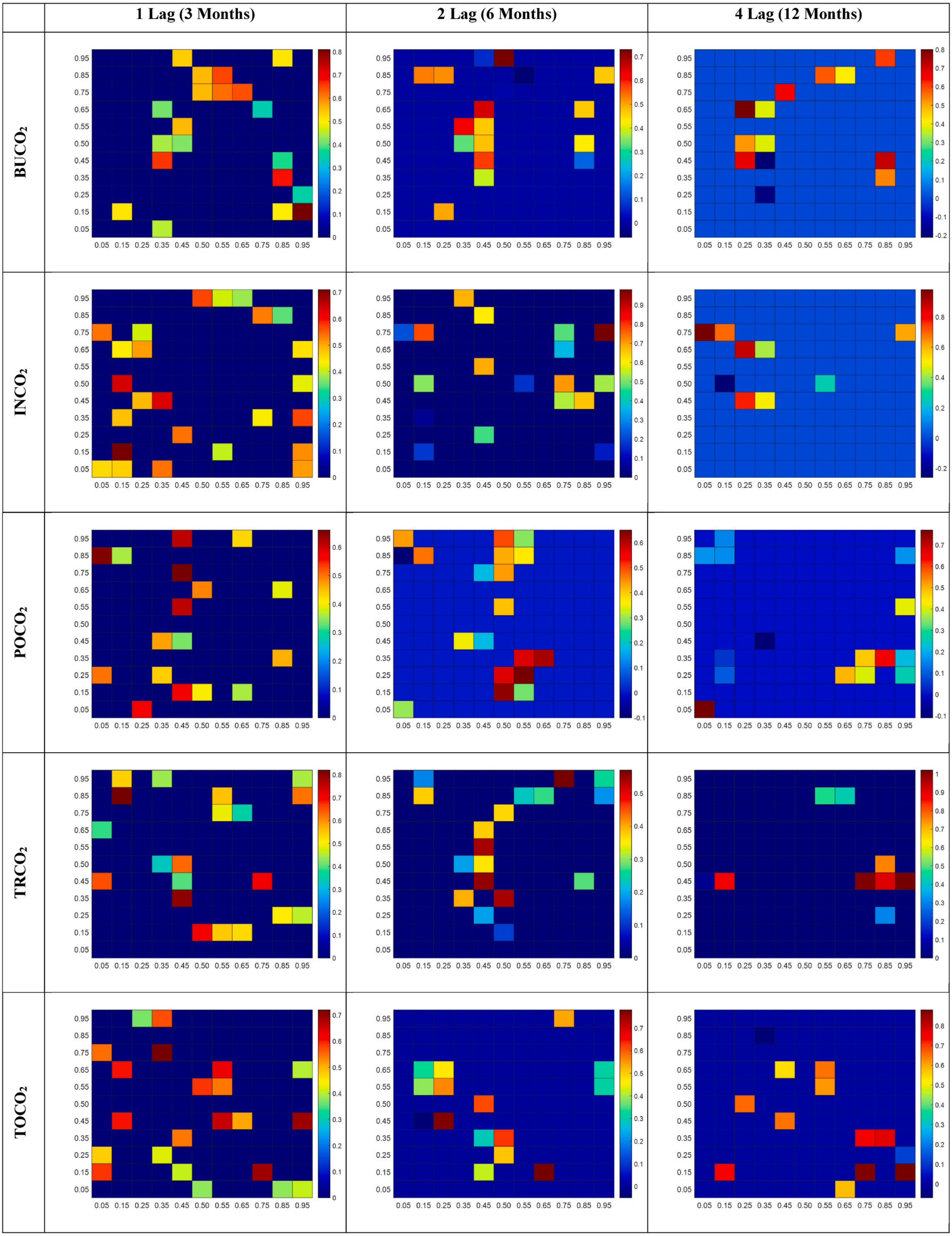


Fig. 8. CQ Results for ENTRI Effect on CO_2
Note: y and x axes denote CO_2 and ENTRI, respectively.

Table 7
Correlation between QQ & QR methods.

Variable Pair	Correlation (%)	Variable Pair	Correlation (%)
ENTRI on ECESR	99.99	ENTRI on $BUCO_2$	99.99
ENTRI on ENESR	99.91	ENTRI on $INCO_2$	99.99
ENTRI on GRESR	99.99	ENTRI on $POCO_2$	99.99
ENTRI on RLESR	99.87	ENTRI on $TRCO_2$	99.99
ENTRI on TOESR	99.99	ENTRI on $TOCO_2$	99.99

discussed for the USA case.

From the point of view of the effect on ESR, unfortunately, energy transition is not so much effective. On the other hand, energy transition is highly effective on CO_2 emissions. These findings reveal some critical facts for the USA policymakers. Based on these determinations, USA policymakers should further rely on curbing CO_2 emissions by benefitting from the energy transition. USA policymakers should promote the energy transition process and implement eco-friendly regulations including environmental ones for sustainable development. Hence, they can deal with further energy transition and decline CO_2 emissions in this way.

However, it is not the same case to decrease ESR. That is why energy transition is not highly effective in declining ESR. According to current knowledge, countries including the USA should invest more in clean energy and use less nonclean energy for long-term energy security. But, the results of this study do not support this point of view for the USA-case. Accordingly, the USA must take other measures to combat ESR rather than relying on only energy transition from nonclean to clean energy.

Another important point is that the effect of the energy transition on both ESR and CO_2 emissions differs according to disaggregated and aggregated level analysis. For example, energy transition is almost inefficient on ESR at an aggregated level, whereas it has a declining effect on environmental ESR at higher quantiles at disaggregated levels. It is also a bit similar to disaggregated level emissions. In detail, energy transition is almost inefficient on disaggregated level emissions at the aggregated level, however, it curbs CO_2 emissions in building and transport sectors at lower quantiles at a disaggregated level. In line with these determinations, USA policymakers must follow up on the effect of the energy transition on both disaggregated and aggregated levels of ESR and CO_2 emissions. Otherwise, they may disregard an important side and this may be a misleading point of view for policymakers in taking necessary measures on time.

Moreover, while some measures can be helpful, their effect may also vary as time passes. It is clear that the effect of energy transition becomes stronger in curbing CO_2 emissions, whereas it becomes weaker in declining ESR. This determination also requires the USA policymakers, which should monitor the progress of the effects of the energy transition on both ESR and CO_2 emissions not only for disaggregated and aggregated levels but also across various time lags.

5.3. Future research

By focusing on the USA case, the study way, the study finds an answer (to the research question of whether countries can benefit from energy transition) that this is possible for curbing sectoral CO_2 emissions, but not valid for decreasing sub-types of ESR for the USA case. In this context, the study follows up a comprehensive theoretical and empirical approach by making a disaggregated level analysis through using quantile-based methods. Thus, it is possible to present new insights from this study. However, it is not free from research limitations.

First, new research can focus on some other countries, such as Singapore, and GCC countries, that have higher ESR because this study analyzes only the USA case, which has a relatively low ESR with regard to other countries.

Second, new investigations can focus on some countries that have relatively lower energy transition. Besides, the countries, that have higher energy efficiency and lower energy use in this way, can be examined in new studies.

Third, the countries, that have lower CO_2 emissions, can also be investigated. Hence, whether the energy transition effect on ESR and CO_2 emissions varies across levels of CO_2 emissions can be analyzed.

Fourth, new studies can apply other novel techniques, Fourier-based models, Wavelet-based models, and artificial intelligence-based models including machine learning algorithms as well. By considering these points, the literature can be enriched much more.

Disclosure statement

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethics approval and consent to participate

Not applicable.

Consent for publication

The authors are willing to permit the Journal to publish the article.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Mustafa Tevfik Kartal: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Conceptualization. **Dilvin Taşkın:** Writing – original draft. **Muhammad Shahbaz:** Writing – review & editing. **Derviş Kirikkaleli:** Writing – original draft. **Serpil Kılıç Depren:** Writing – original draft.

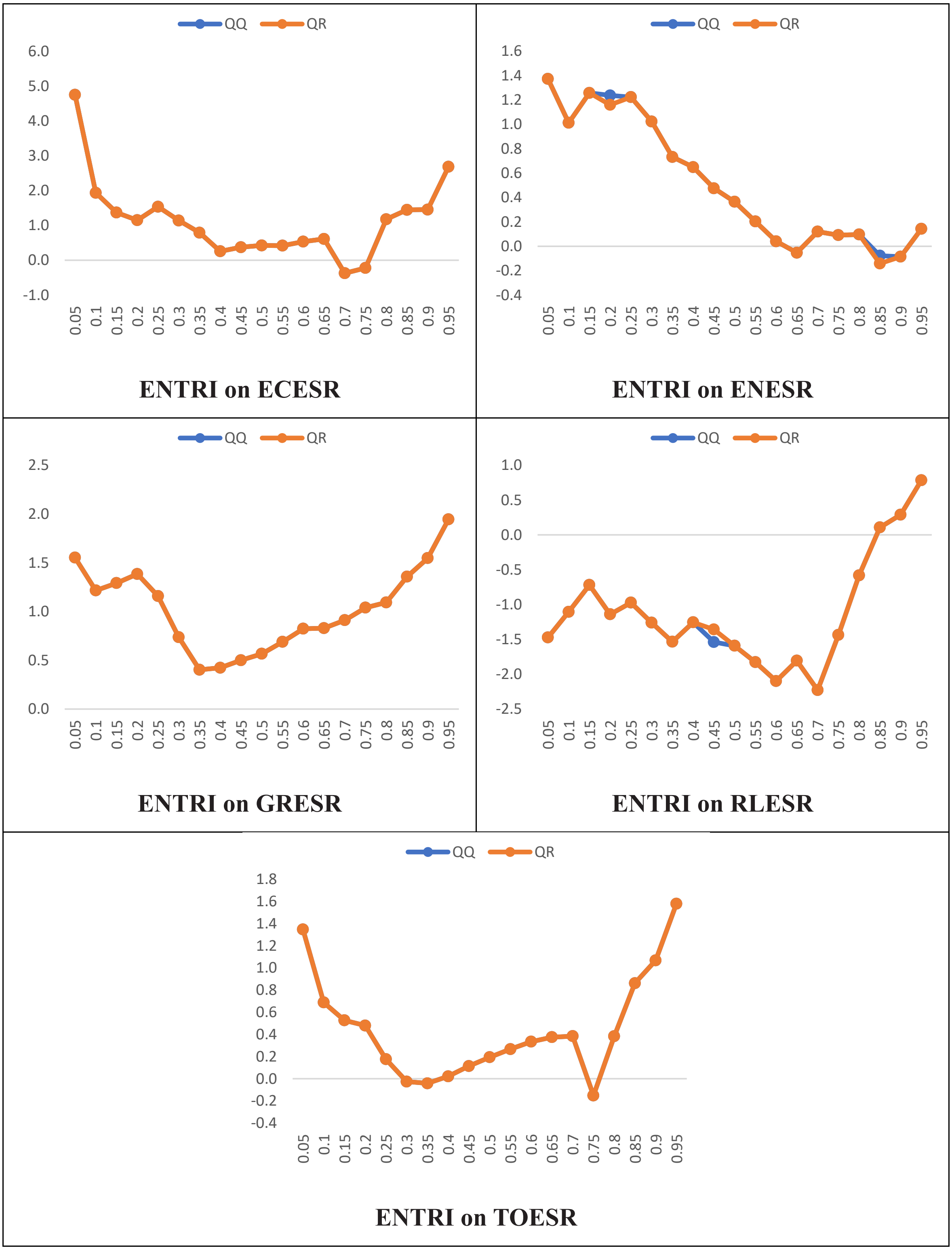
Declaration of competing interest

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

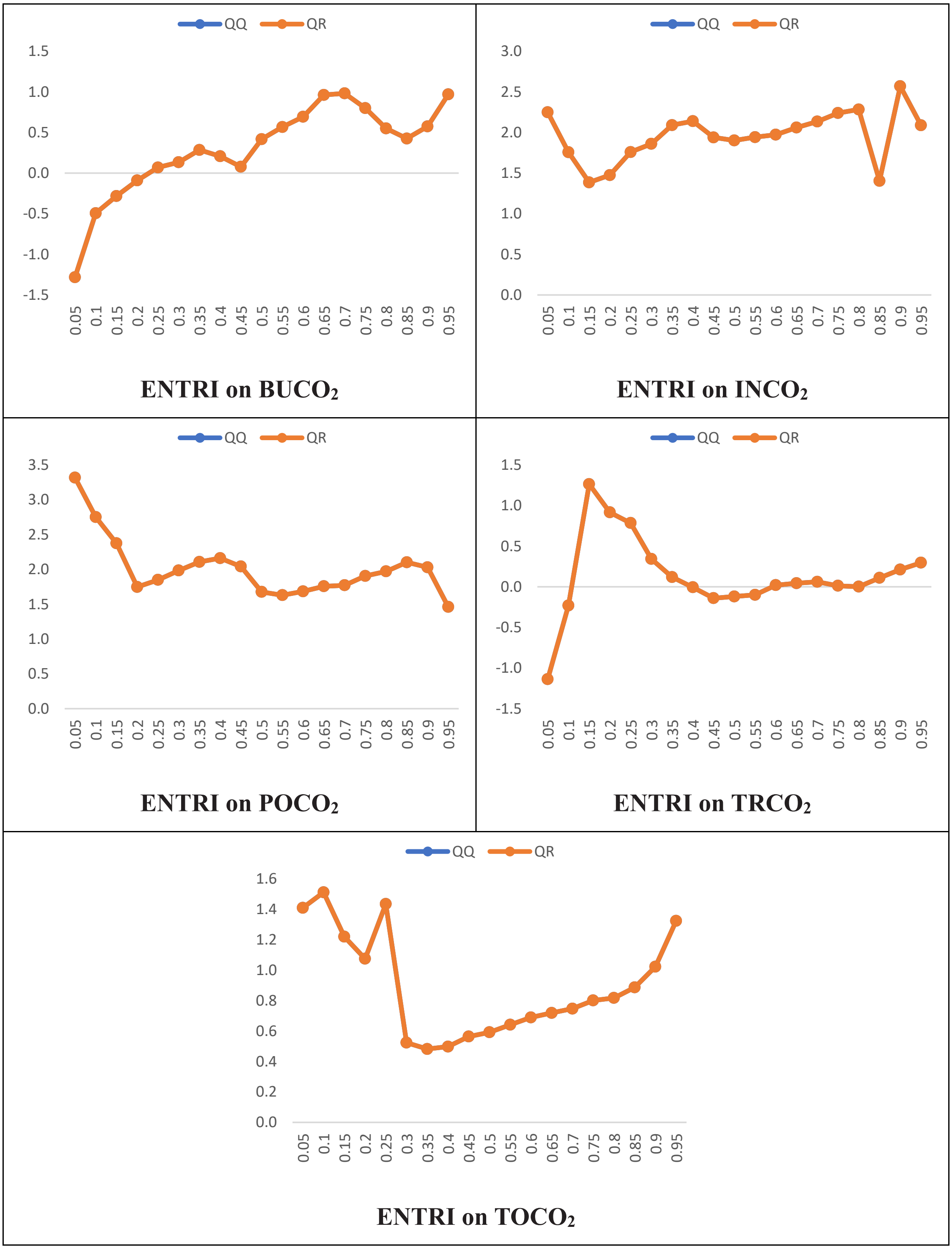
Acknowledgments

Not applicable.

Annex 1. QQ and QR Comparison for ENTRI Effect on ESR



Annex 2. QQ and QR Comparison for ENTRI Effect on CO_2



Acronyms

BDS	Broock, Scheinkman, Dechert, and LeBaron
COP	Conference of Parties
CQ	Cross Quantilogram
EDGAR	Emissions Database for Global Atmospheric Research

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(*continued*)

EF	Ecological Footprint
ESR	Energy Security Risk
ENTRI	Energy Transition Index
GQ	Granger Causality-in-Quantiles
PP	Phillips-Perron
QQ	Quantile-on-Quantile Regression
QR	Quantile Regression
UNCTAD	United Nations Conference on Trade and Development
USC	U.S. Chamber of Commerce's Global Energy Institute

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